K-25

K/ER-259

OAK RIDGE K-25 SITE

MARTIN MARIETTA

Mesosopic Structural Analysis of Bedrock Exposures at the Oak Ridge K-25 Site, Oak Ridge, Tennessee

P. J. Lemiszki

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from 615-576-8401 (fax 615-576-2865).

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Environmental Restoration Division
K-25 Environmental Restoration Program

**Mesoscopic Structural Analysis of Bedrock Exposures
at the Oak Ridge K-25 Site,
Oak Ridge, Tennessee**

Date Issued—July 1995

Prepared by
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee
and
Department of Geological Sciences
University of Tennessee
Knoxville, Tennessee
under subcontract 11X-SK271V

Prepared for
U.S. Department of Energy
Environmental Management and Enrichment Facilities
under budget and reporting codes EU 20 and EW 20
Oak Ridge K-25 Site
Oak Ridge, Tennessee 37831-7101
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

This document has been approved
for release to the public by:

S. B. Hilliland
Technical Information Officer

Oak Ridge K-25 Site

7/20/95

Date

ds
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

CONTENTS

FIGURES	iv
PREFACE	vi
EXECUTIVE SUMMARY	vii
1. INTRODUCTION	1
2. GEOLOGIC OVERVIEW	3
3. K-25 SITE STRUCTURAL DOMAINS	7
4. STRUCTURAL DOMAIN CHARACTERISTICS BASED ON OUTCROP MESOSCOPIC STRUCTURAL ANALYSIS	9
4.1 STRUCTURAL DOMAIN A	9
4.1.1 Site A1: Perimeter Road	9
4.1.2 Site A2: Northwest of K-25 Pumping Station	13
4.1.3 Site A3: Southeast of K-25 Pumping Station	16
4.1.4 Site A4: Poplar Creek in K-25 Site Area	19
4.2 STRUCTURAL DOMAIN B	19
4.2.1 Site B1: Campbell's Bend	22
4.2.2 Site B2: Gallaher Area	25
4.2.3 Site B3: Grid D4 Northeast Bank of Poplar Creek	28
4.2.4 Site B4: Boeing Property Quarry	28
4.3 STRUCTURAL DOMAIN C	31
4.3.1 Site C1: McKinney Ridge Quarry	36
4.4 STRUCTURAL DOMAIN D	36
4.5 STRUCTURAL DOMAIN E	39
5. DISCUSSION	40
5.1 FRACTURE SYSTEM	40
5.2 MESOSCOPIC FAULT SYSTEM	47
5.3 GEOLOGIC FACTORS INFLUENCING THE DEVELOPMENT OF OPEN FRACTURE PATHWAYS	51
6. CONCLUSIONS	60

FIGURES

1	An example of the complex interaction between fracture sets exposed on a weathered bed top in the Mascot Dolomite	2
2	Generalized geologic map of the Oak Ridge Reservation with the location of the study area surrounding the K-25 Site	4
3	Bedrock geologic map of the K-25 Site (Lemiszki 1994)	5
4	Geologic map of the K-25 site with designated structural domains A, B, C, D, and E used in this report	8
5	Stratigraphic section of the rock units in the K-25 area	10
6	Equal area, lower hemisphere stereonets of poles to bedding planes within each structural domain	11
7	Site A1 equal area, lower hemisphere stereonets of structural data	12
8	Bed top view of a fracture (f) transecting a jasperoidal chert pod in the Mascot Dolomite ...	14
9	Site A2 equal area, lower hemisphere stereonets of structural data	15
10	Site A3 equal area, lower hemisphere stereonets of structural data	17
11	An example of 2 mutually crosscutting extensional vein sets (large arrows) on a bed top of the Murfreesboro Limestone	18
12	Site A4 equal area, lower hemisphere stereonets of structural data	20
13	An example of the mesoscopic fold style observed at site A4	21
14	Site B1 equal area, lower hemisphere stereonets of structural data	23
15	An example of 2 conjugate normal faults at site B1 within the Murfreesboro Limestone	24
16	Site B2 equal area, lower hemisphere stereonets of structural data	26
17	An example of the normal faults at site B2	27
18	An example of the low angle thrust zone (t) and steep extension fractures (e) within the Carters Limestone at site B2	29
19	Site B3 equal area, lower hemisphere stereonets of structural data	30
20	Site B4 equal area, lower hemisphere stereonets of structural data	32
21	Mesoscopic anticline and related fractures in the hanging wall of the major thrust exposed at site B4	33
22	An example of left stepping (l) and right stepping (r) en echelon calcite vein sets exposed on a bed top of Ridley Limestone at site B4	34
23	An example of calcite slickensides exposed on the face of a steeply dipping en echelon vein set in the Ridley Limestone	35
24	Site C1 equal area, lower hemisphere stereonets of structural data	37
25	Major thrust fault (arrow) with folded and faulted hanging wall and footwall beds of the Knox Group at site C3	38
26	An example of the solutionally enlarged bedding strike-parallel and bedding strike-perpendicular fracture sets commonly observed in the area	41
27	Geologic map of the K-25 Site with a plot of the strike the dominant fracture sets observed at each study site	42
28	An example of two extension fracture sets exposed on the bed top of the Mascot Dolomite .	43
29	Sketch of the three-dimensional fracture architecture and the increased fracture complexity that occurs as additional fracture sets are added to the system	44
30	Thin clay seams between thin bedded limestones are common fracture termination points within the limestones and prevent the development of long fractures perpendicular to bedding	46

31	An example from the Ridley Limestone of the increased fracture intensity within thin, brittle, chert pods (c) as compared to the surrounding limestone	48
32	A typical example of the increase in fracture frequency associated with thin versus thick bedded limestones of the Murfreesboro Limestone	49
33	Geologic map of the K-25 area with the mean orientation of folds and faults observed at each study site	50
34	Normal fault in the Murfreesboro Limestone (f)	53
35	Local fracture development associated with faulting and folding in the Murfreesboro Limestone at site B1	54
36	Schematic of some various geologic factors influencing contaminant (groundwater) infiltration in the vadose zone in dipping carbonates	55
37	Photo of solutionally enlarged near vertical fractures in thicker bedded limestone of the Carters Limestone	56
38	Small cavity formed at the intersection between two steeply dipping fractures, that may be normal faults	57
39	Schematic of some various geologic factors that influence groundwater flow below the water table in dipping carbonates that is based on the relationship between the inclination of the water table and the dip direction of bedding	58
40	Schematic block diagram of the bedrock geology of the K-25 Site depicting the various map scale structures (faults and folds) that influence the geometry of stratabound flow units and that can increase the local fracture frequency within carbonates of the Chickamauga Supergroup	59

PREFACE

This report, *Mesosopic Structural Analysis of Bedrock Exposures at the Oak Ridge K-25 Site, Oak Ridge, Tennessee*, K/ER-259, was prepared to document site characterization data collected during scoping phase investigations in accordance with requirements under the Comprehensive Environmental Response, Compensation, and Liability Act. This work was performed under Work Breakdown Structure 1.4.12.4.1.05.03.03, Activity Data Sheet 4305 (K-25 Groundwater Program). Scoping phase data are collected to support ongoing and future remedial investigations on the K-25 Site.

EXECUTIVE SUMMARY

The purpose of this study was to investigate the small scale geologic structures, such as fractures, faults, and folds exposed in outcrops throughout the Oak Ridge K-25 Site. This report discusses the collection and interpretation of data using techniques of structural geology. The format was requested by the K-25 Groundwater Program staff within the Environmental Restoration Division to fully document the findings and the resulting interpretations. A critical need of the K-25 Groundwater Program is to understand the geology of the site, because various aspects of the groundwater system are directly influenced by stratigraphic and structural characteristics of the bedrock.

This work provides the first database on the mesoscopic fault and fracture system in the K-25 Site area. The data are used to interpret the relationship between fracture characteristics and factors such as lithology, bed thickness, and structural position. These observations can be used to develop criteria on which to predict fracture characteristics in areas with poor bedrock exposure. This work and the previous mapping on which it is based are required foundations for any future characterization of either the geology or the hydrology of areas requiring environmental restoration.

The complex bedrock geology of the K-25 Site has been divided into five structural domains. A structural domain is defined as a region with a unique map scale structural style commonly bounded by either faults or suspected faults. Not all structural domains could be studied, however, because of the absence of suitable bedrock exposures. Structural domains A and B, composed of the Knox and Chickamauga carbonates, contained eight of the nine study sites in this project. Mesoscopic structural analysis at these sites has lead to the following interpretations:

- (1) At each site there are at least two well developed extensional fracture sets that are commonly perpendicular to bedding. These two sets form an orthogonal system on bed tops, which consists of a bedding strike-parallel set and a bedding strike-perpendicular set. These fracture sets are represented by calcite veins and open fractures. These sets maintain their geometric relationship to bedding regardless of bedding orientation.
- (2) Additional fracture sets are present at most sites with strikes that are commonly within 30° , but as much as 45° clockwise or counterclockwise to the bedding strike-parallel fracture set. These sets also tend to be normal to bedding and are represented in both vein and open fracture measurements.
- (3) The close correlation between vein and open fracture sets suggests that the veins are opening as a result of weathering and stress relief. Therefore, new fracture sets are not forming as a result of uplift and erosion within the present-day stress field.
- (4) Thrust faults and reverse faults occur at all sites within structural domain B and represent typical geometries that develop within a foreland thrust belt. Thrust fault geometries throughout domain B are closely related to bedding geometry and generally strike and dip in the same direction as either the footwall or hanging wall beds. The lateral extent of each of the thrust faults observed generally cannot be ascertained because of poor exposure. Offset on many of these thrust faults appears to be minor, based on the lack of stratigraphic duplication.
- (5) Normal faults are best exposed in structural domain B at sites B1 and B2. At both sites the normal faults generally strike subparallel to, but cut steeply through bedding with minor displacement. The difference between the normal faults at these two sites is their orientation with respect to the macroscopic fold axes. At site B1 the normal faults strike perpendicular to the fold axis of the

perpendicular and fold hinge parallel normal faults with minor displacement may occur throughout structural domain B.

- (6) The majority of faults and folds observed in structural domain A occur at the southeast end of site A3 and at site A4, near the boundary between structural domains A and B. The structures appear to be concentrated along a nearly bedding strike-parallel zone of deformation within the Carters Limestone that was located during previous mapping. The uniqueness, abundance, and nearly consistent position along bedding strike of these structures is used to hypothesize that a thrust fault strikes nearly parallel to bedding across the area and probably dips to the southeast.
- (7) Two models depicting some of the stratigraphic and structural factors that influence the development of open fracture pathways are presented based on outcrop observations. One model focuses on factors influencing infiltration pathways in the vadose zone. The other model describes the combined influence of a groundwater mound, such as formed by a ridge, and the geologic factors influencing preferred groundwater flow directions. Although the applicability of either model still needs to be tested, they provide a framework in which to evaluate groundwater flow test results.

1. INTRODUCTION

At the request of the K-25 Groundwater Program, a detailed study of outcrop mesoscopic structures was conducted as a continuation to the geologic mapping completed in 1992-1993 (Lemiszki 1994). The purpose of this study was to document the geometry and style of outcrop scale (mesoscopic) structures, such as fractures and faults and relate them to the map scale (macroscopic) structures present in the Oak Ridge K-25 Site area. Mesoscopic structural data from work on other parts of the Oak Ridge Reservation (ORR) could not be used to infer the characteristics of the mesoscopic structures in the K-25 Site area because the site geology is unique. This work will benefit the Groundwater Program by providing the first database on the mesoscopic fault and fracture system in the K-25 Site area. Additionally, this work and the previous mapping are necessary foundations for any future characterization of the geology or the hydrogeology at the K-25 Site.

A preliminary analysis of the fracture system present in the K-25 Site area was completed as part of the 1992-1993 geologic mapping project (Lemiszki 1994). These early results hinted at the complex fracture sets present in the area and the need for a more detailed study to properly characterize them (Fig. 1). The previously collected data are incorporated in the present study. No other information on the fracture sets is available because all previous geologic studies focused on defining the stratigraphy and large-scale structures in the area.

The scope of the project involved detailed outcrop measurements and observations at nine study sites in and around the K-25 Site. The study sites include all of the major exposures that were previously mapped and are the most suitable sites for mesoscopic analysis in the area. The exposures are all within the Knox Group and Chickamauga Supergroup. No suitable outcrop exposures existed in the Rome Formation; however, approximately 15 ft (4.6 m) of core was examined. Study sites consisted of two old quarries, large road or natural exposures, and small exposures exposed along the river banks grouped together. All mesoscopic structural features were recorded, which includes folds, faults, veins, open fractures, and bedding. Hand samples consisting of filled fractures and faults were collected and thin sectioned to examine crystal textures indicative of fracture displacement modes and filling history. All structural measurements were made with a Brunton compass. Orientation data were plotted on stereonet, rose diagrams, and maps to facilitate discussion of structural features present at each outcrop and their relationship to the map structures. Furthermore, data from this study were used to develop a preliminary conceptual model of the geologic factors controlling groundwater flow paths in dipping carbonate bedrock units.

Fig. 1. An example of the complex interaction between fracture sets exposed on a weathered bed top in the Mascot Dolomite. At least 3 differently oriented systematic fracture sets occur in this outcrop. Note the random development of deep weathering pockets along fractures.

2. GEOLOGIC OVERVIEW

The ORR is located in the western part of the Appalachian Valley and Ridge physiographic province in east Tennessee (Fenneman 1938). The Valley and Ridge topography is the product of the differential resistance to erosion of folded and thrust faulted Cambrian through Pennsylvanian sedimentary rocks of the southern Appalachian fold-thrust belt (Rodgers 1953). The three regional thrust faults that are responsible for the bedrock structures present on the ORR are the Copper Creek, Whiteoak Mountain (WM), and Kingston faults (McMaster 1962). These thrust faults strike northeast, dip southeast and cause carbonate and noncarbonate Paleozoic stratigraphic units to be repeated three times (Fig. 2). The structural style of each thrust fault is unique, however, and represents a different element within a foreland thrust system (Lemiszki and Hatcher 1992). As a result of the unique structural style, mesoscopic structures such as fractures, folds, and faults differ within each thrust sheet.

The bedrock stratigraphic units on the ORR consist of Early Cambrian to Early Mississippian sedimentary rocks, but not all are present in the K-25 Site area. The stratigraphic units in the K-25 Site area are the Rome Formation underlying Pine Ridge and parts of the valley to the northwest, the Knox Group underlying Black Oak Ridge and McKinney Ridge, and the Chickamauga Supergroup, which underlies the low lying areas between by the foregoing ridges (Fig. 2). The Conasauga Group underlies Sugar Grove Valley to the northwest and Bear Creek Valley to the southeast of the site area. Neither shales nor carbonates of the Conasauga Group were found exposed in the site area, but it is possible that fault slices containing the Conasauga may exist at depth.

The K-25 Site area is located on the trailing edge of the Kingston thrust sheet adjacent to the WM fault (Lemiszki 1994). The WM fault places a hanging wall flat in the Rome Formation against a footwall ramp (Fig. 2). Bedrock structures in the footwall ramp are related to southeast-northwest directed shortening as a result of displacement on the WM fault. This shortening is expressed as fault-bound blocks of the Rome Formation and Knox Group adjacent to the WM fault, upright to overturned synclines of Ordovician to Mississippian age rocks farther into the footwall, and minor thrusting northwest of the synclines in Chickamauga carbonates. Bedrock structure in the site area is related to the development of the East Fork Ridge syncline, which is one of the doubly plunging and overturned footwall synclines that trends northeast-southwest parallel to the WM fault (Fig. 3). The southwest hinge of the syncline plunges gently to the northeast and is offset by the K-25 fault. The K-25 fault strikes parallel to bedding in East Fork Valley, but changes orientation and strikes northwest and intersects the WM fault on the southwest side of McKinney Ridge. In the hanging wall, the K-25 fault contains a continuous sequence of synclinally folded upper Knox Group through lower Chickamauga Supergroup and fault slices of the lower Rome Formation and lower Knox Group. In the footwall the fault cuts obliquely through northeast trending folds in the upper part of the Chickamauga Supergroup and then strikes parallel to bedding in the Carters Limestone. A steep fault dip is suggested by the closely spaced stratigraphic cutoffs in both the hanging wall and footwall. Displacement along the K-25 fault is interpreted to be towards the northwest, with the northwest striking portion of the fault acting as an oblique ramp and the northeast striking portion of the fault acting as a thrust. Within the site area, a nearly bedding strike-parallel zone of deformation mapped within the upper Carters Limestone may be defining a thrust that dips southeast and underlies the folded carbonates (Lemiszki 1994). Mesoscopic structures associated with this deformation zone will be described in this report. Additional subsurface data are needed, however, to determine whether this deformation zone represents a throughgoing thrust, and furthermore to constrain interpretations about the geometry of many of the faults within the K-25 Site area.

Study Area

Fig. 2. Generalized geologic map of the Oak Ridge Reservation with the location of the study area surrounding the K-25 Site. The Conasauga Group and Chickamauga Group underlie valleys all other rock units underlie ridges.

Fractures are the most pervasive mesoscopic structure on the ORR and occur in all stratigraphic units (Hatcher et al. 1992). The fracture system consists of systematic and nonsystematic fractures (Hodgson 1961, Dennis 1972). Systematic fractures are defined as planar fractures of a common orientation that are typically regional in extent. Systematic fractures are commonly divided into sets based on style, geometry, and timing of development. Nonsystematic fractures are random, planar to curvilinear, and commonly terminate at systematic fractures. Nonsystematic fractures are frequently encountered either mixed with systematic fracture sets or alone, pervasively fracturing the host rock unit. The systematic fracture sets were the focus of this study because their regularity and connectivity is considered a major factor controlling groundwater flow and conduit development.

The present geometry of the systematic fracture sets that comprise the fracture system in the area is related to the timing of individual fracture events (Hatcher et al. 1992). Fracture sets that formed prior to regional folding and thrust faulting are assumed to have formed in beds with a subhorizontal dip. Therefore one factor affecting their present orientation, with respect to geographic coordinates, will be the orientation of bedding produced as a result of regional thrusting and folding. Fracture sets formed during regional deformation will be related to structural position as well as structural history of the different thrust sheets. Fracture sets that formed after regional deformation should have a geometry independent of bedding attitude or structural position but rather be closely related to the neotectonic stress field. In addition to the complex stress history affecting the rock units in the area, differences in fracture orientations can arise solely by variations in mechanical properties between rock units, formation fluid pressure, and deviatoric stress during any particular fracturing event.

Fractures in outcrop and core on the ORR have been grouped from two to as many as four regional pre-thrusting fracture sets and local sets related to folding and thrusting (Hatcher et al. 1992). The two dominant pre-thrusting fracture sets define an orthogonal system on bed tops and are perpendicular to bedding. In particular, one set is bedding strike-parallel with moderate northwest dip and the other set is bedding strike-perpendicular with steep northeast or southwest dip (Hatcher et al. 1992). Most fractures are extension fractures, although offset chert pods and fossils indicate that hybrid and shear fractures also occur. The extension fracture sets are interpreted to have formed prior to folding and faulting because they (1) are cut by bed-parallel veins, (2) commonly have strained (twinned) calcite filling, and (3) have orientations controlled by bedding geometry. The early formed fracture sets, however, may have been reactivated during the development of the fold-thrust belt. Besides bedding strike-parallel and bedding strike-perpendicular fracture sets, a number of additional fracture sets occur adjacent to regional thrust faults and folds and within particular stratigraphic units. See Hatcher et al. (1992) for a detailed discussion of the geology of the ORR and Solomon et al. (1992) for an overview of the hydrology.

3. K-25 SITE STRUCTURAL DOMAINS

One way to describe the geology of the K-25 Site and discuss the mesoscopic structural data collected at individual outcrops is by dividing the area into structural domains. Structural domains can be designated at many different scales of observation. Based on the available outcrop exposures in the area, a structural domain is defined here as a region with a unique map scale structural style that is commonly bounded by either faults or suspected faults. With this definition in mind, the K-25 Site area can be divided into five different structural domains designated A, B, C, D, and E (Fig. 4). Domain A consists of the Knox Group on Black Oak Ridge and the Stones River Group to the southeast up to a previously defined bedding strike-parallel zone of deformation in the upper part of the Carters Limestone. At the surface the rock units in domain A are a homoclinally southeast dipping panel. Domain B consists of the folded and faulted Chickamauga carbonates underlying the main site area. Domain B is bounded to the northwest by the deformation zone, the WM fault to the southeast, and the K-25 fault to the northeast. Domain C consists of the Knox Group underlying McKinney Ridge and the Chickamauga Supergroup at the southwest hinge of the East Fork Ridge syncline. Domain C is bounded by the K-25 fault to the northwest and the frontal splay from the WM fault to the southeast. Domain D consists of the fault bounded slices of the Rome Formation adjacent to McKinney Ridge and to the southeast of the East Fork Ridge syncline and is bounded on the southeast by the WM fault. Domain E consists of the Rome Formation in the WM thrust sheet.

The mesoscopic structures present in outcrop are genetically linked to deformational events that affected all of the domains and to structures unique to a particular domain. Furthermore, the style of deformation within a structural domain is closely related to the mechanical characteristics of the deforming stratigraphic units. This is an important aspect of the domain concept, in that structures found in widely spaced outcrops can be extrapolated through the entire domain because the structural style remains the same. In addition, constraining observations in this way prevents confusion arising from mixing data from different domains. Of course it should be kept in mind that mesoscopic structures observed in an outcrop may be related to a buried map-scale structure and therefore not explainable based on the known structures. For this reason the development of anomalous mesoscopic structures within some study sites has been used to predict the location of a buried fault.

Fig. 4. Geologic map of the K-25 site with designated structural domains A, B, C, D, and E used in this report. Also shown are the 9 primary study sites and core location discussed in this report.

4. STRUCTURAL DOMAIN CHARACTERISTICS BASED ON OUTCROP MESOSCOPIC STRUCTURAL ANALYSIS

This section contains a detailed discussion of the mesoscopic structural data collected at each study site. Suitable study sites are not evenly distributed between domains or within each domain. In particular domains D and E did not have any large outcrops that could be studied, although the core from the Rome Formation is from domain E. In addition, the only exposure suitable for detailed study in domain C was the quarry in the Knox Group near Blair Road. Domains A and B are the best studied and underlie the largest portion of the site area. As with the domains, the fracture characteristics of each stratigraphic unit within each domain underlying the K-25 Site cannot be described because of the lack of exposure. This is unfortunate because the carbonates in the Chickamauga Supergroup are defined based on differences in lithology, thickness in bedding, and regularity in bedding, which are important parameters that control fracture development. Refer to Fig. 5 for the units available for study within each particular structural domain. Following are the results of mesoscopic structural analysis from the nine sites across the area based on structural domain.

4.1 STRUCTURAL DOMAIN A

Structural domain A is the largest domain in the area (Fig. 4). The domain includes Black Oak Ridge and the southwest extension of East Fork Valley. Stratigraphically the domain includes all of the Knox Group and the Stones River Group. The southwest extension of this domain is uncertain because a change in the map structure occurs where the rocks define the footwall position of the East Fork Ridge syncline fold hinge. The characteristic macroscopic structure that defines this domain is a northeast striking and southeast dipping homoclinal package of carbonates. A plot of 100 poles to bedding indicates that the mean strike and dip is 49/35SE (Fig. 6). Assuming that the structural style does not change significantly at depth, the rocks comprising domain A project beneath domain B and underlie the southern part of the site area at depths of approximately 800 ft (244 m). The results here therefore may be used to infer the mesoscopic structural characteristics of the Knox Group and Stones River Group carbonates at depth under the site area.

4.1.1 Site A1: Perimeter Road

The site is within the upper part of the Mascot Dolomite of the Knox Group. At this site massively bedded, dolostone bed tops and faces are exposed along strike for approximately 200 ft (61 m). Jasperoidal chert is abundant within the middle part of the outcrop within one massive dolostone bed. Bedding has a mean orientation of 60/40SE (Fig. 7).

Faults are rare to absent at this site. Three E-W striking fractures exposed on bed tops appear to have a minor amount of apparent left-lateral displacement.

Bedding plane normal calcite veins and open fractures are the most pervasive mesoscopic structure (Fig. 7A). A plot of vein and open fracture poles with a cylindrical best fit results in the mean bedding orientation, which indicates that the fractures are primarily normal to bedding, as observed in outcrop. The veins and open fractures cover a wide range of orientations but can be grouped into four main sets with approximately 10 degrees of strike and dip deviation in each set: 59/62NW, 90/65N, 300/80NE, and 338/85SW (Fig. 7B). Veins primarily represent the EW and NW sets, however, which may be a function of outcrop orientation highly favoring the exposure of the NW oriented veins.

		Lithology	Average Thickness (m)	Map Symbol	Structural Domain	Study Site	Rock Unit			
ORDOVICIAN	MIDDLE		120	Ocy	B & C	—	CATHEYS FORMATION	NASHVILLE GROUP	CHICKAMAUGA SUPERGROUP (Och)	
			27	Ocn	B & C	—	CANNON LIMESTONE			
			35	Oh	B & C	B3	HERMITAGE LIMESTONE			
			137	Oca	A, B & C	A3 A4 B2 B3	CARTERS LIMESTONE			
			40	Olb	A, B & C	A3 B4	LEBANON LIMESTONE			
			73	Ord	A, B & C	A2 B4	RIDLEY LIMESTONE			
			99	Om	A, B & C	A2 B1	MURFREESBORO LIMESTONE			
			116	Ops	A, B & C	A2	POND SPRING FORMATION			
	LOWER		122	Oma	A & C	A1	MASCOT DOLOMITE	KNOX GROUP (Ock)		
			174	Ok	A & C	C1	KINGSPORT FORMATION			
			35	Olv	A & C	C1	LONGVIEW DOLOMITE			
			227	Oc	A & C	C1	CHEPULTEPEC DOLOMITE			
CAMBRIAN	UPPER		279	Scr	A & C	C1	COPPER RIDGE DOLOMITE			
		CONASAUGA GROUP (Cc) NOT IN MAP AREA								
	LOWER		400?	Gr	D & E	—	ROME FORMATION			

Fig. 5. Stratigraphic section of the rock units in the K-25 area. Listed are the rock units exposed at each study site and within each structural domain.

Fig. 6. Equal area, lower hemisphere stereonets of poles to bedding planes within each structural domain. See text for discussion.

Fig. 7. Site A1 equal area, lower hemisphere stereonets of structural data. (A) Poles to fracture planes and mean bedding orientation at the site, V= Vein and J= Open Fracture. (B) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

A number of additional observations were made that are not quantifiable. The veins and fractures are primarily Mode I extension fractures because where they intersect chert pods there is no shear offset except for the three cases noted above (Fig. 8). Vein apertures range from hairline to 0.12 in. (3 mm), and open fractures are solutionally enlarged to various degrees. Bedding planes defined by bed-parallel stylolites are common fracture termination points, but the large outcrop scale fractures cut many beds. Highly siliceous zones commonly have a greater abundance of fractures. Fractures vary from long, continuous, and planar to short, stepping, and anastomosing zones that do not distinguish between sets.

The outcrop also exposes some down-dip flow features that may be characteristic of flow in the vadose zone in the Knox Group. There is a clear increase in the intensity of near surface weathering adjacent to infiltration points that diminishes with depth. Water bearing zones in the outcrop consist of bedding planes and steep fractures. For example, near the northeast end of the outcrop there is a bed-parallel solution opening feeding into a vertical drain that developed along a northeast striking bed normal fracture. Broken calcite formations have been transported down to the vertical drain and arch-shaped collapse fractures occur in the bedrock over the drain. The geometry suggests that flow occurs in a stair step fashion on the southeast sides of ridges underlain by the Knox Group (see discussion section).

4.1.2 Site A2: Northwest of K-25 Pumping Station

The site consists of a series of small, discontinuous exposures along the bank of the Clinch River from the K-25 Pumping Station to the last northwest outcrop. The site encompasses a zone of 15° rotation to the northwest of bedding strike associated with the hinge zone of the map scale syncline. Most of the data were collected from dolostone beds of the Mascot Dolomite and Kingsport Formation of the Knox Group and from limestones of the Pond Springs Formation and Murfreesboro Limestone of the Stones River Group. Although individual exposures are not very large, the data are best interpreted by combining results from a number of small exposures to provide a representative view of the fracture system in the area. Mean bedding orientation at the site is 45/37SE (Fig. 9A). No faults or folds were observed.

Bedding plane normal calcite veins and open fractures are the most pervasive mesoscopic structure (Fig. 9A). A plot of vein and open fracture poles with a cylindrical best fit results in the mean bedding orientation, which indicates that the fractures are primarily normal to bedding, as observed in outcrop. The veins and open fractures cover a wide range of orientation, but can be grouped into four main sets with approximately 10 degrees of strike and dip deviation in each set: 45/61NW, 81/70NW, 288/76NE, and 324/87NE (Fig. 9B). All sets are evident in both the vein measurements and open fracture measurements except for a NE striking vein set that is rare. The strikes of the main fracture sets are similar to those mapped at site A1 if the northwestward rotation of bedding is taken into account.

A number of additional observations were made that are not quantifiable. The veins and fractures are primarily Mode I extension fractures because where they either intersect each other or bedding there is no shear offset. Vein apertures range from hairline to 0.63 in. (16 mm), and open fractures are solutionally enlarged to various degrees. Bedding planes defined by bed-parallel stylolites or a distinct change in bed lithology, such as mudstone, are common fracture termination points, but some large outcrop scale fractures cut many beds. Highly siliceous zones commonly have a greater abundance of fractures. Fractures vary from long, continuous, and planar to short, stepping, and anastomosing zones that do not distinguish between sets.

Fig. 8. Bed top view of a fracture (f) transecting a jasperoidal chert pod in the Mascot Dolomite. The lack of shear offset of the chert pod indicates that this is an extension fracture.

Fig. 9. Site A2 equal area, lower hemisphere stereonets of structural data. (A) Poles to fracture planes and mean bedding orientation at the site, V= Vein and J= Open Fracture. (B) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

4.1.3 Site A3: Southeast of K-25 Pumping Station

The site consists of a series of discontinuous exposures along the bank of the Clinch River from the K-25 Pumping Station to the last outcrop to the southeast. Mean bedding orientation at the site is 59/40SE, which is similar to site A1 and representative of structural domain A (Fig. 10B). The site encompasses the northwest limb of the site area syncline. Most of the data were collected from limestone beds of the Murfreesboro Limestone through Carters Limestone of the Stones River Group. Although individual exposures are not large, the data are best interpreted by combining results from a number of small exposures to provide a representative view of the fracture system in the area.

Mesosopic normal faults, thrust faults, and folds were observed at site A3 (Fig. 10A). Five normal faults are distributed throughout the site, four of which had a mean orientation of N82W/47NE and the other is conjugate to them. The normal faults displacements range from near 0 to 2 ft (0 to 0.6 m). Calcite slickensides and blocky calcite partially cover the commonly weathered fault surfaces. Thrust faults and folds are concentrated at the southeast end of site A3 in a deformed zone where bedding dips flip-flop from southeast to northwest over a span of 100 ft (30.5 m). The presence of these structures was used by Lemiszki (1994) to hypothesize that the K-25 fault extends to the southwest into this area. Three thrust faults cluster around 15/15SE, the moderately dipping thrust was in a fold, and the other is a steeply dipping EW reverse fault. Displacements are unknown, except for about 1 ft (0.3 m) offset on one thrust. Mesoscopic folds generally trend ENE/WSW and plunge gently, but one fold trends SE and plunges moderately. A cylindrical best fit of poles to bedding contains a main cluster of southeast dips, but a girdle related to the folding associated with northwest bedding dips in the deformed zone suggests that the local fold axis has a mean trend and plunge of 73/11, which is consistent with mesoscopic fold axis measurements.

Bedding plane normal calcite veins and open fractures are the most pervasive mesoscopic structure at this site (Fig. 10B). A plot of vein and open fracture poles with a cylindrical best fit results in the mean bedding orientation, which indicates that the fractures are primarily normal to bedding, but there are many examples of bed oblique fractures. The veins and open fractures cover a wide range of orientation which is unique to this site, but can be grouped into five main sets with approximately 10 degrees of strike and dip deviation in each set: 39/69NW, 72/55NW, 279/67NW, 300/81NE, and 339/84SW (Fig. 10C). All sets are evident in both the vein measurements and open fracture measurements except for a NE striking vein set that is rare. There appears to be more scatter to the data, which may be an artifact of the increased number of measurements at this site compared to the previous sites. A more likely possibility, however, is that new fractures sets developed in this area related to the deformation zone. Some of the moderately dipping open fractures that do not fall into one of the sets have a similar orientation as the normal faults. A few local en echelon veins oriented 184/75NW, step left on bed tops along a trend of 335° (Fig. 11). Tracing these veins through beds indicates that they also are segmented and step vertically through bedding.

A number of additional observations were made that are not quantifiable. The veins and fractures are primarily Mode I extension fractures because where they intersect each other or cut across fossils there is no shear offset. Minor shear offset was observed on a few number of veins. Vein apertures range from hairline to 2 in. (50 mm), and open fractures are solutionally enlarged to various degrees. Bedding planes defined by bed-parallel stylolites or a distinct change in bedding characteristics from massive to cobbly are common fracture termination points, but some large outcrop scale fractures cut many beds. Highly siliceous zones commonly have a greater abundance of fractures. Fractures vary from long, continuous, and planar to short, stepping, and anastomosing zones that do not distinguish between sets.

Fig. 10. Site A3 equal area, lower hemisphere stereonets of structural data. (A) Poles to normal faults, reverse faults, and trend and plunge of fold axes. (B) Poles to fracture planes and mean bedding orientation at the site, V = Vein and J = Open Fracture. (C) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

Fig. 11. An example of two mutually cross-cutting extensional vein sets (large arrows) on a bed top of the Murfreesboro Limestone. Note that the intersection between the vein sets is not orthogonal, but an acute angle. Also present is a left-stepping en-echelon vein set that crosscuts one of the extensional vein sets (small arrows)

4.1.4 Site A4: Poplar Creek in K-25 Site Area

The site consists of a series of discontinuous exposures along the bank of Poplar Creek within the center of the site. Most of the data were collected from limestone beds of the Ridley Limestone through Carters Limestone of the Stones River Group. Mean bedding orientation at the site is 49/27SE, but bedding is folded and faulted. Most of the data from the site were collected within and near a deformation zone. Therefore, the data are most likely representative of the types of structures that formed adjacent to the deformation zone and not those seen within structural domain A. Although individual exposures are not large, the data are best interpreted by combining results from a number of small exposures to provide a representative view of the mesoscopic structural style in the area.

Mesoscopic thrust faults and folds are concentrated in a poorly defined deformation zone consisting of steep and overturned(?) bedding (Fig. 12A). Thrust faults have a mean orientation of 49/39SE. The faults are nearly parallel to bedding strike and cut obliquely through bedding at low angles. Where measurable, offset is minor. Mesoscopic folds generally trend ENE and plunge gently, but one fold trends SE and plunges moderately (Fig. 13). The folded and faulted beds are sheared, pulled-apart, polished on bedding planes, and may be brecciated. A cataclastic (fault rock) fabric was observed in thin sections from a block of limestone found in the area.

Although large exposures at this site are rare, bedding plane normal calcite veins and open fractures appear to be the most pervasive mesoscopic structure (Fig. 12B). A plot of vein and open fracture poles with a cylindrical best fit results in the mean bedding orientation, which indicates that the fractures are primarily normal to bedding, but there are many examples of bed oblique fractures. The veins and open fractures cover a wide range of orientation but can be grouped into four main sets with approximately 10 degrees of strike and dip deviation in each set: 49/72NW, 270/77NW, 309/86NE, and 1/77NW (Fig. 12C). All sets are evident in both the vein measurements and open fracture measurements.

A number of additional observations were made that are not quantifiable. The veins and fractures are primarily Mode I extension fractures because where they intersect each other or cut across fossils there is no shear offset. Vein apertures range from hairline to 0.24 in. (6 mm), and open fractures are solutionally enlarged to various sizes. Bedding planes defined by bed-parallel stylolites or a distinct change in bedding characteristics from massive to thin bedded with clay seams are common fracture termination points, but some large outcrop scale fractures cut many beds. Fractures vary from long, continuous, and planar to short, stepping, and anastomosing zones that do not distinguish between sets.

4.2 STRUCTURAL DOMAIN B

Structural domain B is the second largest domain in the area. The characteristic macroscopic structure that defines this domain is an anticline-syncline fold pair in the main site area. Stratigraphically the domain includes all of the units in the Chickamauga Supergroup, but most of the exposure is in the Stones River Group. The boundary between domain B and domain A to the northwest is the hypothesized location of a northeast-southwest striking deformation zone in the upper Carters Limestone. The boundary between domains B and D to the northeast is the known K-25 fault. The boundary between domains B and E to the southeast is the WM fault. The southwest boundary to domain B is not defined. A cylindrical best fit of 87 poles to bedding indicates that the macroscopic folds under the site plunge gently 4° along a 67° trend (Fig. 6). The fold axes are interpreted to trend more easterly towards the southwest in Campbell's Bend (see Fig. 4). Some macroscopic thrusts may occur within the folds as suggested by results below, however, their map-scale extent still needs to be resolved.

Fig. 12. Site A4 equal area, lower hemisphere stereonets of structural data. (A) Poles to thrust faults and trend and plunge of fold axes. (B) Poles to fracture planes and mean bedding orientation at the site, V = Vein and J = Open Fracture. (C) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

Fig. 13. An example of the mesoscopic fold style observed at site A4. Thin to cobbly beds of the Carters Limestone are deformed in open, chevron folds.

4.2.1 Site B1: Campbell's Bend

The site consists of a single large exposure that forms a prominent bluff on the southwest bank of the Clinch River on Campbell's Bend. Most of the data were collected from thin to thick, regular, and uneven to evenly bedded micrites of the Murfreesboro Limestone, but some data from massive beds of the overlying Ridley Limestone are also included. Mean bedding orientation at the site is 311/22NE, and represents the hinge zone of the map scale syncline that plunges to the northeast under the site. The projection of the deformed zone located at site A3 is northwest of this site, which places the site within domain B.

Faulting at this site consists primarily of conjugate sets of mesoscopic normal faults that strike perpendicular to the macroscopic fold hinge (Fig. 14A). The faults can be traced through the entire exposure as narrow, steeply dipping zones of deformation with minor displacement. Five normal faults were measured at the site, three of which had a mean orientation of 345/47NE and two that are conjugate to them. In general, the faults strike parallel to bedding but dip steeper than bedding. Maximum recorded fault displacement is approximately 4 ft (1.2 m), but faults can be traced vertically through beds from regions of maximum offset to no offset. The amount of displacement is also reflected in the style of deformation along the fault zone. For example, structures associated with one set of conjugate normal faults change from single, continuous faults in regions of maximum displacement to regions of minor bed folding and associated fracturing where offset is decreasing and then into discontinuous, en echelon veins zones where there is no offset (Fig. 15). Normal faults are some of the most continuous structures through the entire exposure and tend not to be affected by changes in bedding characteristics. One steeply dipping reverse fault zone with approximately 8 in. (20.3 cm) of displacement has a similar orientation as the normal faults. Besides this single reverse fault, no other folds or thrusts (faults cutting bedding at a low angle) were found.

Bedding plane normal calcite veins and open fractures are the most pervasive mesoscopic structure. A cylindrical best fit great circle to vein and open fracture poles is 322/14NE, which comes close to the mean bedding orientation indicating that the fractures are primarily normal to bedding (Fig. 14B). The veins and open fractures can be grouped into four main sets with approximately 10 degrees of strike and dip deviation in each set: 40/88NW, 332/69SW, 302/75SW, and 353/82SW (Fig. 14C). The different orientation of the fracture sets at this site is a result of the change in bedding orientation associated with the hinge of the syncline. The fracture sets at this site, however, have a similar geometry with respect to bedding as seen in domain A. In other words, if bedding is rotated parallel to the mean bedding orientation in domain A, then the fracture sets have a similar orientation as in domain A. Based on orientation, veins and open fractures form the same sets except that only two northeast striking veins were recorded as compared to numerous open fractures. Determining the true dip on many of the vertically dipping fractures was difficult because they are associated with weathered planar bed faces and solutionally enlarged fractures. Open fractures that extend through the entire exposure are generally irregular, non-planar zones of dissolution.

Numerous additional observations were made that are not quantifiable. The veins and fractures are primarily Mode I extension fractures because where they intersect each other there is no shear offset and faint plumose structures are preserved on a few fracture faces. Vein apertures range from hairline to 0.12 in. (3 mm), and open fractures are solutionally enlarged to various degrees. Bedding planes defined by bed-parallel stylolites or a distinct change in bedding characteristics from regular and even to cobbly beds are common fracture termination points, but some large outcrop scale fractures cut many beds. The style and abundance of fracturing varies between beds of different lithology and regularity. For example, highly siliceous beds with chert pods commonly have a greater abundance of fractures. Fracture styles within each set vary from long, continuous, and planar to short, discontinuous, and irregular.

Fig. 14. Site B1 equal area, lower hemisphere stereonets of structural data. (A) Poles to reverse faults and normal faults. (B) Poles to fracture planes and mean bedding orientation at the site, V= Vein and J = Open Fracture. (C) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

Fig. 15. An example of 2 conjugate normal faults at site B1 within the Murfreesboro Limestone. Within the top half of the photo the normal faults are single, continuous fractures (a). As the faults converge, a number of additional synthetic faults formed. Where the conjugate faults intersect, intense veining occurs, especially in the limestone bed with chert pods (b).

4.2.2 Site B2: Gallaher Area

The site is an approximately 300 ft (91.4 m) long escarpment oriented northwest-southeast on the southwest bank of Poplar Creek near Gallaher Cemetery. The data were collected from thin to medium, irregular, uneven, bedded limestones interbedded with thick, regular, and even bedded limestones of the Carters Limestone. Mean bedding orientation at the site is 68/23SE, and represents the southeast limb close to the hinge of a map scale anticline. This site also lies near the southeast boundary of domain B close to the WM fault. In fact, the WM fault may be adjacent to the site because along the creek bank to the southeast are intensely fractured limestones adjacent to maroon and green shale saprolite that may be from the Rome Formation. The area was mapped as part of the shaley beds in the Hermitage Limestone (Lemiszki 1994), but the association with intensely fractured (brecciated?) limestone beds may favor them being lower Rome shales along the WM fault.

All along the top of the escarpment is a series of moderately dipping normal faults with a mean orientation of 34/33NW (Fig. 16A). Displacements range from 0.08 to 5 ft (0.025 to 1.52 m). Most faults are long, continuous, planar surfaces that are not affected by changes in bedding characteristics. Other normal faults consist of a two or three synthetic faults defining a fault zone (Fig. 17). Some hanging wall blocks are slightly rotated back towards the bounding normal faults suggesting that some of the poorly exposed faults may have a listric (curved) geometry. A few normal faults with similar characteristics were also mapped along the base of the escarpment. Secondary fracturing associated with normal fault development was absent.

Thrust faults at this site are confined to a narrow, nearly bed-parallel zone close to the base of the escarpment. The faults have a mean orientation of 67/32SE, which is parallel to bedding strike and steeper than bedding dip (Fig. 16A). Displacement along the thrust faults could not be determined in most cases, but a few faults offset chert pods approximately 1 ft (0.3 m). The faults are commonly planar and at a low angle to bedding, but a few curve into bedding planes.

Bedding plane normal calcite veins and open fractures are the most pervasive mesoscopic structure (Fig. 16B). A cylindrical best fit to vein and open fracture poles results in the mean bedding orientation, which indicates that the fractures are normal to bedding. In general, the veins and open fractures can be grouped into four main sets with approximately 10 degrees of strike and dip deviation in each set: 47/72NW, 330/89NE, 309/89NE, and 5/88NW (Fig. 16C). All sets are evident in both the vein measurements and open fracture measurements. The few open fractures with moderate northwest dips may be normal faults with minimal displacement, because they are subparallel to known normal faults and are long and continuous.

The veins and open fractures are primarily extension fractures because where they intersect each other and bedding there is no shear offset. Vein apertures range from hairline to 0.12 in. (3 mm), and open fractures are solutionally enlarged to various degrees. Bedding planes defined by bed-parallel stylolites or a distinct change in bedding characteristics from regular and even to cobbly beds are common fracture termination points, but some large outcrop scale fractures cut many beds. The style and abundance of fracturing varies between beds of different lithology and regularity. For example, thin bedded limestones have a greater abundance of short fractures, and massive beds tend to have the longest most continuous fractures. Fracture styles within each set vary from long, continuous, and planar to short, discontinuous, and irregular.

Solution widened zones at this site appear to commonly follow steeply dipping fractures. Solution widening along bedding planes and low angle thrust faults is rare. At one location, a small cavity, now being used as an animal den, formed where a near vertical fracture intersects the low angle thrust zone

Fig. 16. Site B2 equal area, lower hemisphere stereonets of structural data. (A) Poles to thrust faults and normal faults. (B) Poles to fracture planes and mean bedding orientation at the site, V= Vein and J = Open Fracture. (C) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

Fig. 17. An example of the normal faults at site B2. Shown are two synthetic normal faults offsetting beds in the Carters Limestone. Most faults at this site have minor displacement and lack fault zone fractures.

(Fig. 18). The near vertical fracture strikes northeast and extends through but does not offset the thrust zone. The fracture appears to be the main locus of solutioning and cavity development, but the additional local fracturing associated with the thrust faults may have had an influence on the location of the cavity.

4.2.3 Site B3: Grid D4 Northeast Bank of Poplar Creek

The site is located on the northeast bank of Poplar Creek in map grid D4 approximately 1640 ft (500 m) northeast of site B2. Measurements were made in the upper part of the Carters Limestone and lowermost part of the Hermitage Limestone. The Carters is thin to thick bedded, fucoidal, gray-blue limestone with black chert pods and fossil hash zones. The Hermitage Limestone is irregularly bedded, very fossiliferous, argillaceous limestone. Bedding across the site defines a large anticline-syncline fold pair with the southeast limb of the anticline offset by a northwest-dipping thrust fault. The thrust anticline hinge zone seen at this site is interpreted to belong to the map scale anticline occurring in domain B, however, the folds may only be parasitic folds related to the larger scale anticline. A cylindrical best fit of poles to bedding at this site indicates that the local anticline fold axis plunges 13° along a trend of 71° , which is consistent with the orientation of mesoscopic fold axes in this domain (Fig. 19A).

The site is characterized by a northwest dipping thrust fault oriented $71/49\text{NW}$. At the base of the exposure the thrust is parallel to bedding in the hanging wall ($72/44\text{NW}$), but towards the top of the exposure, hanging wall beds dip southeast and are cut obliquely by the fault (hanging wall anticline). The thrust strikes parallel to, but cuts obliquely through beds in the footwall, which are oriented $72/24\text{SE}$. The amount of offset along the thrust fault is unknown. Offset may be large, however, because of the amount of deformation adjacent to the fault. Deformation related to the northwest dipping thrust fault is primarily concentrated in the footwall beds as thrusts with minor slip and folds (Fig. 19B). However, the footwall is better exposed than the hanging wall. All mesoscopic thrust faults strike-parallel to bedding. Normal faults were not observed at this site.

Only 31 calcite veins and open fractures could be found at this site. Veins and open fractures are commonly perpendicular to bedding (Fig. 19C). The veins and open fractures can be grouped into two main sets based on orientation with approximately 10 degrees of strike and dip deviation in each set. The 64° striking set dips both to the northwest and southeast, which is related to rotation of this set within the limbs of the large folds at this site (Fig. 19D). The other set is oriented $315/80\text{SW}$ with much less spread in orientation as a result of local folding. Other sets may be present, but data are sparse. For example, two measurements correspond to an east-west striking fracture set as seen at other sites.

The veins and open fractures are primarily extension fractures because where they intersect each other, chert pods, and bedding there is no shear offset. Vein apertures range from hairline to 0.2 in. (5 mm), and open fractures are solutionally enlarged to various degrees. The style and abundance of fracturing varies between beds of different lithology and regularity. For example, veins and fractures in argillaceous beds of the Hermitage Limestone are rare. Fracture styles within each set vary from long, continuous, and planar to short, discontinuous, and irregular.

4.2.4 Site B4: Boeing Property Quarry

Site B4 is an old quarry on the Boeing property located on the southwest side of the Clinch River. The quarry floor is not exposed, but the walls offered the largest and most continuous exposure in the area. The upper part of the Ridley Limestone and lower part of the Lebanon Limestone are exposed in the quarry. The Ridley Limestone is composed of regular to even, medium to massively bedded, micritic limestone. The Lebanon Limestone is thin, irregularly and unevenly bedded, dark gray micrites with clay

Fig. 18. An example of the low angle thrust zone (t) and steep extension fractures (e) within the Carters Limestone at site B2. A small cavity formed between two steeply dipping fractures near their intersection with a bed oblique zone of thrusting.

Fig. 19. Site B3 equal area, lower hemisphere stereonets of structural data. (A) Poles to bedding define the local fold axis orientation. (B) Poles to thrust faults and trend and plunge of fold axes. (C) Poles to fracture planes, V= Vein and J = Open Fracture. (D) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

seams. The mean bedding orientation in the quarry is 84/20SE and represents the southeast limb of the map scale anticline as well as the limb of a local map scale syncline that trends northwest and plunges to the southeast under the WM fault (see Fig. 4).

Faulting in the quarry is restricted to a zone of thrusts and folds along the back wall. The zone of thrusting has a mean orientation of 76/37SE (Fig. 20A) and is bounded by two subparallel thrusts that can be traced from the bottom to the top of the quarry. The thrusts strike subparallel to bedding strike and dip steeper than bedding in both the hanging wall and footwall, which is indicative of a hanging wall ramp on footwall ramp position. Offset on the upper thrust is approximately 5 ft (1.5 m), which is based on offset of a distinctive sequence of beds. Along the upper thrust, synthetic thrusts bound two thin limestone blocks. Faults are smooth, continuous surfaces with calcite slickensides oriented S32E/24 down the dip of the fault plane. Bedding in the hanging wall is thick to massive and has fewer fractures than the medium to thick beds in the footwall. The three steeply dipping, solutionally enlarged fractures in the hanging wall terminate at the fault zone. Offset on the thrust bounding the lower part of the zone could not be determined. Folding of the hanging wall occurs where the fault climbs through bedding, which has caused a local increase in fracture frequency (Fig. 21). Slickensides are not present on the fault surface.

Calcite veins and open fractures can be divided into at least five bedding perpendicular fracture sets based on orientation (Fig. 20C). The fracture sets are oriented 41/79NW, 76/86NW, 284/80NE, 321/85NE, and 344/83NE and have approximately 10 degrees of strike and dip deviation (Fig. 20D). This site also contains numerous examples of short, en echelon veins that step either to the right or left (Fig. 22). The orientation of the en echelon veins is not unique but is similar to the main fracture sets defined above (Fig. 20B). The stepping trend of both left and right stepping zones ranges from N42-85E. Exposed faces of a few en echelon vein zones contained nearly horizontal calcite slickensides indicative of dextral strike-slip offset (Fig. 23).

Bed normal veins commonly terminate and/or step over at bed-parallel stylolites. Also, veins commonly terminate at bedding contacts, but there are some open fractures can be traced through many beds. Vein apertures range from hairline to 0.51 in. (13 mm). The style and thickness of bedding was observed to have a strong control on the style of fracturing. For example, thick to massive beds commonly have either well developed en echelon vein sets or long continuous veins, but thin irregular, argillaceous beds commonly have short, discontinuous veins. As a result, large, vertical solution zones tend to be rare in the thin, irregularly bedded sequences compared to thick to massively bedded limestone sequences. Fractures vary from long, continuous, and planar to short, stepping, and anastomosing zones within all sets.

4.3 STRUCTURAL DOMAIN C

The characteristic macroscopic structure that defines structural domain C is the southwest hinge of the East Fork Ridge syncline. The southwest hinge of the syncline plunges approximately 2° along a trend of 66°, which is parallel to the macroscopic folds in domain B (Lemiszki 1994). Bedding has a mean orientation of 301/41NE (Fig. 6). Domain C is bounded on the northwest by the K-25 fault, and along the south/southeast by a fault contact with the Rome Formation in domain D. Although a number of small exposures exist, the only site suitable for mesoscopic structural analysis is the old quarry in the Knox Group off Blair Road. In general, the macroscopic structure in the Knox Group underlying McKinney Ridge is poorly constrained and is primarily based on structures exposed in the quarry (Lemiszki 1994).

Fig. 20. Site B4 equal area, lower hemisphere stereonets of structural data. (A) Poles to thrust faults and mean thrust pole. (B) Poles to left and right stepping en echelon fracture sets, and great circle plots of fractures with trend and plunge of slickensides. (C) Poles to fracture planes and mean bedding orientation at the site, V = Vein and J = Open Fracture. (D) Rose diagram of fracture strikes superimposed on a contour plot of poles to fracture planes, C.I. = Contour Interval.

Fig. 21. Mesoscopic anticline and related fractures in the hanging wall of the major thrust exposed at site B4. The hammer is on the plane of the thrust fault. The rock unit is the Ridley Limestone.

Fig. 22. An example of left stepping (l) and right stepping (r) en echelon calcite vein sets exposed on a bed top of Ridley Limestone at site B4.

Fig. 23. An example of calcite slickensides exposed on the face of a steeply dipping en echelon vein set in the Ridley Limestone.

4.3.1 Site C1: McKinney Ridge Quarry

Mapping in the quarry indicates that four formations of the Knox Group may be exposed because of thrusting and folding (Fig. 24A). The Chepultepec Dolomite and the Copper Ridge Dolomite is exposed in the hanging wall syncline of the major reverse fault exposed along the east wall of the quarry. The sandstone beds at the contact between these two formations were not found, which is why Lemiszki (1994) placed a fault between them. An alternative hypothesis is shown here based on assuming that the sandstone beds are present but unexposed, in which case there is a continuous stratigraphic sequence in the limb of the syncline. The gently dipping footwall beds consist of the Longview Dolomite and Kingsport Formation. Characteristic gastropod limestone of the upper part of the Kingsport Formation and massive white chert of the Longview Dolomite are in stratigraphic contact along the north wall of the quarry.

Structures in the quarry consist of the large hanging wall syncline and numerous thrust faults. A plot of poles to bedding with a cylindrical best fit indicates that the syncline plunges 14° on a trend of 85° , which is similar to the strike of the crest of McKinney Ridge (Fig. 24B). The major quarry fault places a hanging wall ramp in the Chepultepec Dolomite against a footwall ramp in the Longview Dolomite and Kingsport Formation (Fig. 25). This fault strikes approximately N70E with a listric geometry associated with a southeast directed dip change with depth from 66° to 46° . Faint slickensides with stepped breaks indicate that the fault is a reverse fault with top to the northwest. Dolomite beds adjacent to the fault appear brecciated in places. Synthetic and antithetic reverse faults (thrusts) occur in the hanging wall syncline, with apparently minor displacement (Fig. 24C). Some bedding(?) planes are smooth and contain local fractures suggesting that some slip may have occurred during folding. At least one additional thrust oriented 48/57SE offsets beds 10 to 15 ft (3.1 to 4.8 m) in the Longview Dolomite.

Fracturing is ubiquitous throughout the quarry and is a mixture of natural and quarrying induced fractures (Fig. 24D). Most fractures are unfilled, which is probably related to the greater susceptibility to weathering of calcite filling versus dolomite bedrock. Only three veins were recorded. A plot of poles to veins and open fracture planes indicates no particular systematic fracture sets. Until more data can be obtained, the folded and faulted dolomite beds in McKinney Ridge appear to contain a random system of fractures. Fractures that developed prior to deformation are folded and offset by faults and new fractures have formed as a result of folding and faulting.

4.4 STRUCTURAL DOMAIN D

Structural domain D consists of the poorly exposed Rome Formation that comprises the thrust sheet between McKinney Ridge and the WM fault. The lower Rome Formation shales underlie topographically low areas based on a few shale outcrops, and upper Rome sandstones underlie the hills based on the presence of sandstone blocks. The K-25 fault borders the southwest side of the domain. Previous drilling results indicate that the fault dips towards the northeast, placing the Rome Formation on Chickamauga carbonates. A number of hypotheses concerning the geometry of this and the other bounding thrusts are possible, which can only be tested by collecting additional subsurface data. Nothing is known about the fracture system in this domain, because there are no bedrock outcrops suitable for mesoscopic structural analysis. The available bedding data indicate that the Rome Formation is folded and probably faulted throughout this domain. The deformation within the Rome Formation probably occurred during emplacement of the thrust slice which was associated with displacement along the WM fault.

Fig. 24. Site C1 equal area, lower hemisphere stereonet of structural data. (A) Sketch of the quarry walls depicting the locations of the contacts between formations in the Knox Group and major structures. (B) Plot of poles to bedding and the corresponding fold axis orientation. (C) Poles to thrust faults. (D) Poles to fracture planes, V= Vein and J = Open Fracture.

Fig. 25. Major thrust fault (arrow) with folded and faulted hanging wall and footwall beds of the Knox Group at site C3.

4.5 STRUCTURAL DOMAIN E

Structural domain E includes Pine Ridge and the valley to the northwest up to the WM fault. The domain is comprised of the Rome Formation in the WM thrust sheet, which extends northeast-southwest across the bottom part of the study area. Upper Rome Formation sandstones underlie Pine Ridge and lower Rome Formation shales, and some carbonates underlie the valley. Outcrops are rare and none are suitable for mesoscopic structural analysis. The location of the WM fault is poorly constrained, but the fault generally strikes northeast-southwest and dips moderately to the southeast. Based on geologic mapping, a seismic reflection profile, and balanced structural cross sections, the fault is interpreted to place a hanging wall flat in the Rome Formation against a footwall ramp (see Hatcher et al. 1992). Mean bedding orientation in this domain is 59/50SE (Fig. 6). Fracture data from the Rome Formation in the WM thrust sheet on the rest of the ORR indicates that there are two predominant extensional fracture sets oriented 67/45NW and 320/88SW (Hatcher et al. 1992).

Two cores from the lower part of the Rome Formation were collected during the spring of 1994 as part of a building site investigation. Each core is approximately 7 ft (2.1 m) long. The cores are primarily gray, unfossiliferous limestone with some interbedded shale. One core is more highly weathered than the other. Bedding(?) defined by thin dark gray thin clay seams or a strong foliation dips steeply (70°) in both cores, but dip direction is unknown. Faults with minor offset, veins offsetting and cut by the foliation, and open fractures occur in the weathered core. The unweathered core only contains calcite veins. The limestone of the weathered core contains filled vugs and open vugs with blocky calcite crystals lining the walls.

The cores were drilled along strike to the southwest from a weathered shale and limestone exposure found in a creek bed during previous mapping. The structural characteristics of the cores suggest that they are within the deformation zone associated with the Whiteoak Mountain fault. Although exposures are rare, the interbedded shales and limestones observed in core are typical of the lower Rome in this area.

5. DISCUSSION

This discussion will focus on various aspects of the bedrock fault and fracture system as determined from mesoscopic structural analysis. The results are only representative of structural domains A and B, because that is where all but one of the study sites are located. The first part of this chapter will discuss the relationship between mesoscopic and macroscopic structural geometries. The second part of this chapter will describe some additional observations that link the local mesoscopic structural style to the concept of stratabound controlled groundwater flow paths (Ketelle and Lee 1992).

5.1 FRACTURE SYSTEM

Because there is a close correlation between fracture set orientations and bedding orientation, one way to discuss the fracture sets in the area is in the context of bedding strike and dip. At every site there exists one fracture set that is bed-normal and strikes parallel to bedding strike and a second fracture set that is also bed-normal, but strikes nearly perpendicular to bedding strike (Fig. 26). These two fracture sets form an orthogonal system of extension fractures that occurs throughout the ORR (Hatcher et al. 1992). The orientation of the orthogonal sets is fairly consistent within domains A and B, because bedding attitude varies only slightly (Fig. 27). The orthogonal sets are rotated approximately 90° counterclockwise at site B1, which is located in the hinge of the macroscopic syncline. Rotation of the orthogonal fracture sets in the hinge zone corresponds to the rotation in bedding orientation at this site. The results suggest that the predominate fracture sets in the area formed prior to regional thrusting and folding. These fracture sets were passively rotated and some were probably reactivated as faults during thrust sheet emplacement. These results can be used to predict the dominant fracture orientations in an area based solely on bedding orientation.

In structural domains A and B at least two additional extension fracture sets occur at all sites, but B3 (Fig. 27). These fracture sets are also defined by veins and open fractures that are normal to bedding (Fig. 28). Within structural domain A one of these additional sets is a nearly east-west striking fracture set occurring at all study sites. At sites A1, A3, and A4, a second set strikes nearly perpendicular to the east-west set. Two additional sets at sites A2 and A3 strike within 30° of the bedding strike-parallel set. Within structural domain B there is a bit more variability to the orientation of the additional fracture sets defined at each site. At sites B3 and B4, one additional fracture set strikes nearly north-south. The remaining fracture sets at site B1, B2, and B4 tend to strike within 30° clockwise and/or counterclockwise of the bedding strike-parallel set. This is similar to the additional fracture sets defined at sites A2 and A3. Similar to the orthogonal fracture sets, these fanning sets are reoriented at site B1 in the syncline hinge. It is important to note here that the absence of a particular fracture set at a site is probably a result of poor exposure and may not be due to the lack of development. As mentioned in the previous section, the designation of fracture sets is based on those sets that are best represented at each site, but other fractures were recorded that probably correspond to those fracture sets better developed at other sites.

Mutual crosscutting and abutting relationships commonly occur in outcrop between extensional fracture sets. Rarely is the exposed bed top large enough to gather sufficient data on timing relationships. Commonly the bedding strike-parallel set or the bedding strike-perpendicular set is the most continuous within a particular outcrop (Fig. 29). Abutting fractures between orthogonal sets form T-shaped intersections. Individual fractures also terminate by stepping off to a subparallel fracture, with commonly a minor amount of overlap to the fracture tips. Stepping fractures can link-up by either one or both curving into near perpendicularity with the other. Beds are segmented into rectilinear blocks when the

Fig. 26. An example of the solutionally enlarged bedding strike-parallel and bedding strike-perpendicular fracture sets commonly observed in the area. Bed top view of the Mascot Dolomite at site A2.

Fig. 28. An example of two extension fracture sets exposed on the bed top of the Mascot Dolomite. Bedding strike is defined by the line of intersection between the bedding plane and the water level. One set is nearly perpendicular to bedding-strike and the other forms an acute angle less than 30° . A third nearly bedding strike-parallel fracture set is also present.

Fig. 29. Sketch of the three-dimensional fracture architecture and the increased fracture complexity that occurs as additional fracture sets are added to the system. The shape and size of fracture bounded blocks depends on the number of fracture sets that develop in an area. (A) Two orthogonal sets produce rectilinear block shapes. (B) and (C) Adding additional fracture sets increases the connectivity between fractures and divides the bed into polygonal shapes.

development of the bedding strike-parallel set and the bedding strike-perpendicular set dominates (Fig. 29A). The presence of additional fracture sets that tend to fan around the bedding strike-parallel set continues to break the bed into smaller blocks with polygonal shapes (Fig. 29B and C). Furthermore, as shown in Fig. 29, as the number of fracture sets increases within an area, the number of connections between fractures also increases.

The prethrusting fracture sets are overprinted by fractures that formed as a result of folding and thrusting. Although evident in mesoscopic structures observed in outcrop, the distribution of fracture sets across the K-25 area does not clearly indicate the development of new fractures related to map-scale structures. New fracture sets may have developed adjacent to some of the major thrust faults, but most study sites are not adjacent to major structures, so the data are insufficient to constrain this. Study sites A3 and A4 are assumed to be either adjacent to or within a deformation zone. At these sites, the best indication of the presence of the deformation zone is the development of new fracture sets and the development of thrusts and folds.

Considering the long and complex stress history for the rocks in the area, an effort was made to determine if the open fractures represent preexisting veins that have been solutionally enlarged or if the open fractures are new and related to the present day stress field. Results suggest that the open fracture sets have the same geometry and style as the vein sets, which indicates that the calcite filling of the veins is being weathered and no new fracture sets are developing as a result of erosion and uplift in the present day stress field. The data can also be used to suggest that the bedding strike-parallel vein set is preferentially opened over the other vein sets. At many of the sites the bedding strike-parallel vein set is present, but there is a greater number of open fracture measurements than vein measurements. The preferential weathering of this set could be related to its importance in controlling groundwater flow paths parallel to the valley-and-ridge topography. The orientation of the set is such that stress relief along valley walls during uplift would tend to favor their opening and resultant widening by weathering. This correlation between veins and open fractures may prove useful for core analysis because the orientation of veins in core can be used to infer the orientation of open fracture sets that also may exist but were not sampled by the core.

A number of vein apertures were measured to provide some data on the possible initial apertures present before the fracture becomes widened by dissolution. Aperture measurements are quite variable because the aperture was observed to commonly change along the vein for no apparent reason. An exception are stepover zones along some fractures that formed small pull aparts where the local aperture increased significantly. Mechanical arguments have been proposed to suggest that in an ideal stress system as the fracture grows longer the aperture of the fracture must also increase, which has lead to a direct relationship between vein aperture and length (e.g., Pollard and Aydin 1988). The point here is to suggest that this is not the case in the K-25 Site area. Vein aperture does not correlate with vein length because many examples were observed where veins with a hairline aperture extend for a few feet and where thick veins are short.

Fracture development is strongly controlled by the physical characteristics of the bedding. In carbonates there are two major factors that appear to cause fractures to terminate. First, fractures were observed to either terminate or be segmented at bed-parallel stylolites. In some cases the formation of the bed-parallel stylolite may have acted to cause a once continuous vein to be segmented, but in other cases a continuous vein terminates at the stylolite seam. The second factor causing fractures to terminate vertically through beds is a dramatic change in bedding characteristics. One common transition that is observed in the limestones of the Chickamauga Supergroup is a change from massive (meters thick), fairly regularly bedded carbonates to irregular and uneven (cobbly) beds with thin clay seams (Fig. 30). Fracturing in the massive carbonates tended to produce long, continuous fractures between fracture steps

Fig. 30. Thin clay seams between thin bedded limestones are common fracture termination points within the limestones and prevent the development of long fractures perpendicular to bedding. This is an example from the Lebanon Limestone at site B4.

that cut the entire bed. Long fractures in the massive carbonates tended to terminate at the contact with the cobbly bedded carbonates. Fracturing in the cobbly carbonates commonly consisted of short discontinuous fractures because the argillaceous seams that surrounded the limestone cobbles caused the fractures to terminate. Sometimes the discontinuous fractures defined a fracture zone that could be traced through an entire cobbly bedded sequence, but these fractures appear to be poorly connected.

Dolostones in the Knox Group commonly consist of stacks of thick to massive beds. These beds commonly fractured as a single unit leading to the some of the longest fractures observed, but termination at bed-parallel stylolites and bed contacts does occur. Within dolomite beds, highly siliceous zones containing pods and lenses of chert are also commonly intensely fractured. Most of the fracturing is concentrated within the more brittle chert but also affects the enclosing dolomite. At site A1, chert rich zones did not appear to act as stress concentration points where fractures initiate and propagate off into the dolomite. Cherts in the limestone beds of the Chickamauga Supergroup also are preferentially fractured (Fig. 31). Furthermore, there are a number of cases where the intensity of fracturing increases as the thickness of bedding decreases, although there does not appear to be a relationship between bed thickness and fracture spacing (Fig. 32). Lithologies that acted as important fracture termination points and that appeared to have the least well developed fractures are argillaceous carbonates and calcareous shales, such as in the Hermitage Formation. Because of their lack of fracturing, these lithologies have the ability to confine flow along more intensively fractured limestone intervals.

5.2 MESOSCOPIC FAULT SYSTEM

Mesoscopic fault systems in the area represent both thrust faults and normal faults. A majority of the faults and folds are interpreted to represent "penetrative" structures that are related to the macroscopic folds in structural domain B and therefore occur throughout the domain. In addition, a consistent style of deformation is used to interpret the location of a "non-penetrative" and discrete thrust fault that is used as the boundary between structural domain A and B. Faults are considered important pathways for groundwater flow because faults are commonly long, continuous zones of deformation that contain local fracture sets and that connect and juxtapose stratigraphically controlled flow systems.

The majority of faults and folds observed in structural domain A occur at the southeast end of site A3 and at site A4 near the boundary between structural domains A and B (Fig. 33). The structures appear to be concentrated along a nearly bedding strike-parallel zone of deformation within the Carters Limestone that was located during previous mapping (Lemiszki 1994). Similar structures have not been observed elsewhere in structural domain A and the tightness of the folds makes these structures unique to structural domain B. The uniqueness, abundance, and nearly consistent position along bedding strike is used to hypothesize that a macroscopic thrust fault strikes nearly parallel to bedding across the area and probably dips to the southeast. This thrust fault may be an important structure that separates the folded hanging wall beds comprising structural domain B from the homoclinally dipping footwall beds comprising structural domain A. Furthermore, the location of the proposed fault projects northeast to the known fault (previously called the K-25 fault) that bounds the Knox Group on the northwest side of McKinney Ridge (Lemiszki 1994). An alternative hypothesis, however, is that the fault is unrelated to the K-25 fault. Extending the fault towards the southwest across the Clinch River cannot be constrained because there are no outcrops.

Thrust faults and reverse faults occur at all sites within structural domain B and represent typical geometries that develop within a foreland thrust belt. Thrust faults commonly cut bedding obliquely and place hanging wall ramps on footwall ramps and hanging wall flats on footwall ramps. Thrust fault geometries throughout domain B are closely related to bedding geometry and generally strike and dip in

Fig. 31. An example from the Ridley Limestone of the increased fracture intensity within thin, brittle, chert pods (c) as compared to the surrounding limestone. Increased fracturing in the chert pods is related to the change in lithology and shape. The chert pod offset is associated with a stepover zone in the vein (v). Also note that the change in limestone texture associated with a fossil hash zone (h) did not affect the vein.

Fig. 32. A typical example of the increase in fracture frequency associated with thin versus thick bedded limestones of the Murfreesboro Limestone.

Fig. 33. Geologic map of the K-25 area with the mean orientation of folds and faults observed at each study site.

the same direction as either the footwall or hanging wall beds. For example, at site B2 a narrow zone of thrusting is nearly parallel to, but dips southeast slightly steeper than, bedding in the hanging wall and footwall. At site B3, however, the major thrust fault parallels bedding in the hanging wall and dips to the northwest, which opposes the dip of bedding in the footwall (Fig. 33). The lateral extent of each of the thrust faults observed at sites B2 through B4 cannot be ascertained because of poor exposure. Even where sites are relatively close, such as B2 and B3 there appears to be no continuity in the structure. The northwest dipping fault at site B3, however, does project to an area of poor exposure to the northwest of the outcrop used as site B2. Offset on many of these thrust faults appears to be minor based on the lack of stratigraphic duplication. Mesoscopic thrusts subparallel to macroscopic fold axes are common in fold-thrust belts, suggesting that thrust faults are a fairly prevalent structure throughout structural domain B. In addition, mesoscopic thrusts are commonly well developed in the footwall to regional thrust faults, such as the WM fault.

Normal faults are best exposed in structural domain B at sites B1 and B2 but also occur at site A3 (Fig. 33). At sites B1 and B2, the normal faults generally strike subparallel to bedding, but cut steeply through it with minor displacement. At site A3 the faults generally dip steep, but strike normal to bedding. The difference between the normal faults at sites A3 and B1, and site B2 is their orientation with respect to the macroscopic fold axes. At sites A3 and B1 the normal faults strike perpendicular to the fold axis of the macroscopic syncline. At site B2, however, the normal faults strike parallel to the axis of the macroscopic anticline. The faults are interpreted to be related to folding and represent hinge-parallel extension of bedding at site B2 and fold hinge-perpendicular extension at site A3 and B1. Similar normal fault systems associated with folds have been reported in other fold-thrust belts (De Sitter 1956). The normal faults probably did not form prior to folding because bedding parallel slip during folding should have offset some of the steep fault planes, which was never observed. Considering the extent of the macroscopic folds, a system of fold hinge perpendicular and fold hinge parallel normal faults with minor displacement may occur throughout structural domain B.

Even where displacement is small, faults are commonly the most continuous structures within a particular exposure and therefore act to juxtapose and link together stratigraphic units with different fracture characteristics (Fig. 34). Furthermore, fault-related fractures overprint preexisting fracture sets, which would tend to increase the local fracture porosity (Fig. 35). Fracture development adjacent to a fault, however, is dependent on the characteristics of the fault zone. Fracturing adjacent to faults is rare when the amount of displacement along the fault is minor to none. In this case, thrust and normal faults are commonly smooth, continuous, bed-oblique faults. Faults with greater displacement also tend to be smooth and continuous, but they commonly have synthetic and antithetic faults as well as fractures in the footwall and/or hanging wall. Another class of fault related fractures is restricted to the normal faults observed at site B1. In this case, fault related en echelon fracture sets appear to have formed in front of the advancing fault tip as a precursor to displacement. As the fault develops, the en echelon fractures link up to form a continuous fault zone. The en echelon fracture sets at site B4 are also interpreted to be related to the dextral strike-slip fault zones present in that area. This suggests that the en echelon fracture sets may be a useful indicator of the presence of a local fault zone.

5.3 GEOLOGIC FACTORS INFLUENCING THE DEVELOPMENT OF OPEN FRACTURE PATHWAYS

As previously discussed, fracture development within individual and groups of beds is closely controlled by lithology and bedding characteristics, which can lead to the development of stratabound units that conduct groundwater flow (Ketelle and Lee 1992). At a larger scale, Crawford and Ulmer (1994) were able to divide the Stones River Group in middle Tennessee into aquifers and confining units.

For example, the lower Ridley Limestone aquifer there is about 40 ft (12.2 m) thick and is bounded by upper and lower confining units that are 50 and 20 ft (15.2 and 6.1 m) thick, respectively. Data from the K-25 Site area are insufficient to divide the stratigraphy into aquifers and confining units at any scale, but geologic factors that influence open fracture development and the importance of known fracture geometries that influence groundwater flow paths can be discussed based on outcrop observations.

Many of the larger sites exposed connected open fractures and bedding planes that appeared to be preferred groundwater flow paths at some time in the past and probably represent vertical infiltration pathways within the vadose zone. Stratigraphic and structural characteristics of these sites are shown schematically in Fig. 36, which is an untested hypothesis for what may be occurring in the vadose zone. Vertical infiltration within dipping carbonates is best developed on the fractures and faults with the steepest dips (Fig. 37). Within massively bedded limestones, long, bed-normal fractures appeared to be preferentially open and are the locus of cavity development. The widened cavities are commonly found near the base of the fracture where a change in bed lithology caused the fracture to terminate and prevented further vertical infiltration (Fig. 37). In some cases the open fracture did not widen into a cavity at the contact with the confining bed but intersected a planar dissolution zone down bedding dip parallel to the bedding contact. In this case the stratabound flow unit is located above the confining bed with flow occurring either along the bed contact or in the fracture system. Once the confining bed is breached, vertical infiltration will occur along steep fractures until the next confining bed, which will define the next stratabound flow unit (Fig. 36). In the Chickamauga, uneven, irregular, cobbly bedded limestones with shale stringers are commonly fracture termination points and also act as confining beds that can cause flow to be directed down the dip of bedding. A stratabound flow zone therefore is bounded above by a breached confining bed and below by a confining bed that prevents further vertical infiltration. The stratabound flow in the overlying beds can occur within open fractures and along the contact with the underlying confining bed. Finally, besides a natural change in bedding, stratigraphic duplication or omission caused by faulting can also be responsible for the location of confining beds that control the development of stratabound flow zones (Fig. 38).

Flow paths in dipping carbonate below the water table are also influenced by the relationship between fracture geometries and lithologically controlled confining units. As shown schematically in Fig. 39, the preferred flow direction may differ depending on the relationship between the inclination of the water table and the bedding dip direction. The water table mound depicted could be any scale, from that developed under a ridge to something more local. If the water table is inclined in the same direction as bedding dip, then strike perpendicular flow is favored. In this case, down-dip flow is towards lower heads and can occur along bedding planes and the strike-perpendicular fractures. Although along strike flow can occur along bedding planes and strike-parallel fractures, there is little to inhibit down dip flow. Flow opposing bedding dip is unlikely because it would be towards higher heads. In the case where bedding dip direction opposes the water table, then bedding strike-parallel flow is favored along bedding planes and strike-parallel fractures. Flow towards lower head along strike-perpendicular fractures is inhibited, however, because it opposes bedding dip and requires the breaching of confining beds. Finally, down bedding dip flow in this case is unlikely because it would be towards higher heads.

In addition to the local fracture and bedding geometries presented above, deformation related to folding and faulting in the site area will add even more complexity to the system (Fig. 40). As previously discussed, fold hinges and faults commonly cause a local increase in fracture intensity on the mesoscopic scale, which is probably true at the map scale. Furthermore, folding will reorient bedding controlled stratabound flow zones. For example, stratabound flow zones may be directing flow towards the hinge zone of the site area syncline where it will be constrained to flow parallel to the fold axis. Faulting within the syncline, however, could complicate the situation and also act to redirect flow. To further constrain the various geologic controls on groundwater flow pathways in carbonates and clastic rock units within the K-25 Site area, additional subsurface geologic and hydrologic studies need to be conducted.

Fig. 34. Normal fault in the Murfreesboro Limestone (f). Note that the fault is the most continuous structure that cuts bedding and can juxtapose rock units with very different characteristics.

Fig. 35. Local fracture development associated with faulting and folding in the Murfreesboro Limestone at site B1. Intense fracturing occurs where a minor normal fault bends and offsets a limestone bed with thin chert lenses.

VADOSE ZONE INFILTRATION IN DIPPING CARBONATES

Fig. 36. Schematic of some various geologic factors influencing contaminant (groundwater) infiltration in the vadose zone in dipping carbonates. Assumes that only the orthogonal extension fracture sets are present. Listed are the various factors controlling stratabound flow.

Fig. 37. Photo of solutionally enlarged near vertical fractures in thicker bedded limestone of the **Carters Limestone**. One of the fractures has a widened cavity at its termination point with a slightly more argillaceous limestone bed that may be acting as a confining unit. Bedding parallel dissolution is primarily above the argillaceous limestone bed.

Fig. 38. Small cavity formed at the intersection between two steeply dipping fractures, that may be normal faults. Increased fracturing associated with faulting may have influenced the location of cavity development within the Carters Limestone.

Fig. 39. Schematic of some various geologic factors that influence groundwater flow below the water table in dipping carbonates that is based on the relationship between the inclination of the water table and the dip direction of bedding. Assumes that only the orthogonal extension fracture sets are present.

Fig. 40. Schematic block diagram of the bedrock geology of the K-25 Site depicting the various map scale structures (faults and folds) that influence the geometry of stratabound flow units and that can increase the local fracture frequency within carbonates of the Chickamauga Supergroup.

6. CONCLUSIONS

An investigation of the mesoscopic structures exposed in outcrops throughout the K-25 Site has lead to a better understanding of the fracture and fault system in the area. The complex bedrock geology of the site has been divided into five structural domains defined by a unique map scale structural style that is commonly bounded by either faults or suspected faults. Not all structural domains could be studied, however, because of the absence of bedrock exposures. Structural domains A and B, composed of the Knox and Chickamauga carbonates, contained eight of the nine sites examined in this study. The other site was within structural domain C. Mesoscopic structural analysis at these sites has lead to the following conclusions:

- (1) At each site there is are at least two well represented extensional fracture sets that are normal to bedding. These two sets form an orthogonal system on fractured bed tops and consist of a bedding strike-parallel set and a bedding strike-perpendicular set. These fracture sets are represented by veins and open fracture measurements. These sets maintain their geometric relationship to bedding regardless of bedding orientation.
- (2) Additional fracture sets are present at most sites that are commonly within 30° but as much as 45° clockwise or counterclockwise to the bedding strike-parallel fracture set. These sets also tend to be normal to bedding and are represented in both vein and open fracture measurements.
- (3) The close correlation between vein and open fracture sets suggests that the veins are opening as a result of weathering and stress relief. Therefore, new fracture sets are not forming as a result of uplift and erosion within the present-day stress field.
- (4) Thrust faults and reverse faults occur at all sites within structural domain B and represent typical geometries that develop within a foreland thrust belt. Thrust fault geometries throughout domain B are closely related to bedding geometry and generally strike and dip in the same direction as either the footwall or hanging wall beds. The lateral extent of each of the thrust faults observed generally cannot be ascertained because of poor exposure. Even where sites are relatively close, such as B2 and B3, there appears to be no continuity in the structure. Offset on many of these thrust faults appears to be minor based on the lack of stratigraphic duplication. Mesoscopic thrusts subparallel to macroscopic fold axes are common in fold-thrust belts suggesting that thrust faults are a fairly prevalent structure throughout structural domain B.
- (5) Normal faults are best exposed in structural domain B at sites B1 and B2. At both sites the normal faults generally strike subparallel to bedding, but cut steeply through it with minor displacement. The difference between the normal faults at these two sites is their orientation with respect to the macroscopic fold axes. At site B1 the normal faults strike perpendicular to the fold axis of the macroscopic syncline. At site B2, however, the normal faults strike parallel to the axis of the macroscopic anticline. Considering the extent of the macroscopic folds, a system of fold hinge perpendicular and fold hinge parallel normal faults with minor displacement may occur throughout domain B.
- (6) The majority of faults and folds observed in structural domain A occur at the southeast end of site A3 and at site A4 near the boundary between structural domains A and B. The structures appear to be concentrated along a nearly bedding strike-parallel zone of deformation within the Carters

Limestone that was located during previous mapping. The uniqueness, abundance, and nearly consistent position along bedding strike is used to hypothesize that a macroscopic thrust fault strikes nearly parallel to bedding across the area and probably dips to the southeast.

- (7) Two models depicting some of the stratigraphic and structural factors that influence the development of open fracture pathways are presented based on outcrop observations. One model focuses on factors influencing infiltration pathways in the vadose zone. The other model describes the combined influence of a groundwater mound, such as formed by a ridge, and the geologic factors influencing preferred groundwater flow directions. Although the applicability of either model still needs to be tested, they provide a framework with which to evaluate groundwater flow test results.

7. REFERENCES

- Crawford, N. C., and C. S. Ulmer 1994. "Hydrogeologic Investigations of Contaminant Movement in Karst Aquifers in the Vicinity of a Train Derailment Near Lewisburg, Tennessee," *Environmental Geology*, 23, 41-42.
- Dennis, J. G. 1972. *Structural Geology*, Ronald Press, New York.
- De Sitter, L. U. 1956. *Structural Geology*, McGraw-Hill, London.
- Fenneman, N. M. 1938. *Physiography of the Eastern United States*, McGraw-Hill, New York.
- Hatcher, R. D., et al. 1992. *Status Report on the Geology of the Oak Ridge Reservation*, ORNL/TM-12074, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Hodgson, R. A. 1961. "Regional Study of Jointing in Comb-Navajo Mountain Area, Arizona and Utah," *American Assoc. Petrol. Geologists Bull*, 45, 65.
- Ketelle, R. H., and R. R. Lee 1992. *Migration of a Groundwater Contaminant Plume by Stratabound Flow in Waste Area Grouping 1 at Oak Ridge National Laboratory, Oak Ridge, Tennessee*, ORNL/ER-126, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.
- Lemiszki, P. J., and R. D. Hatcher, Jr. 1992. "Structural Analysis of the Copper Creek and Whiteoak Mountain Faults in East Tennessee: Implications for the Thrusting Sequence and Growth of the Southern Appalachian Foreland Fold-Thrust Belt," *Geological Society of America Abstracts with Programs*, 24, A362.
- Lemiszki, P. J. 1994. *Geological Mapping of the Oak Ridge K-25 Site, Oak Ridge, Tennessee*, K/ER-111, Martin Marietta Energy Systems, Oak Ridge K-25 Site.
- McMaster, W. M. 1962. *Geologic Map of the Oak Ridge Reservation, Tennessee, Scale 1:31,680*, ORNL/TM-713, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab.
- Pollard, D. D., and A. Aydin 1988. "Progress in Understanding Jointing Over the Past Century," *Geological Soc. America Bull*, 100, 1181-204.
- Rodgers, J. 1953. "Geologic Map of East Tennessee with Explanatory Text, Scale 1:125,000," *Tennessee Division of Geology Bulletin*, 58.
- Solomon, D. K., et al. 1992. *Status Report: A Hydrologic Framework for the Oak Ridge Reservation*, ORNL/TM-12026, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab.

Appendix A
STRUCTURAL DATA

Appendix A. STRUCTURAL DATA

Table A-1 lists the mesoscopic structural data collected at each study site. The following is an explanation of the table headings and abbreviations:

Rock Unit	Stratigraphic group; see Fig. 5 for symbol abbreviations.
Lithology	Ch = chert Dol = dolostone Ls = limestone
Fracture Strike	Compass azimuth of strike direction.
Fracture Dip	Angle of dip from horizontal.
DD	Dip direction.
Filling	V = vein with calcite filling U = unfilled fracture F = fracture face formed outcrop face
Aperture	Width of the fracture opening.
Structure	Refers to the presence of a thrust fault, extension fault, and fold.
Fold Axis	Trend and plunge of mesoscopic fold axis.
Slicks	Trend and plunge of calcite slickensides on fault planes.

Table A.1. K-25 Site structural data

	Fracture						Bedrock			Fold			
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD	Structure	Axis	Slacks
	Unit						(mm)						
Site A1	OCk	Dol	322	84	S	F		57	39	S			
	OCk	Dol	308	86	N	V		61	41	S			
	OCk	Dol	296	86	S	V							
	OCk	Dol	299	86	S	V							
	OCk	Dol	336	86	S	F							
	OCk	Dol	284	90	N	U							
	OCk	Dol	39	68	N	F							
	OCk	Dol	20	77	N	F							
	OCk	Dol	315	86	N	V							
	OCk	Dol	321	80	N	V							
	OCk	Dol	299	77	N	V							
	OCk	Dol	319	84	N	V	1						
	OCk	Dol	290	82	S	V							
	OCk	Dol	310	74	N	V							
	OCk	Dol	300	84	N	V							
	OCk	Dol	276	84	N	V							
	OCk	Dol	312	84	N	U							
	OCk	Dol	35	58	N	U							
	OCk	Dol	71	90	N	V							
	OCk	Dol	296	80	S	V							
	OCk	Ch/Dol	280	76	N	U							
	OCk	Ch	334	90	N	U							
	OCk	Ch/Dol	276	81	N	U							
	OCk	Dol	90	78	N	V/F							
	OCk	Dol	320	72	S	U							
	OCk	Dol	310	90	N	U							
	OCk	Dol	280	90	N	V							
	OCk	Dol	303	82	N	U/F							
	OCk	Dol	46	59	N	U/F							
	OCk	Dol	75	56	N	U							
	OCk	Dol	336	90	N	F							
	OCk	Dol	319	90	N	V							
	OCk	Dol	336	90	N	U/F							
	OCk	Dol	30	65	N	U							
	OCk	Dol	301	74	N	U/V	Micro to 1						
	OCk	Dol	286	62	N	U/V							
	OCk	Dol	84	54	N	V							
	OCk	Dol	291	66	N	V							
	OCk	Dol	80	65	N	V							
	OCk	Dol	315	86	S	U							
	OCk	Dol	42	64	N	U							
	OCk	Dol	90	64	N	V							
	OCk	Dol	290	69	N	U							
	OCk	Dol	74	56	N	U							
	OCk	Dol	272	62	N	V							
	OCk	Dol	30	82	S	V							
	OCk	Dol	64	64	N	V							
	OCk	Dol	280	69	N	V							
	OCk	Dol	30	69	N	V	3						
	OCk	Dol	306	90	N	U							
	OCk	Dol	286	71	N	U/V							
	OCk	Dol	334	84	N	U							
	OCk	Dol	360	90	N	U							
	OCk	Dol	349	76	S	U							
	OCk	Dol	300	70	N	U							
	OCk	Dol	360	82	E	U							
	OCk	Dol	78	71	N	U							
	OCk	Dol	334	75	N	U							
	OCk	Dol	45	60	N	F							
	OCk	Dol	84	66	N	U/V							

Table A.1. (continued)

			Fracture					Bedrock			Structure	Fold Axis	Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD			
	Unit						(mm)						
	Ock	Dol	306	74	N	U							
	Ock	Dol	65	56	N	U/V							
	Ock	Ch	90	57	N	U							
	Ock	Ch	76	71	N	U							
	Ock	Ch	340	90	N	U							
	Ock	Ch	348	90	N	U							
	Ock	Dol	56	56	N	U							
	Ock	Dol	290	90	N	V							
	Ock	Dol	71	66	N	U							
	Ock	Dol	290	69	N	U							
	Ock	Dol	56	57	N	U							
	Ock	Dol	290	90	N	U							
	Ock	Dol	333	82	S	U							
	Ock	Dol	321	82	S	U							
	Ock	Dol	274	66	N	U							
	Ock	Dol	273	69	N	V							
	Ock	Dol	84	56	N	V							
	Ock	Ch/Dol	85	58	N	U							
	Ock	Ch/Dol	276	59	N	U							
	Ock	Dol	351	64	S	U							
	Ock	Dol	304	90	N	V							
	Ock	Dol	314	90	N	V							
	Ock	Ch	350	81	N	F							
	Ock	Ch	278	59	N	F							
	Ock	Dol	90	69	N	U							
	Ock	Ch	64	56	N	F							
	Ock	Dol	10	72	N	F							
	Ock	Dol	330	54	S	U							
	Ock	Dol	54	64	N	F							
	Ock	Dol	306	70	N	U							
	Ock	Dol	356	81	S	F							
	Ock	Dol	346	80	S	U							
	Ock	Dol	7	66	N	U							
Site A2	Och	Ls						42	32	S			
	Och	Ch	349	61	S	U							
	Och	Ch	289	76	N	U							
	Och	Ls	336	90	N	F							
	Och	Ls	51	64	N	F							
	Och	Ls	81	59	N	U/F							
	Och	Ls	40	44	N	U/F							
	Och	Ls	316	90	N	F							
	Och	Ls	284	72	N	V	3						
	Och	Ls	340	84	S	V	Micro						
	Och	Ls	69	56	N	V	13						
	Och	Ls	289	82	N	V	Micro						
	Och	Ls	81	66	N	V							
	Och	Ls	41	44	N	F							
	Och	Ls	46	66	N	F							
	Och	Ls	36	44	N	F							
	Och	Ls						59	31	S			
	Och	Ls	41	54	N	F							
	Och	Ls	86	72	N	V							
	Och	Ls	86	72	N	U/F	3						
	Och	Ls	296	86	N	V	3						
	Och	Ls	289	78	N	V							
	Och	Ls	339	85	S	V	6						
	Och	Ls	90	65	N	V	Micro						
	Och	Ls	90	65	N	F							
	Och	Ls	54	51	N	U/F							

Table A.1. (continued)

	Fracture							Bedrock			Structure	Fold Axis	Slicks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip	DD			
	Och	Ls	84	64	N		13 to 16						
	Och	Ls	330	90	N	V	16						
	Och	Ls	292	74	N	V							
	Och	Ls	321	79	N	V							
	Och	Ls	336	82	S	V							
	Och	Ls	275	69	N	V							
	Och	Ls	30	74	N	V							
	Och	Ls	32	70	N	F							
	Och	Ls	76	74	N	F							
	Och	Ls	81	66	N	V	6						
	Och	Ls	334	72	S	V	6						
	Och	Ls						45	30	S			
	Och	Ls	81	72	N	V	13						
	Och	Ls	328	86	N	V	6						
	Och	Ls	80	71	N	V	Micro						
	Och	Ls	6	69	N	V							
	Och	Ls	280	67	N	V	Micro						
	Och	Ls	321	90	N	V							
	Och	Ls	41	64	N	U							
	Och	Ls	49	64	N	U							
	Och	Ls						55	32	S			
	Och	Ls						54	42	S			
Site A3	Och	Ls						49	34	S			
	Och	Ls	280	62	N	V	2						
	Och	Ls	75	82	N	V	Micro						
	Och	Ls	9	70	N	V							
	Och	Ls	66	80	N	V							
	Och	Ls	282	64	N	V							
	Och	Ls	359	71	S	V	1						
	Och	Ls	66	81	N	V							
	Och	Ls	86	42	N	F							
	Och	Ls	81	60	N	V							
	Och	Ls	310	79	N	V	15						
	Och	Ls	290	56	N	V	50						
	Och	Ls	76	74	N	V							
	Och	Ls	344	86	S	V	Micro						
	Och	Ls	72	50	N	V							
	Och	Ls	336	84	S	V							
	Och	Ls	79	40	N						Extension		
	Och	Ls	41	54	N								
	Och	Ls	59	46	N	F							
	Och	Ls	288	84	N	F							
	Och	Ls	276	68	N	V							
	Och	Ls	302	78	N	V							
	Och	Ls	80	84	S	U/F							
	Och	Ls	74	56	N	U							
	Och	Ls						70	34	S			
	Och	Ls	70	56	N	V							
	Och	Ls	299	74	N	V							
	Och	Ls						54	39	S			
	Och	Ls	59	48	N	U/F							
	Och	Ls	16	59	N	F							
	Och	Ls	82	54	N	V							
	Och	Ls	9	71	N	V							
	Och	Ls	19	74	N	V							
	Och	Ls	74	50	N	V							
	Och	Ls	336	90	N	F							
	Och	Ls	16	64	N	V							
	Och	Ls	72	53	N	V							

Table A.1. (continued)

			Fracture					Bedrock			Structure	Fold Axis	Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD			
	Unit						(mm)						
	Och	Ls	306	74	N	V							
	Och	Ls	38	80	N	F							
	Och	Ls	305	90	N	F							
	Och	Ls	50	50	N	F							
	Och	Ls	50	49	N	F							
	Och	Ls	309	82	N	F							
	Och	Ls	349	75	S	U							
	Och	Ls	80	52	N	U							
	Och	Ls	76	49	N	F							
	Och	Ls	305	74	N	F							
	Och	Ls	321	86	S	F							
	Och	Ls	45	49	N	F							
	Och	Ls	84	45	N	U							
	Och	Ls	66	69	N	F							
	Och	Ls	290	28	N								
	Och	Ls	66	41	N	U							
	Och	Ls	316	69	N	F							
	Och	Ls	26	20	S						Thrust		
	Och	Ls	280	68	N	F							
	Och	Ch	344	85	S	F							
	Och	Ch/Ls	74	56	N	V							
	Och	Ch/Ls	292	71	N	V							
	Och	Ch/Ls	276	90	N	U/F							
	Och	Ch/Ls	339	80	S	V							
	Och	Ls	279	54	N	U							
	Och	Ls						46	34	S			
	Och	Ls	314	82	S	U							
	Och	Ls	275	46	N						Extension		
	Och	Ls	40	76	N	F							
	Och	Ls						74	42	S			
	Och	Ls						55	46	S			
	Och	Ls	299	81	N	V	6						
	Och	Ls	80	72	N	V	Micro						
	Och	Ls	36	69	N	U							
	Och	Ls	275	75	N	V							
	Och	Ls	300	74	N	V							
	Och	Ls	71	62	N	V							
	Och	Ls	277	69	N	V							
	Och	Ls	296	81	N	V	3						
	Och	Ls	74	71	N	V							
	Och	Ls	34	90	N	U							
	Och	Ls	271	74	N	V							
	Och	Ls	4	84	N	V							
	Och	Ls	272	80	N	V							
	Och	Ls	90	84	N	V							
	Och	Ls	291	81	N	V							
	Och	Ls						42	32	S			
	Och	Ls						48	40	S			
	Och	Ls	349	72	S	U							
	Och	Ls	330	35	N	V	6						
	Och	Ls						62	46	S			
	Och	Ls						60	32	S			
	Och	Ls	276	90	N	V							
	Och	Ls	300	74	N	V							
	Och	Ls	356	76	S	V							
	Och	Ls	294	90	N	V	3						
	Och	Ls	68	69	N	V							
	Och	Ls	311	84	S	V	Micro						
	Och	Ls	359	70	S	V							
	Och	Ls	304	90	N	V							
	Och	Ls	60	54	N	V							

Table A.1. (continued)

	Fracture		Fracture		DD	Fracture		Bedrock			Structure	Fold Axis	Slicks
	Rock	Lithology	Strike	Dip		Filling	Aperture	Strike	Dip	DD			
	Unit						(mm)						
	Och	Ls	341	84	S	V							
	Och	Ls						30	35	S			
	Och	Ls						56	24	S			
	Och	Ls						90	18	N			
	Och	Ls						275	22	N			
	Och	Ls	42	66	S	U							
	Och	Ls						300	29	N			
	Och	Ls	90	31	N	U							
	Och	Ls	276	77	N	F							
	Och	Ls	281	34	N	U							
	Och	Ls	278	90	N	V	6						
	Och	Ls	330	80	S	V							
	Och	Ls	288	82	N	V							
	Och	Ls	85	65	N	V							
	Och	Ls	349	65	S	V					Fold	0 S 34 E	
	Och	Ls	358	81	S	V							
	Och	Ls	296	84	S	V	13						
	Och	Ls	351	75	S	V	Micro						
	Och	Ls	82	71	N	V							
	Och	Ls	289	69	N	V	6						
	Och	Ls	80	74	N	V	Micro						
	Och	Ls	25	59	N	F							
	Och	Ls	299	81	S	F							
	Och	Ls	80	66	N	V							
	Och	Ls	305	81	N	V							
	Och	Ls	280	76	N	V							
	Och	Ls	13	64	N	U							
	Och	Ls	275	74	N	V							
	Och	Ls	44	66	N	U/F							
	Och	Ls	301	90	N	F							
	Och	Ls	34	74	N	F							
	Och	Ls	48	56	N	U							
	Och	Ls	275	66	N	U							
	Och	Ls	272	64	N	V							
	Och	Ls	300	90	N	V							
	Och	Ls	44	64	N	U/F							
	Och	Ls	315	86	S	U/F							
	Och	Ls	41	72	N	U							
	Och	Ls	272	80	S	V							
	Och	Ls	294	51	N						Extension		
	Och	Ls	271	78	S						Extension		
	Och	Ls	34	44	N	U/F							
	Och	Ls	286	66	N	V							
	Och	Ls	276	90	N	V							
	Och	Ls	305	90	N	V	6						
	Och	Ls	86	81	N	V	3						
	Och	Ls	344	84	S	V							
	Och	Ls	336	90	N								
	Och	Ls	81	64	N	U							
	Och	Ls	291	71	N	V	3						
	Och	Ls	300	71	N	V							
	Och	Ls	9	79	N	V							
	Och	Ls	299	81	N	V							
	Och	Ls	299	81	N	F							
	Och	Ls	331	90	N	V							
	Och	Ls	336	90	N	V							
	Och	Ls	278	71	N	V							
	Och	Ls	304	90	N	F							
	Och	Ls	54	61	N	U/F							
	Och	Ls	38	66	N	U							
	Och	Ls	334	81	S	U							

Table A.1. (continued)

			Fracture					Bedrock			Structure	Fold Axis	Slacks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip	DD			
	Och	Ls	54	58	N	U							
	Och	Ls	78	74	N	V							
	Och	Ls	272	68	N	V							
	Och	Ls	272	68	N	F							
	Och	Ls	336	90	N	V							
	Och	Ls	60	56	N	U/F							
	Och	Ls	280	54	N						Extension		
	Och	Ls	86	81	S			46	22	S			
	Och	Ls	338	90	N	F							
	Och	Ls	336	80	S	F							
	Och	Ls	319	90	N	F							
	Och	Ls	60	51	N	F							
	Och	Ls	301	72	N	F							
	Och	Ls	86	84	N	F							
	Och	Ls	339	90	N	F							
	Och	Ls	280	39	N	U							
	Och	Ls	281	84	S	U/F							
	Och	Ls	90	82	S	U/F							
	Och	Ls	4	70	N	F							
	Och	Ls	315	90	N	V							
	Och	Ls	295	64	N	U							
	Och	Ls						66	40	S			
	Och	Ls	301	29	N	U/F							
	Och	Ls	294	74	N	V							
	Och	Ls	340	90	N	V							
	Och	Ls	78	40	N	V							
	Och	Ls	25	39	N	F							
	Och	Ls	336	64	S	F							
	Och	Ls	41	49	N	V							
	Och	Ls	288	61	N	V							
	Och	Ls	349	72	S	F							
	Och	Ls						76	46	S			
	Och	Ls	62	46	S	F							
	Och	Ls	356	74	N	U/F							
	Och	Ls	316	88	N	U/F							
	Och	Ls	320	78	N	U/F							
	Och	Ls	64	70	N	U							
	Och	Ls						310	74	S	Fold	40 S 30 E	
	Och	Ls	350	80	S	U/F							
	Och	Ls	324	74	S	U/F							
	Och	Ls	350	71	N	U							
	Och	Ls	328	79	S	F							
	Och	Ls	319	90	N	U/F							
	Och	Ls	71	44	S						Thrust		
	Och	Ls	6	85	N	U/F							
	Och	Ls	16	20	S						Thrust		
	Och	Ls	12	11	S						Thrust		
	Och	Ls						54	55	S			
	Och	Ls	318	69	N	F							
	Och	Ls						52	60	S			
	Och	Ls						290	69	N			
	Och	Ls						66	65	S			
	Och	Ls						66	51	S			
	Och	Ls	69	59	N	U/F							
	Och	Ls	350	71	N	U/F							
	Och	Ls	349	59	N	U/F							
	Och	Ls	90	80	S						Thrust		
	Och	Ls	285	90	N	U							
	Och	Ls						80	60	S	Fold	26 N 88 E	
	Och	Ls						81	79	S	Fold	19 N 80 E	
	Och	Ls	35	70	N	U							

Table A.1. (continued)

	Fracture		Fracture		Fracture		Bedrock		Bedrock		Bedrock		Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip	DD	Structure	Fold Axis	
	Unit												
	Och	Ls	325	80	S	U							
	Och	Ls						64	61	S			
	Och	Ls	344	81	N	F							
	Och	Ls						48	49	N			
	Och	Ls						75	58	S			
	Och	Ls						61	89	N	Fold	20 S 65 W	
	Och	Ls						75	41	S			
	Och	Ls						66	11	S			
Site A4	Och	Ls	1	52	N	F							
	Och	Ls	349	76	S	V							
	Och	Ls	80	79	N	V							
	Och	Ls	344	82	S	V	3						
	Och	Ls	296	80	N	F							
	Och	Ls	16	82	N	V	Micro						
	Och	Ls	274	74	N	V	Micro						
	Och	Ls	54	76	N	V	Micro						
	Och	Ls	82	64	N	F							
	Och	Ls	288	54	N	V							
	Och	Ls	272	71	S	V	Micro						
	Och	Ls	49	48	N	V	Micro						
	Och	Ls	62	45	N	V	Micro						
	Och	Ls	284	85	S	V	Micro						
	Och	Ls	44	68	N	V	6						
	Och	Ls	2	79	N	F							
	Och	Ls	90	82	N	F							
	Och	Ls	2	70	N	U/F							
	Och	Ls	45	80	N	V							
	Och	Ls	308	86	N	V							
	Och	Ls	355	90	N	V							
	Och	Ls						50	28	S			
	Och	Ls	322	34	N	V							
	Och	Ls	88	85	N	F							
	Och	Ls	84	85	N	V							
	Och	Ls	84	79	N	U							
	Och	Ls	72	60	N								
	Och	Ls	62	61	N	U							
	Och	Ls	45	42	S						Thrust		
	Och	Ls	90	72	N	U							
	Och	Ls	68	41	S						Thrust		
	Och	Ls	11	41	S						Thrust		
	Och	Ls	330	85	N	F							
	Och	Ls	65	74	N	F							
	Och	Ls	70	74	N	U							
	Och	Ls	320	82	N	F							
	Och	Ls	70	60	N	F							
	Och	Ls	339	79	N	F							
	Och	Ls	46	49	S						Thrust		
	Och	Ls	48	38	S						Thrust		
	Och	Ls	76	41	S						Thrust		
	Och	Ls	51	34	S						Thrust		
	Och	Ls						50	54	S	Fold	58 20	
	Och	Ls						279	90	N			
	Och	Ls						340	45	N			
	Och	Ls						40	22	S			
Site B1	Och	Ls						320	19	N			
	Och	Ls						310	18	N			
	Och	Ls	38	81	N	U/F							
	Och	Ls	38	80	N	F							

Table A.1. (continued)

			Fracture					Bedrock			Structure	Fold Axis	Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD			
	Unit						(mm) 2 to 3						
	Och	Ls	354	70	S	V							
	Och	Ls	339	70	S	U							
	Och	Ls	322	66	S	U							
	Och	Ls	339	46	S	V							
	Och	Ls	345	80	N	U					Extension		
	Och	Ls	5	67	N	U					Extension		
	Och	Ls	339	56	S	V							
	Och	Ls	339	56	S	U							
	Och	Ls	37	90	N	U/F							
	Och	Ls	336	58	S	V							
	Och	Ls	42	76	N	F							
	Och	Ls	32	90	N	U/F							
	Och	Ls	31	90	N	F							
	Och	Ls	328	64	N	U							
	Och	Ls	316	76	S	U							
	Och	Ls	70	83	S	U							
	Och	Ls	350	66	S	V							
	Och	Ls	345	84	N						Reverse		
	Och	Ls	349	53	S						Thrust		
	Och	Ls	350	55	S						Thrust		
	Och	Ls	340	90	N						Thrust		
	Och	Ls	32	90	N	U/F							
	Och	Ls	50	90	N	U							
	Och	Ls	54	90	N	U		299	26	N			
	Och	Ls	330	84	N						Extension		
	Och	Ls	339	79	N						Extension		
	Och	Ls	345	55	S						Extension		
	Och	Ls						325	20	N			
	Och	Ls	346	76	S	V							
	Och	Ls	348	0	N	V							
	Och	Ls	326	80	S	V							
	Och	Ls	324	72	S	V							
	Och	Ls	280	69	S	V							
	Och	Ls	275	79	S	F							
	Och	Ls	330	59	S	F							
	Och	Ls	35	90	N	F							
	Och	Ls	40	0	N	V							
	Och	Ls	290	78	S	V							
	Och	Ls	290	78	S	F							
	Och	Ls	305	80	S	V							
	Och	Ls	305	80	S	F							
	Och	Ls	358	82	S	U							
	Och	Ls	336	80	S	U							
	Och	Ls	304	70	S	V							
	Och	Ls	355	0	N	V							
	Och	Ls	273	0	N	V							
	Och	Ls	292	90	N	V							
	Och	Ls	292	90	N	F		321	24	N			
	Och	Ls	302	90	N	V							
	Och	Ls	302	90	N	F							
	Och	Ls	59	87	S	V							
	Och	Ls	59	87	S	U							
	Och	Ls	324	79	S	V							
	Och	Ls	324	79	S	F							
	Och	Ls	275	90	N	F							
	Och	Ls	295	90	N	F							
	Och	Ls	330	90	N	F							
	Och	Ls	65	90	N	F							
	Och	Ls	324	90	N	F							
	Och	Ls	330	90	N	F							
	Och	Ls	350	90	N	F							

Table A.1. (continued)

	Fracture						Bedrock			Structure	Fold Axis	Slicks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip			
	Och	Ls	286	90	N	F						
	Och	Ls	358	90	N	F						
	Och	Ls	305	90	N	F						
	Och	Ls	46	90	N	F						
	Och	Ls	50	90	N	U/F						
	Och	Ls	300	90	N	U/F						
	Och	Ls	26	84	S	U						
	Och	Ls	306	59	S	F						
	Och	Ls	45	90	N	F						
	Och	Ls	40	90	N	F						
	Och	Ls	44	86	S	U/F						
	Och	Ls	311	64	S	U						
	Och	Ls	296	74	S	U						
	Och	Ls	40	87	S	U		305	21	N		
	Och	Ls	320	86	S	U						
	Och	Ls						309	21	N		
	Och	Ls	341	64	S	V						
	Och	Ls	358	66	S	V						
	Och	Ls	320	71	S	V	3	305	26	N		
	Och	Ls	339	60	S	V						
	Och	Ls	330	72	S	V						
	Och	Ls	356	76	S	V						
	Och	Ls	307	62	S	F						
	Och	Ls	308	66	S	F						
	Och	Ls	2	66	S	F						
	Och	Ls	304	71	S	F						
Site B2	Och	Ls						78	6	S		
	Och	Ls						48	9	S		
	Och	Ls						90	25	S		
	Och	Ls	20	74	N	U						
	Och	Ls	329	90	S	U						
	Och	Ls	340	90	S	V	1 to 3					
	Och	Ls	330	90	S	U						
	Och	Ls	50	84	N	U	76					
	Och	Ls	50	80	N	U						
	Och	Ls	4	41	N	U		80	21	S	Extension	
	Och	Ls	340	90	S	U						
	Och	Ls						76	20	S		
	Och	Ls	338	90	S	U						
	Och	Ls	51	86	N	U						
	Och	Ls	70	66	N	U						
	Och	Ls	55	76	S	U						
	Och	Ls	40	90	S	U						
	Och	Ls	318	90	S	F						
	Och	Ls						45	26	S		
	Och	Ls	70	35	N						Extension	
	Och	Ls	50	56	N	U						
	Och	Ls	336	64	S	U						
	Och	Ls	345	70	S	U						
	Och	Ls	360	90	S	U						
	Och	Ls	24	84	N	U						
	Och	Ls	90	56	N	U						
	Och	Ls	330	72	S	U						
	Och	Ls						90	32	S		
	Och	Ls	320	85	N	F						
	Och	Ls	54	66	N	U						
	Och	Ls	49	24	N	U					Fault?	
	Och	Ls										
	Och	Ls	331	76	N	F						

Table A.1. (continued)

	Fracture							Bedrock			Structure	Fold	Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD			
	Unit						(mm)						
	Och	Ls	290	70	N	F							
	Och	Ls	15	34	N						Extension		
	Och	Ls	20	34	N						Extension		
	Och	Ls											
	Och	Ls						60	40	S			
	Och	Ls	18	44	N						Extension		
	Och	Ls	44	70	N	F							
	Och	Ls						46	26	S			
	Och	Ls	71	86	S	F							
	Och	Ls	7	61	N	F							
	Och	Ls	278	72	N	F							
	Och	Ls						71	26	S			
	Och	Ls	330	86	N	F							
	Och	Ls	330	86	N	V							
	Och	Ls	305	90	S	U							
	Och	Ls	315	90	S	F							
	Och	Ls						64	18	S			
	Och	Ls	14	84	S	V							
	Och	Ls	14	84	S	U							
	Och	Ls	299	76	N	F							
	Och	Ls	299	76	N	V							
	Och	Ls	309	84	N	V							
	Och	Ls	309	84	N	F							
	Och	Ls	62	61	S	U							
	Och	Ls	289	65	N	U							
	Och	Ls	356	85	N	U							
	Och	Ls	349	71	S	U							
	Och	Ls	328	74	S	U							
	Och	Ls	4	90	N	V							
	Och	Ls	10	90	N	V							
	Och	Ls	3	90	N	V							
	Och	Ls	46	90	N	V							
	Och	Ls	2	90	N	V							
	Och	Ls	306	90	N	V							
	Och	Ls	10	90	N	V							
	Och	Ls	350	81	S	F							
	Och	Ls	298	42	N	F							
	Och	Ls	316	90	S	F							
	Och	Ls	42	90	S	F							
	Och	Ls	10	59	N						Extension?		
	Och	Ls	301	90	N	U							
	Och	Ls											
	Och	Ls	15	16	N	V							
	Och	Ls	330	90	N	U							
	Och	Ls	54	54	N	U							
	Och	Ls	41	51	N	U							
	Och	Ls	31	82	N	U							
	Och	Ls	31	29	N	U							
	Och	Ls	326	90	N	F							
	Och	Ls						45	F	S			
	Och	Ls	298	90	N	F							
	Och	Ls	41	39	N	F							
	Och	Ls	326	90	N	F							
	Och	Ls	44	74	N	U					fault?		
	Och	Ls	84	82	N	F							
	Och	Ls	336	90	N	F							
	Och	Ls	24	84	S	F							
	Och	Ls	308	90	N	V	1						
	Och	Ls	308	90	N	F							
	Och	Ls						72	13	S			
	Och	Ls	299	90	N	V							

Table A.1. (continued)

			Fracture				Bedrock			Structure	Fold Axis	Slacks	
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip				DD
	Unit												
	Och	Ls	299	90	N	F							
	Och	Ls	328	90	N	F							
	Och	Ls	329	90	N	F							
	Och	Ls	330	90	N	F							
	Och	Ls	54	90	N	F							
	Och	Ls	50	90	N	F							
	Och	Ls	48	90	N	F		75	25	S			
	Och	Ls	41	32	S						Thrust?		
	Och	Ls						67	32	S			
	Och	Ls	320	90	N	U/F							
	Och	Ls						31	19	S			
	Och	Ls	56	64	S	U/F							
	Och	Ls	31	70	N	U/F							
	Och	Ls	24	76	N	U/F							
	Och	Ls	38	74	N	U							
	Och	Ls	355	90	N	U/F							
	Och	Ls	51	44	S						Thrust		
	Och	Ls	61	39	S						Thrust		
	Och	Ls	90	8	N						Thrust		
	Och	Ls											
	Och	Ls	61	40	S						Thrust		
	Och	Ls						71	18	S			
	Och	Ls	80	34	S						Thrust		
	Och	Ls	72	36	S						Thrust		
	Och	Ls	37	64	N	U/F							
	Och	Ls	336	90	N	F							
	Och	Ls						66	14	S			
	Och	Ls	319	90	N	U/F							
	Och	Ls	329	90	N	U/F							
	Och	Ls	306	69	N	F							
	Och	Ls	328	68	N	U/F							
	Och	Ls	24	84	N	U							
	Och	Ls	42	66	N	U/F							
	Och	Ls	12	90	N	F							
	Och	Ls	90	35	S						Thrust		
	Och	Ls	30	90	N	U							
	Och	Ls	316	90	N	F							
	Och	Ls	21	84	N						Extension		
	Och	Ls						78	34	S	HW		
	Och	Ls						76	34	S	HW		
	Och	Ls	60	20	N						Extension		
	Och	Ls	60	24	N						Extension		
	Och	Ls	32	39	N						Extension		
	Och	Ls	350	56	N						Extension		
	Och	Ls	360	0	N						Extension		
	Och	Ls	341	52	N	F							
	Och	Ls	305	90	N	U/F							
	Och	Ls	1	54	S	U/F							
	Och	Ls	51	55	N						Extension		
	Och	Ls	360	70	E	U							
	Och	Ls	36	84	S	U							
	Och	Ls						73	24	S			
	Och	Ls	81	34	S						Thrust		
	Och	Ls	72	34	S						Thrust		
	Och	Ls	314	71	N	F							
	Och	Ls	339	68	S	U/F							
	Och	Ls	40	52	N	F							
	Och	Ls						90	24	S			
	Och	Ls	34	86	N	U							
	Och	Ls						71	16	S			
	Och	Ls	82	51	N	U/F							

Table A.1. (continued)

			Fracture					Bedrock			Structure	Fold Axis	Slicks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip	DD			
Site B3	Och	Ls						72	24	S			
	Och	Ls	279	86	N	V	1						
	Och	Ls	304	90	N	V							
	Och	Ls	310	90	N	V	micro						
	Och	Ls	310	90	N	F							
	Och	Ls	68	71	N	F							
	Och	Ls	309	74	S	U							
	Och	Ls/Ch	300	85	S	U							
	Och	Ls	23	24	S			51	56	S	Thrust?		
	Och	Ls	80	66	S						Thrust		
	Och	Ls	72	68	S						Thrust		
	Och	Ls	62	79	S						Thrust		
	Och	Ls	70	74	S						Thrust		
	Och	Ls	71	74	S						Thrust		
	Och	Ls	23	28	S			41	35	S			
	Och	Ls	334	90	N	V							
	Och	Ls	82	24	N						Thrust		
	Och	Ls	82	41	S						Thrust		
	Och	Ls	312	90	N	V	3						
	Och	Ls	302	84	N	V	3						
	Och	Ls	314	90	N	V	5						
	Och	Ls	344	86	S	F							
	Och	Ls	75	26				80	80	N	Fold		
	Och	Ls	84	12				85	66	N	Fold		
	Och	Ls	315	84	S	F							
	Och	Ls						72	44	N			
	Och	Ls	344	62	S	F							
	Och	Ls	66	69	S	F							
	Och	Ls	66	69	S	V							
	Och	Ls	330	70	S	F							
	Och	Ls	330	80	S	F							
	Och	Ls	63	55	S	U							
	Och	Ls	296	28	N						Thrust		
	Och	Ls	80	56	S	V							
	Och	Ls	320	82	S	F							
	Och	Ls	320	82	S	V							
	Och	Ls	315	78	S	V							
	Och	Ls	316	80	S	F							
	Och	Ls	65	90	N	U							
	Och	Ls	65	90	N	V							
	Och	Ls	68	90	N	V	1 to 2						
	Och	Ls						90	29	N			
	Och	Ls	71	49	N						Thrust		
	Och	Ls	349	84	S	V							
	Och	Ls											
	Och	Ls	65	69	S						Thrust		
	Och	Ls	44	45	N	F							
	Och	Ls	279	79	N	U							
	Och	Ls						30	24	S			
	Och	Ls	86	41	S						Thrust		
	Och	Ls	88	26	N						Thrust?		
	Och	Ls	45	62	N	U							
Site B4	Och	Ls	0	90	N	V	Micro						
	Och	Ls	27	86	S	V							
	Och	Ls	326	84	N	V							
	Och	Ls	276	90	N	V	Micro						
	Och	Ls	78	86	N	V							
	Och	Ls	299	90	N	V	3						

Table A.1. (continued)

	Fracture							Bedrock			Structure	Fold Axis	Slicks
	Rock	Lithology	Strike	Dip	DD	Filling	Aperture	Strike	Dip	DD			
	Unit						(mm)						
	Och	Ls	2	90	N	V	Micro						
	Och	Ls	71	90	N	V							
	Och	Ls						40	15	S			
	Och	Ls	74	90	N	V							
	Och	Ls	344	75	S	V	6						
	Och	Ls	320	90	N	V							
	Och	Ls	326	90	N	V							
	Och	Ls	44	90	N	V							
	Och	Ls	326	90	N	V							
	Och	Ls	349	86	N	V							
	Och	Ls	40	90	N	V							
	Och	Ls	341	90	N	V							
	Och	Ls	0	90	N	V							
	Och	Ls	329	84	N	V							
	Och	Ls	335	86	N	V							
	Och	Ls	22	90	N	V							
	Och	Ls	286	84	N	V							
	Och	Ls	330	90	N	V							
	Och	Ls	281	84	N	V							
	Och	Ls	328	90	N	V							
	Och	Ls	80	90	N	V	13						
	Och	Ls	304	90	N	V							
	Och	Ls	26	90	N	V							
	Och	Ls	71	51	S	V							
	Och	Ls	345	90	N	V							
	Och	Ls						282	16	S			
	Och	Ls	299	90	N	V							
	Och	Ls	345	75	N	V							
	Och	Ls						285	24	S			
	Och	Ls	326	80	N	V							
	Och	Ls	329	90	N	V							
	Och	Ls	50	90	N	F							
	Och	Ls	352	90	N	V							
	Och	Ls	45	76	N	V							
	Och	Ls	279	90	N	V							
	Och	Ls	339	68	N	V							
	Och	Ls	81	90	N	V	13						
	Och	Ls	336	72	S	V							
	Och	Ls	74	86	S						Dextral	N74E 0	
	Och	Ls	280	86	N	V					Dextral	N80W 6	
	Och	Ls	330	87	S	V					Dextral?	S26E 5	
	Och	Ls	331	87	N	V	13						
	Och	Ls	71	78	S	V							
	Och	Ls	320	87	N	V							
	Och	Ls	320	87	N	F							
	Och	Ls	320	86	N	V							
	Och	Ls	328	86	N	V					Sinistral		
	Och	Ls	65	36	S						Thrust		
	Och	Ls	75	42	S						Thrust		
	Och	Ls						48	27	S			
	Och	Ls	29	69	N	U/F							
	Och	Ls	322	90	N	F							
	Och	Ls	81	37	E						Thrust		S32E 24
	Och	Ls	339	76	N	V	6						
	Och	Ls	66	79	N	U							
	Och	Ls	39	78	N	F							
	Och	Ls	39	78	N	V							
	Och	Ls	51	90	N	U							
	Och	Ls	70	59	N	U							
	Och	Ls	90	29	S		13				Thrust		S51E 2
	Och	Ls	57	46	S						Thrust		

Table A.1. (continued)

			Fracture				Bedrock			Structure	Fold Axis	Slicks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip			
	Och	Ls	66	83	N	U						
	Och	Ls	273	36	S						Thrust	
	Och	Ls						280	19	S		
	Och	Ls						279	21	S		
	Och	Ls	51	76	N	F						
	Och	Ls	345	81	S	F		276	26	S		S13E 14
	Och	Ls	339	87	S	V						
	Och	Ls	62	84	S	U						
	Och	Ls	70	71	N	F						
	Och	Ls	76	70	N	F						
	Och	Ls	286	71	S	U		82	19	S		
	Och	Ls	289	79	N	F						
	Och	Ls	61	71	N	U						
	Och	Ls	279	69	N	U/F						
	Och	Ls	344	90	N	F						
	Och	Ls	309	90	N	U						
	Och	Ls	6	90	N	F						
	Och	Ls	351	90	N	F						S2E 11
	Och	Ls	80	90	N	F						
	Och	Ls						72	26	S		
	Och	Ls	289	71	N	V						
	Och	Ls	350	81	N	V						
	Och	Ls	350	81	N	F						
	Och	Ls	322	84	N	U/F						
	Och	Ls	322	84	N	V						
	Och	Ls	339	81	N	F					Dextral	S20E 30
Site C1	OCk	Dol						85	82	N		
	OCk	Dol										
	OCk	Dol	332	38	N						Thrust?	
	OCk	Dol										
	OCk	Dol	72	46	S						Thrust	234 16
	OCk	Dol										
	OCk	Dol						346	11	N		
	OCk	Dol	34	44	S	U						
	OCk	Dol	279	90	N	F						
	OCk	Dol						353	24	N		
	OCk	Dol	331	68	E	U						
	OCk	Dol	270	77	N	U						
	OCk	Dol	335	28	E	U						
	OCk	Dol	125	60	S	U						
	OCk	Dol	241	73	N	U						
	OCk	Dol	219	64	W	U						
	OCk	Dol	230	57	N	U						
	OCk	Dol	213	48	W	U						
	OCk	Dol	248	56	N	U						
	OCk	Dol	221	54	W	U						
	OCk	Dol	296	81	S	U/F						
	OCk	Dol	356	76	S	U						
	OCk	Dol	284	46	N	U						
	OCk	Dol						50	28	S		
	OCk	Dol						40	31	S		
	OCk	Dol						65	24	S		
	OCk	Dol	360	85	N	U						
	OCk	Dol	48	57	S						Thrust	
	OCk	Dol	311	80	N	U						
	OCk	Dol	286	85	N	F						
	OCk	Dol	86	41	S						Thrust	
	OCk	Dol						55	24	S		
	OCk	Dol						71	9	S		

Table A.1. (continued)

			Fracture				Bedrock			Structure	Fold	Slicks
	Rock Unit	Lithology	Strike	Dip	DD	Filling	Aperture (mm)	Strike	Dip			
	OCk	Dol						55	21	S		
	OCk	Dol	336	31	N						Thrust?	
	OCk	Dol	69	74	N						Stylolite	
	OCk	Dol	66	67	N							
	OCk	Dol	90	41	S						Thrust?	
	OCk	Dol	298	37	S						Thrust?	
	OCk	Dol	80	64	S						Thrust?	
	OCk	Dol	10	64	S						Thrust?	
	OCk	Dol	55	50	S						Thrust	
	OCk	Dol	346	52	N						Thrust	
	OCk	Dol						44	39	S		
	OCk	Dol	53	41	S	U						
	OCk	Dol	81	68	S	U						
	OCk	Dol	107	66	S	U						
	OCk	Dol	76	77	S	U						
	OCk	Dol	126	81	S	U						
	OCk	Dol	296	46	N	V						
	OCk	Dol	291	64	N	V						
	OCk	Dol	82	46	N	V						
	OCk	Dol						59	26	S		
	OCk	Dol						288	51	N		
	OCk	Dol						296	48	N		
	OCk	Dol						299	34	N		
	OCk	Dol	279	76	S						Thrust?	
	OCk	Dol	150	13	W	U						
	OCk	Dol	336	88	E	U						
	OCk	Dol	314	62	N	U						
	OCk	Dol	286	52	N	U						
	OCk	Dol	149	44	W	U						
	OCk	Dol	321	71	E	U						
	OCk	Dol	277	68	N	U						
	OCk	Dol	352	67	E	U						
	OCk	Dol	45	64	S	U						
	OCk	Dol	187	45	W	U						
	OCk	Dol						319	39	S		
	OCk	Dol	25	81	S	U						
	OCk	Dol						88	51	N		
	OCk	Dol						316	41	S		
	OCk	Dol						90	62	N		
	OCk	Dol	299	44	N						Thrust	265 44
	OCk	Dol	90	80	W	U						
	OCk	Dol	289	61	N	U						
	OCk	Dol						56	56	S	Thrust?	
	OCk	Dol	299	90	N	U						
	OCk	Dol	318	82	S	U						
	OCk	Dol						75	69	N		
	OCk	Dol						31	41	S		
	OCk	Dol	64	66	S						Thrust	
	OCk	Dol	74	66	S						Thrust	
	OCk	Dol						60	66	S		
	OCk	Dol						80	31	S		
	OCk	Dol						60	46	S		
	OCk	Dol						60	21	S		
	OCk	Dol						280	70	N		
	OCk	Dol	19	72	N	U						
	OCk	Dol	31	46	S	U						
	OCk	Dol	341	81	S	U						

DISTRIBUTION
(K/ER-259)

1.	M. J. Aiken	22.	J. G. Parrot
2.	L. V. Asplund	23.	T. J. Pierce
3.	W. D. Barton	24.	R. S. Poling (6)
4.	D. E. Bohrman	25.	G. E. Rymer
5.	K. P. Brown	26.	A. S. Quist
6.	W. E. Doll	27.	C. T. Rightmire
7.	R. B. Dreier	28.	W. E. Sanford
8.	T. O. Early	29.	M. M. Sherrod
9.	P. L. Goddard	30.	V. D. Smith
10.	R. D. Hatcher, Jr.	31.	J. V. Spence
11.	B. H. Howard	32.	J. Switek
12.	D. D. Huff	33.	L. E. Toran
13.	R. H. Ketelle	34.	D. B. Watson
14.	R. R. Lee	35.	J. L. Williams
15.	S. Y. Lee	36.	S. Winters
16.	P. J. Lemiszki (25)	37.	B. Zerr
17.	J. R. Lyons	38.	T. F. Zondlo
18.	D. M. Matteo (2)	39.	Applied Technology Library
19.	G. K. Moore	40.	ER DMC—RC
20.	C. A. Motley	41.	K-25 ER Project Files
21.	P. T. Owen	42.	File—K-25 ER DMC—RC
-
43.	R. A. Arnseth, SAIC, 301 Laboratory Rd., Oak Ridge, Tennessee 37830
44.	P. E. Barndt, DOE Oak Ridge Operations Office, P.O. Box 2001, Oak Ridge, Tennessee, 37831
45.	G. W. Bodenstein, DOE Oak Ridge Operations Office, P.O. Box 2001, Oak Ridge, Tennessee
46.	M. A. Travaglini, DOE Oak Ridge Operations Office, P.O. Box 2001, Oak Ridge, Tennessee