THE STRUCTURAL GEOLOGY OF PART OF THE LIMESTONE HILLS IN THE WICHITA MOUNTAINS, CADDO AND COMANCHE COUNTIES, OKLAHOMA

By

ABDOLALI BABAEI

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Pahlavi University

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THE STRUCTURAL GEOLOGY OF PART OF THE LIMESTONE

HILLS IN THE WICHITA MOUNTAINS, CADDO

AND COMANCHE COUNTIES, OKLAHOMA

Thesis Approved:

R. N. Donovan
Thesis Adviser

Alex R. Ross

Gary F. Stewart

Norman N. Durham
Dean of the Graduate College

PREFACE

The main purpose of this thesis is to map the general geology, and particularly to interpret the structural elements of the limestone hills in the Wichita Mountains, southwestern Oklahoma. The major emphasis of the study is to show the role of regional tectonics and the nature of major fault movements in the area.

I would like to offer special thanks to my thesis supervisor, Dr. R. Nowell Donovan, for his constant encouragement and great help in this project. Sincere appreciation is extended also to other thesis committee members, Dr. Gary F. Stewart and Dr. Alex R. Ross, for their helpful criticism of the manuscript.

I am also greatly indebted to Dr. David J. Sanderson for help in the field, and to Dr. Thomas L. Thompson (Professor, Department of Geology, University of Oklahoma) for his helpful comments. My grateful thanks also go to my typist, Ms. Jeanne Vale, for her care and patience with the manuscript. I acknowledge the support of the Department of Geology, Oklahoma State University.

Finally, most grateful thanks are due my wife, Sima, who helped me greatly, both in the field and during preparation of the thesis maps and diagrams.

TABLE OF CONTENTS

TABLE

LIST OF FIGURES

Figure		Page

LIST OF PLATES

Plate

CHAPTER I

ABSTRACT

Detailed field mapping of the eastern half of Saddle Mountain in the northern Wichita Mountains has delineated a complex of folds developed in the limestones of the Upper Arbuckle Group. The folds trend northwest; the majority plunge in this direction. Two orders of fold magnitude are (a) 600 to 3,000 ft. (first order folds), and (b) 5 to 30 ft. (second order folds). Parallel and similar fold styles are developed in both symmetrical and asymmetrical structures and both open and closed folds exist, the latter showing the development of pressure solution cleavage in hinge regions.

Folds are located in the Lawtonka "graben," a complex fault-controlled structure separated from the Blue Creek Canyon horst to the northeast by the Blue Creek Canyon Fault. The latter has an anomalous trend (N5-10°W as opposed to N50°W elsewhere) in the area mapped and is a braided fault complex here interpreted as a high-angle reverse fault with a downthrow to the southwest.

The folds developed during the final evolution of the southern Oklahoma aulacogen during the Pennsylvanian. The principal stress responsible for folding was N40°E. However, deviation of fold-axis trend in the area of the Blue Creek Canyon Fault suggests secondary compression approximately from N80°E. This compression could have produced reverse movement on the Blue Creek Canyon Fault in the area

mapped (with anomalous trend) and left-lateral wrench movement elsewhere on the fault. This interpretation is in accord with previous interpretation of fault movements in the area based on independent evidence.

CHAPTER II

INTRODUCTION

The objectives of this thesis are:

a) production of a geological map of part of Saddle Mountain which is located in Comanche and Caddo Counties in southwest Oklahoma;

b) analysis of structure in the area as it affects limestones of the Arbuckle Group;

c) determining the effects on this structure of lateral movements postulated along major faults in the area.

Location of Study Area

Saddle Mountain is one of the Limestone Hills which form the northern flank of the Wichita Mountains in southwest Oklahoma. Boundaries of the area studied are: the southwestern sections of Caddo County in the north, Sec. 23, T3N, R12W in the south, Sec. 13, T4N, R12W in the east, the eastern edge of R13W in the west, and Kiowa County line in the northwest (Fig. 1). The area comprises approximately 23 sq. mi. with maximum dimensions of 6 x 7 mi.

Topography and Exposure

The Limestone Hills are monadnocks rising up to 1,200 ft. above the general level of southwestern Oklahoma. The larger hills, of which Saddle Mountain is an example, are well rounded with slopes of 15-20°.

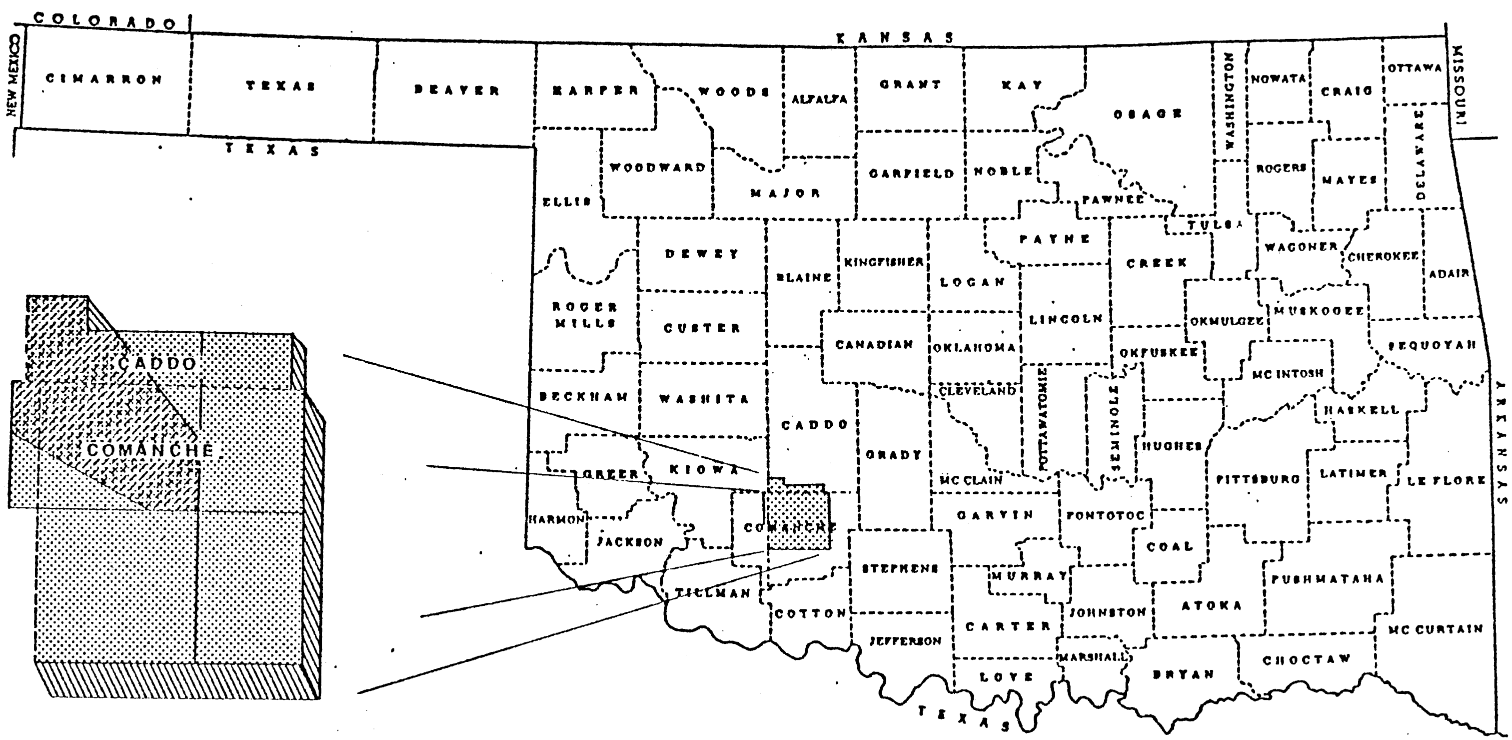


Fig. 1.--Geographical location of area studied.

Smaller hills, which are frequently homoclinal sequences, are cuestas (e.g., Longhorn Mountain).

In general, limestone outcrops trend north-northwest; they are separated from each other and from the igneous Wichita Mountains by broad valleys floored by Permian sediments. In part, the present topography has been inherited from Permian times; the Lower Paleozoic outcrops are mantled by the Post Oak Conglomerate (Chase, 1954) which represents Permian screes and alluvial fans. Beneath the Post Oak unconformity there is evidence of Permian karst weathering (Donovan, personal communication). The limestone hills support sparse vegetation and general exposure is excellent; from 10 to 80 percent of the area is bare rock. Although there are few permanent streams the hills have been well dissected by a generally dendritic pattern of (presently) intermittent streams.

Study Techniques

Field work was conducted during the last month of 1978 and continued through the spring and summer of 1979. An initial reconnaissance of adjacent areas was followed by 11 weeks of detailed field mapping in the study area. Principle difficulty was in determining stratigraphic boundaries within the Arbuckle Group.

Mapping was facilitated by use of aerial photographs, provided by the Agricultural Stabilization and Conservation Service (ASCS) (scale: 1:20,000; 1 mile ≈ 3.1 in.). Approximate stratigraphic contacts and structural attitudes were recorded on acetate overlays during the field work. Precise location of these data were subsequently transferred to 7.5 minute-series topographic maps of the area. Stereoscopic examination was helpful in location of faults, tight and minor folds and other structural phenomena but did not help much in determination of stratigraphic contacts because of the homogeneity of the limestones.

A geologic map and four interpretative cross sections were made on the 7.5 minute-series topographic map. A detailed, larger scale map of the complex geology of the Blue Creek Canyon area was constructed.

Equal-area stereonet analysis of structural attitudes was used to show the major stress direction responsible for the folding.

Use was made of aerial photographs of the area taken by Drs. D. J. Sanderson and R. N. Donovan.

Previous Investigations

Early reconnaissance and general observations about the limestone hills north of the Wichita Mountains were made by Vaughan (1899). Subsequently, various aspects of physiography, stratigraphy, structure, lithology, and paleontology were described by Taff (1904). Taff's stratigraphic correlation of the Lower Paleozoic rocks was modified by Ulrich (1911).

Decker (1933) compared Ordovician rocks of the Arbuckle and Wichita Mountains, and in a later publication (1939), produced a map to show distribution of Precambrian and Lower Paleozoic rocks in the eastern Wichita Mountains.

Harlton (1951 and 1963) analyzed the faults along the northern flank of the Wichita Mountains. He produced a map showing distribution of structural provinces. His later work was based on subsurface data (well logs and cores) and he was first to name the Frontal Wichita Fault System.

Ham et al. (1964), who investigated an area of 17,000 sq. mi. in southern Oklahoma, emphasized the relationship of basement rocks to the structural evolution of the area. This work is illustrated by numerous cross sections, stratigraphic columns and rock descriptions.

The most recent and relevant publications on the limestone hills near the area of investigation are by Brookby (1969) and Barthelman (1969). Both produced Master-of-Science theses describing surface exposures of the limestones of the northeastern Wichita Mountains. The purpose of these reports was to map and document stratigraphy, structure, and paleontology of the Ordovician part of the Arbuckle Group.

In the broader context of the southern Oklahoma aulacogen, significant papers have been produced by Prautt (1975), Wickham et al. (1975), and Powell and Phelps (1977). Prautt (1975), on the basis of geophysical observations, first named the southern Oklahoma aulacogen. Wickham et al. (1975) distinguished discrete stages of structural activity during formation of the aulacogen. Powell and Phelps (1977) recognized the major structural provinces of southern Oklahoma and related the igneous rocks of the Wichita province to the rifting stage of aulacogens.

CHAPTER III

STRATIGRAPHY

Introduction

Rocks in the area studied mostly belong to the upper (Ordovician) part of the Arbuckle Group. They are overlain with profound unconformity by conglomerates of early Permian (Leonardian) age. These conglomerates are referred to as the Post Oak Formation (Chase, 1954). In the study area they are locally-derived fanglomerates deposited on a surface of considerable relief.

In the east of the area outcrops of the Cambrian Carlton Rhyolite are in fault contact (the Blue Creek Canyon Fault) with the Arbuckle Group. The rhyolites are also overlain by Post Oak conglomerates; clast composition indicates major pre-Permian movement of the Blue Creek Canyon Fault.

Rocks of Cambrian Age

Carlton Rhyolite

The Carlton Rhyolite Group outcrops in the east and southeast of the area on the upthrown side of the Blue Creek Canyon Fault. The rhyolite weathers to form smoothly rounded hills, easily distinguishable from adjacent Arbuckle limestone outcrops.

Elsewhere the Carlton Rhyolite Group includes all the rhyolitic rocks in the Wichita Mountains and Arbuckle Mountains, and their equivalents in the subsurface. The Group underlies at least 7,000 sq. mi. of Southern Oklahoma.

The rhyolites have been radiometrically dated as pre-Upper Cambrian (probably Middle Cambrian), with an approximate maximum thickness of 3,600 ft. on Bally Mountain. The rocks comprise rhyolitic flows, tuffs, agglomerates, and welded tuffs (Ham et al., 1964).

Cambro-Ordovician Rocks

The Arbuckle Limestone Group

The Carlton Rhyolites are disconformably overlain by the Arbuckle Limestone Group. The basal Arbuckle Formation is the Reagan Sandstone which comprises calcareous sandstones with conspicuous glauconite.

The overlying Arbuckle formations leave a continuous succession of limestones; individual beds are usually less than 5 ft. in thickness.

Lithologies include dense, fine-grained, medium- to light-gray limestones, cream- to light-brown dolomitic limestone, intraformational conglomerates, calcareous mudstones and calcarenites.

Usually dolomitic beds are not laterally continuous for a long distance; in some areas there is a clear gradational change from limestone to dolomite. The total thickness of the Arbuckle Group is approximately 7,000 ft. of which the top 4,000 ft. are of Ordovician age (Barthelman, 1969; Brookby, 1969; Harltan, 1951). In the study area the formations mapped are Ordovician; in ascending order these are the McKenzie Hill, Cool Creek,Kindblade and West Spring Creek Formations. Significant mapping characteristics are highlighted below.

McKenzie Hill Formation. The McKenzie Hill Formation is divided into two mapping units, a lower non-cherty and an upper cherty member. The formation, which crops out mainly along the western margin of the area, has a total thickness of 1,150 ft., whereas 1,050 ft. is recorded by Chase and others (1956) in the Arbuckle Mountains, or 925 ft. by Brookby (1969).

Basic lithologies in the formation are light- to medium-gray limestones intercalated with mudstones and calcarenites. No algal stromatolites are present, although they are a conspicuous feature in higher formations. In this upper cherty member chert occurs as nodules from 1 to 10 cm. in diameter.

No mappable dolomite units are found in the McKenzie Hill, although total replacement of limestone by dolomite has been found in equivalent strata in the Arbuckle Mountains (Ham, 1950).

Cool Creek Formation. In the area studied, the Cool Creek Formation is exposed in the core of a number of anticlines.

The Cool Creek Formation is characterized by medium-gray interstratified carbonate mudstones, calcarenites and intraformational conglomerates. Some limestone has been replaced by medium- to dark-brown dolomite.

The Cool Creek Formation is easily distinguishable from the basal McKenzie Hill as it contains abundant sandy and oolitic limestone beds, some of which are cross bedded. In particular, a medium-gray quartzose sand which contains oolitic grains can be used as a marker bed for separating the formations. The abundance of quartz sand decreases toward the top of the Cool Creek Formation.

Another characteristic of this Formation is its prolific and different cherts, which may be nodular or discontinuously bedded and have replaced a variety of limestone textures, including oolitic sandstones. Some algal stromatolites are present.

Of the 630 ft. thickness of the Cool Creek Formation, the lower 400 ft. is essentially unfossiliferous, except for algae; fossils, including gastropods and brachiopods, occur only within the top 230 ft.

Kindblade Formation. The Kindblade Formation (Decker, 1933) crops out chiefly along the eastern margin of the area although no complete section of the Formation is exposed in this area. The complete Kindblade Formation is 770 ft. thick.

Light- to medium-gray carbonate mudstones, calcarenites, and intraformational conglomerates are characteristic of Kindblade Formation. Quartz sand is sparse, except in the lower part. Locally, limestone is replaced, either partially or completely, by medium-gray to light-brown dolomite.

The Kindblade Formation contains fewer chert nodules than the Cool Creek Formation. Few stromatolites are present in this formation.

Contact of the Kindblade Formation with the underlying Cool Creek Formation is characterized by a zone of abundant silicified sponges. Contact with the overlying West Spring Creek Formation is marked by a dolomitic quartzose sandstone horizon.

West Spring Creek Formation. Exposures of the West Spring Creek Formation are limited both in the study area and in the Wichita Mountains as a whole. Basically this is due to the coverage of the upper part of the formation by the conglomerates of the Post Oak

Formation. Maximum thickness of the formation has been estimated (in the Arbuckle Mountains) to be 1,375 ft. (Ham, 1956). Only 360 ft. of these rocks were mapped in the Wichita area.

The formation consists of medium-gray carbonate mudstones, calcarenites, and intraformational conglomerates. The lower part of the formation is typified by fine- to medium-crystalline dolomites, interbedded with dark-brown, laminated quartzose sandstones.

Hemispheroidal algal stromatolites and beds of chert nodules are common in this formation.

Permian Rocks

Wichita Formation

In and around the Wichita fault-block complex in southwestern Oklahoma, deposits of Permian age unconformably overlie a thick sequence of Lower Paleozoic limestones and igneous rocks. These Permian rocks are usually referred to as the Wichita Formation. However, the conglomerate facies close to the unconformity is referred to as the Post Oak Formation.

In the mapped area, Post Oak Conglomerates, which have a more or less horizontal attitude, are draped over Lower Paleozoic limestone hills. The present topography is partly an exhumed Permian karst surface.

In the research area, the Post Oak comprises pebble and cobble conglomerates. Clasts are dolomites and rhyolites clearly derived from the surrounding and underlying beds.

The conglomerates have a maximum thickness of 600 ft. in and around the Wichita Mountains and pass laterally into the Wichita

Formation which comprises 400 ft. of interbedded arkose and shale (Chase, 1954).

On the basis of sedimentary structures, paleocurrents, and texture, Chase (1954) interpreted these rocks as the deposits of small, ephemeral streams that drained the Wichita Mountains. The latter were being eroded after Late Paleozoic uplift.

CHAPTER IV

STRUCTURAL GEOLOGY OF THE REGION

Summary

A wide Paleozoic trough, faulted and gently folded during the late Paleozoic into a system of fault basins and uplifts, extends west-northwest from the Ouachita geosyncline in southeastern Oklahoma and northern Texas across the foreland platform of southern Oklahoma into the panhandle of Texas.

Principal Tectonic Controls That Affected the Area Studied

The major relevant structural features in southern Oklahoma (Fig. 2) are the Anadarko and Hollis Basins, which are separated by the Amarillo-Wichita Uplift. The Frontal Wichita Fault System forms the boundary between the Anadarko Basin and the Amarillo-Wichita Uplift; the area studied is located within this fault System.

As exposed in southwestern Oklahoma, the Wichita Uplift is a complex horst, 65 mi. in length and about 20 mi. wide, which covers an area of c. 1,300 sq. mi. (Ham et al., 1964). The Anadarko Basin is one of the greatest known mid-continent depressions, in which up to 40,000 ft. of Paleozoic strata were deposited (Johnson and Denison, 1973). The Frontal Wichita Fault System has a maximum width of about 7 to 10 mi. and comprises a braided complex of faults with a generally

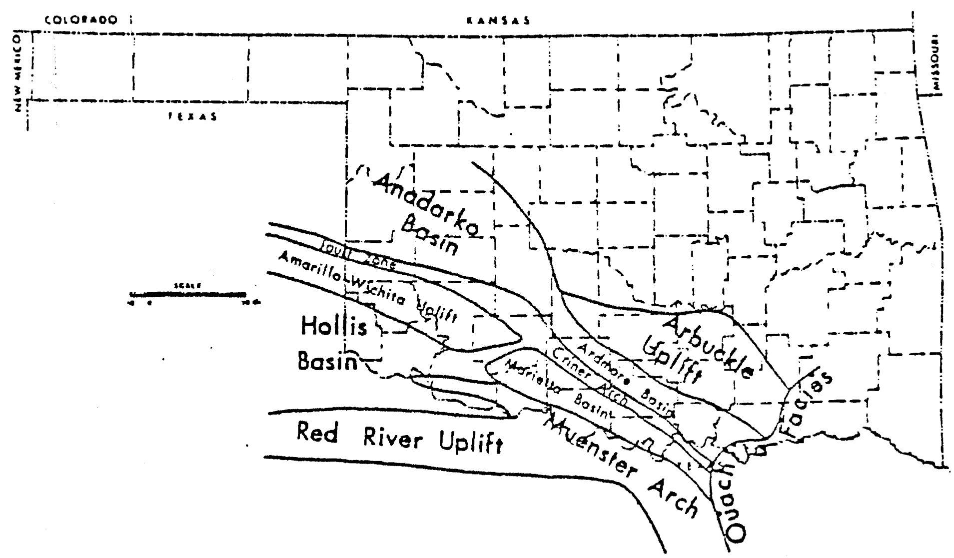


Fig. 2.--Location of principal structural features of southern Oklahoma (from Ferguson, 1979).

northward (basinward) downthrow (Fig. 3).

The Plate Tectonic Interpretation of Southern Oklahoma

The geological development outlined above has been widely interpreted in terms of the aulacogen model (Shatski, 1946). Aulacogens are interpreted as failed arms of the triple junctions which develop during continental rifting (Dewey and Burke, 1973). Typically they are long-lived, deeply subsiding troughs which extend more or less perpendicular to contemporary continental margins. They are a widely-recognized feature of post-Pangaean geography and have been identified in Paleozoic and Precambrian settings (Hoffman et al., 1974). Post-Pangaean analogues are provided by the Afar Triangle region of east Africa, the Benue Trough in west Africa and the Limpopo and Zambesi troughs, opposite Madagascar on the east coast of southern Africa.

Outline of Geological Development in the Paleozoic

Three distinct phases can be delineated in the Paleozoic evolution of the area (Ham et al., 1964). The first (igneous) phase involved the intrusion of layered basic rocks in Late Precambrian or Cambrian times. Subsequently, this phase concluded with the eruption of Cambrian rhyolites and more or less coeval intrusion of the Wichita Granites.

The second phase, which lasted from Late Cambrian until Devonian times, involved the deposition of a considerable thickness of marine, predominantly carbonte rocks. The final phase involved Carboniferous folding and faulting followed by late Pennsylvanian and Permian deposition of continental sediments.

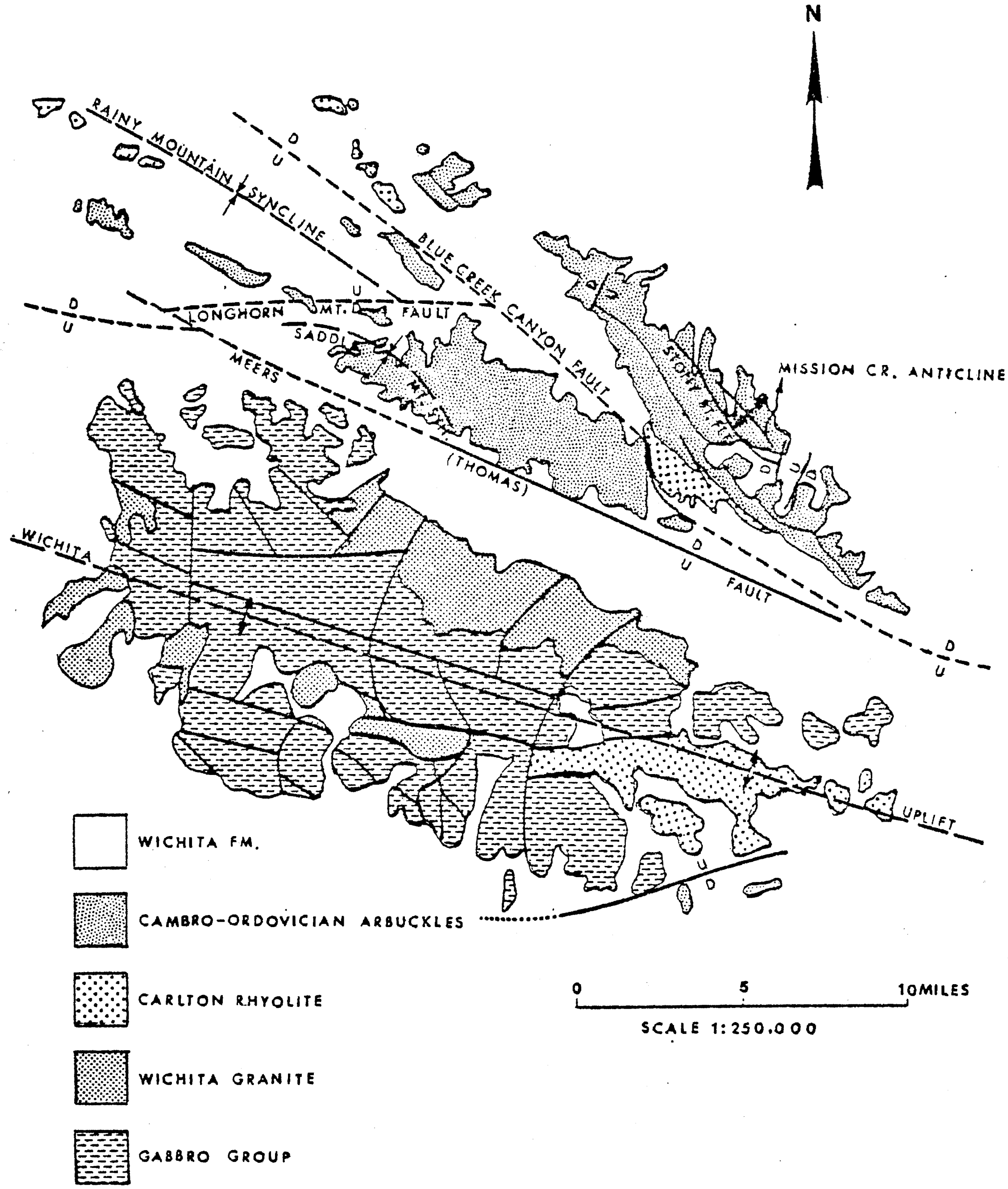


Fig. 3.--Geology of the Wichita Uplift (adapted from Havens, 1977).

Review of Aulacogen Development

Aulacogens are believed to commence forming when a triple junction of tension cracks, radiating at 120° to each other, develops on the site of a large uplift. Such uplifts are generated by thermal expansion of the crust due to underlying magma generation (the "asthenospheric perturbations" of Gass, 1972).

If these uplifts and their associated cracks become integrated with the world-wide plate boundary system then adjacent uplifts will be linked by propagation of the crack pattern and the subsequent development of an integrated rift system. This stage may be followed by ocean development.

Aulacogens are those rifts which fail to integrate. This failure can take place at various stages in integration and thus several types of aulacogen have been recognized (Hoffman et al., 1974). Advanced aulacogens characteristically show an initial igneous phase, a complex sedimentary phase, and a final compressional tectonic phase, the latter associated with aulacogen extinction.

Post-Pangaean aulacogens typically have an orientation transverse to modern expanding oceans and are located at re-entrants of continental margins. More ancient aulacogens, including Oklahoma, extend more or less at right angles to major fold mountain belts (the latter representing closed Paleozoic oceans). In the case of the Oklahoma aulacogen the Ouachita Fold Belt fulfills this role.

Application of Theory to Southern Oklahoma

Hoffman et al. (1974) distinguished seven features in the evolution of an aulacogen, all of which can be recognized in southern Oklahoma.

a. Transverse orientation of structure to regional pattern.

b. Location of re-entrant of continental margin or major ("geosynclinal") fold belt.

c. Contemporaneity of aulacogen initiation and continental break-up.

d. Evolution of graben from narrow rift into a broad downwarp.

e. Dominant alkaline igneous activity.

f. Late compression of supracrustal fill.

g. Combination of increased crustal thickness and positive bouger anomaly.

Five stages related to the above features can clearly be delineated in the development of the southern Oklahoma aulacogen (Table I). In the area studied stages 3 to 5 are represented at the surface.

There are several features of the Oklahoma aulacogen which apparently are not in accord with the model outlined above.

a. The age of basic igneous rocks is ambiguous; they may be much older than the model requires.

b. Pre-quartzite (i.e., rift) continental sediments have not yet been positively identified.

c. Argument exists as to the precise character of some major faults (normal, reverse, wrench). This argument may simply resolve into a recognition of rejuvenation.

Structural Development of the Aulacogen. Wickham et al. (1975) recognized three distinct phases of structural activity which can be related to the stages described in Table I. The earliest rifting phase is characterized by normal faulting, the extrusion of basalts and rhyolites, and the emplacement of gabbros and granites. As this stage concluded the faults bounding the graben apparently "locked," as is

TABLE I

OUTLINE OF THE DEVELOPMENT OF THE OKLAHOMA AULACOGEN

Stage		Character	Result
5	Post Geosynclinal (Permian)	Fanglomerate and other continental sediments	Wichita Formation
4	Compressional (Devonian (minor)-Pennsylvanian)	Folding, normal and reverse faulting	Structure in limestone hills of Wichita and Arbuckle areas
3	Downwarp (Ordovician-Mississippian)	Mollasse phase Calc-flysch phase Flysch phase	Individual phases not satisfactorily identified. Includes Sycamore, Hunton, Viola, Bromide, etc.
2	Transitional (Cambro-Ordovician)	Pre-flysch phase	Arbuckle Group
1	Graben-Rift (Cambrian)	Dolomite phase Quartzite phase Pre-quartzite phase (Accompanied by normal faulting and igneous activity)	Lower Arbuckle Group Reagan Sandstone Tillman Metasediments? Wichita igneous rocks

evidenced by the fact that the Reagan Sandstone (basal formation of the Cambrian) oversteps all pre-existing structure (Fig. 4).

During the second phase subsidence over a broader area than the original rift resulted in a great accumulation of mostly carbonate rocks (Stages 2 and 3, Table I). Given the great thickness of sedimentation it is reasonable to predict, though difficult to prove, the rejuvenation of existing normal faults during the phase.

The final structural phase involved compression and deformation of the sedimentary pile together with the development of the major structural blocks of southern Oklahoma (Fig. 2). This deformation is seen in the widespread folding of limestones in the Arbuckle and Wichita Mountains. Contemporary with this folding was the evolution of the Ouachita fold belt to the east. Late Pennsylvanian and Permian sedimentation infilled the basins which evolved at this time (Stage 5, Table I).

Although tectonic activity had essentially ceased by the end of Pennsylvanian time, minor folding of Permian strata over Pennsylvanian and older structures did take place. Areas in which Permian rocks are slightly folded at the surface include Velma and Cement (Ferguson, 1979).

The Problem of Wrench Faults in the Wichita Mountains

It is clear that the chief structural elements of southwestern Oklahoma are bounded by major west-northwest-trending faults; it is equally clear that movements on those faults have involved enormous vertical displacements (mapped in the subsurface as both normal and reverse faults). However, there is some evidence that lateral movement has also taken place on some of these faults; the evidence is scanty.

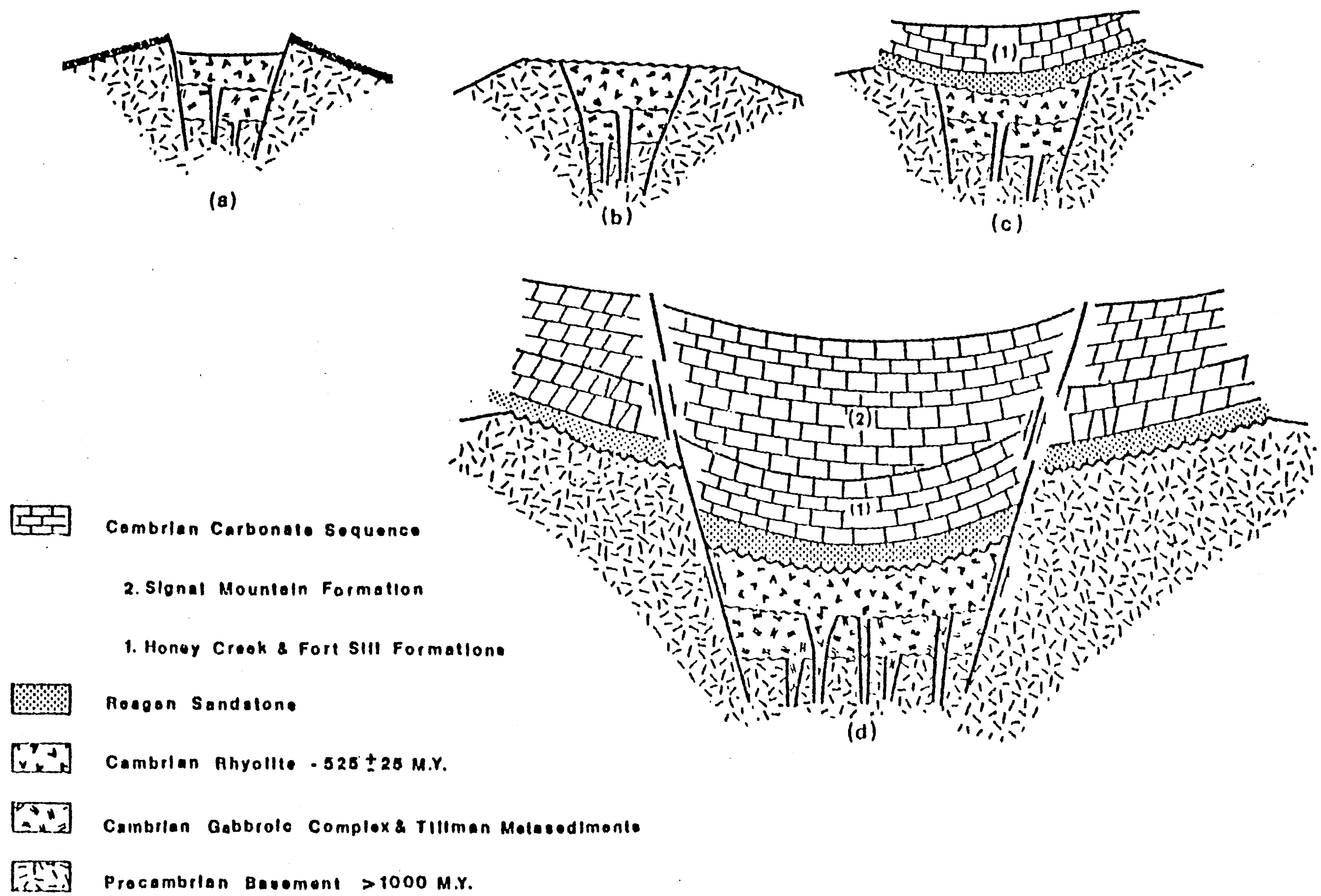


Fig. 4.--Stages in the initiation of faulting in the southern Oklahoma aulacogen (from Carter, 1979).

(a) Rift stage: thermal expansion, doming, magmatic activity, erosion, normal faulting and graben formation.

(b) An intensive erosion and crustal thinning terminates the rift stage (Pre-Reagan Formation).

(c) Subsidence (slow rate) by elastic flexure of the lithosphere. Deposition of the Reagan, Honey Creek, and the Fort Sill Formations.

(d) Differential subsidence along reactivated rift faults (a) at the aulacogen-platform interface. An accelerated subsidence and sediment accumulation in the aulacogen is driven by a gravity anomaly which is related to the Cambrian Gabbroic Complex. Dolomitization of the carbonate rocks occurs in the vicinity of the active faults.

Fig. 4.--(Continued).

In the first place, Ham (1950) indicated a left-lateral strike-slip component of about three miles along some faults in the Arbuckle Mountains. His evidence was the offset of more or less vertical fold axes. Secondly, Tanner (1967) has suggested a 40 mi. left-lateral offset along faults in the Washita Valley Fault System in the Arbuckle Mountains. His evidence is the displacement of a sand-shale facies change in the Oil Creek Formation (Ordovician).

Thompson (personal communication) considers that shear movement initiated in late Ordovician times, but that the main movement took place during the Pennsylvanian deformation. It is likely that rejuvenation of the old normal fault system of the aulacogen provided a locus for the shearing. Plate tectonic reconstruction suggests that, as the Ouachita Fold Belt formed during closure of the so-called "Proto-Atlantic Ocean," the "Ozark region" (all of Oklahoma northeast of the Wichita-Arbuckle region) moved to the northwest relative to the Texas (Llano) region creating a left-lateral shear couple in the weakened crust region.

CHAPTER V

STRUCTURES MAPPED IN THE SADDLE MOUNTAIN AREA

Presentation

Results of mapping in the Saddle Mountain area are presented in Plates 1, 2 and 3. Major features are discussed and illustrated here. The maps differ considerably from that published by the Oklahoma Geological Survey (Map HA-6, Hydrologic Atlas 6, 1977).

Major Structural Features

As noted the area is located in the Frontal Wichita Fault Stystem which separates the Amarillo-Wichita Uplift and the Anadarko Basin (Fig. 2). Specifically the area comprises folded Ordovician limestones located in a complex graben (the Lawtonka graben of Harlton, 1951) between the Blue Creek Canyon and Meers Faults (Fig. 3).

Blue Creek Canyon Fault

This is the principal structure mapped and is a major member of the Frontal Wichita Fault System. Both the apparent throw and trend of the fault are variable; to the east of the Saddle Mountain area the fault trends N60°W and has a downthrow to the south. In the area mapped the downthrow is in the same sense but the fault trend deviates sharply to N5°W. To the north and west of Saddle Mountain the fault deviates again to N45°W and has a downthrow to the north. In the latter area the displacement on the fault is 4,000 ft. (Harlton, 1951), whereas in the area mapped the maximum apparent downthrow is 2,000 ft. in the opposite sense.

For the most part the fault is covered by Permian rocks; the only exposure is in the area mapped where the net effect of the structure is to juxtapose the Carlton Rhyolite in the east against various formations in the upper part of the Arbuckle Group (Fig. 5).

In detail the fault is a braided complex of several major planes of movement (Plate 3, Fig. 6). Within the fault zone are wedges of limestone of uncertain correlation. On lithological grounds these wedges seem to be representative of the Lower Arbuckle Group; they dip at steep angles away from and strike subparallel to the fault complex. Between individual fault planes rocks are greatly sheared and broken (Fig. 7); most slickensides indicate vertical movement. Field observation of hade suggests that the fault is a high-angle reverse fault; this interpretation differs from that of Harlton (1951, 1963) who considers the structure to be a normal fault.

Other Faults

There is only one major fault in the area in addition to the Blue Creek Canyon Fault (Plates 1-3). This fault has a general trend of N45^{o}W and separates a substantial exposure of the Lower Ordovician McKenzie Hill Formation from younger beds to the northeast. Field evidence indicates that the fault is a high-angle reverse fault; because of folding in the limestones the throw of the fault is variable but of the order of 1,000 ft.

Other faults in the area are of minor throw. Some are perpendicular

Fig. 5.--View northwards in Blue Creek Canyon. On the right (east) of the fault is orange-brown-weathering Carlton Rhyolite. Arbuckle limestones of uncertain correlation dip steeply to the west on the downthrown block.

Fig. 6.--View northwards of Blue Creek Canyon Fault Complex. U. S. Highway 58 is in extreme top right of picture. A major fault branch is located in the tree-covered gully at the base of the photograph. The fault trace can be traced northwards and westwards towards the quarry depicted in Fig. 7 (top right of picture). This branch separates limestones of the Cool Creek Formation on the west (left) from limestones of uncertain correlation to the east. The fault truncates the eastern limb of a northwestward-plunging syncline in the Cool Creek Formation.

Fig. 7.--Deformation associated with the Blue Creek Canyon Fault. This small quarry, located near the northern end of the exposed fault trace is the only substantial exposure of the fault zone in a vertical dimension.

to major fold axes and presumably formed as tension, i.e., normal, structures parallel to the principal stress responsible for folding. Other faults are located in fold hinge areas (Fig. 8) and probably formed as a result of local disharmony in fold geometry.

Folds

To the west of the Blue Creek Canyon Fault, within the Lawtonka graben, rocks of the Arbuckle Group are comprehensively folded. In the following account, Figs. 8 to 16 illustrate various features of this folding, Figs. 17 and 18 are stereographic illustrations of fold attitude while Figs. 19 and 20 are stereographic interpretations of areas east (Brookby, 1969) and west (Barthleman, 1968) of the study area.

Two orders of fold are present; first order folds have amplitudes of 600 to 3,000 ft., second order folds have amplitudes of 5 to 30 ft.

First Order Folds

First order folds (Figs. 6 and 9 to 14) trend N30°W adjacent to the Blue Creek Canyon Fault (Fig. 7), but over most of the area have a more westerly trend, averaging N50°W (Fig. 18). There is a tendency for folds to plunge to the northwest; the angle of plunge is steeper adjacent to the ault. Both folding and faulting are clearly of pre-Permian age (Fig. 9).

The folds may be symmetrical or asymmetrical s.s. (Fig. 10) with limb dips of 10 to 45° over most of the area. In the neighborhood of the Blue Creek Canyon Fault folds are consistently asymmetric with the steeper (and more disturbed) limb to the northeast. In this area dips of up to 80° occur.

Fig. 8.--Anticline in the Cool Creek Formation showing a minor thrust plane developed in the fold hinge. The quarter rests on the fault plane which has a displacement of a few inches. Minor faults of this type are common in the hinge zones of tight folds in the area.

Fig. 9.--First order syncline, plunging northeastward, in the Cool Creek Formation. The structure is unconformably overlain by Post Oak Conglomerates which form the featureless terrain to the north (right). The Blue Creek Canyon Fault runs through the valley in the immediate foreground.

Fig. 10.--First order anticline in the Cool Creek Formation. This anticline is a major structure which can be traced northwestwards for several miles from the vicinity of the Blue Creek Canyon Fault. The structure plunges to the northwest and is a parallel fold with an asymmetric form. The steeper limb is to the northeast (towards the Blue Creek Canyon Fault).

Fold types include parallel and similar folds, the latter form usually being associated with tighter, i.e., closed folds. In general the larger folds tend to be parallel. Measurements of bed thickness variation in similar folds indicate thickness change ratios in individual beds of from 2:1 to 4:1 (Fig. 11). As a consequence of parallel form many folds are noticeably disharmonic (Figs. 12 to 14).

In areas where folds plunge steeply it is clear that an en echelon fold pattern is present (Figs. 13 and 14). In essence, individual folds gradually flatten and the fold movement is taken up a few hundred feet away in an oblique direction, i.e., upward (or downward) and sideways. In the "slack area" between such en echelon folds structural terraces are developed (Fig. 14). Minor folds in these areas are oriented in directions oblique to the principal fold trend.

Second Order Folds

Minor second order folds are more variable in orientation than major folds. They are developed in two principal positions related to major first order fold geometry; firstly in hinge folds and secondly where "slack areas" exist between en echelon folds (Fig. 15). Their formation is controlled by this geometry and the competence of individual limestone beds.

Pressure Solution Cleavage

In areas close to the Blue Creek Canyon Fault, where folds are closed with steep limbs, fold axes show a well developed pressure solution cleavage (Fig. 16). This type of cleavage involves recrystallization of calcite in response to compression in well-defined (cleavage)

Fig. 11.--Plunging symmetrical syncline showing similar fold style. In the structure the ratio between limb and hinge thickness in individual beds varies between 1:2 and 1:2.4.

Fig. 12.--General view to the southeast of the western part of the area studied. Most of the area comprises beds of the Cool Creek Formation; the Kindblade Formation comprises the lighter-colored, more massive strata to the south (right). Fold style is mostly parallel and clearly disharmonic as a consequence.

Fig. 13.--View to north of northwestward plunging anticline 2,000 ft. west of Blue Creek Canyon Fault. The fold has a similar form and as a result becomes increasingly disharmonic upwards. The fold axis divides; one branch passes through a zone of minor hinge faulting, the other (western) axis develops from a kink (best seen in the trees at the extreme edge of the photograph) on the western limb of the fold. The two axes are separated by a structural terrace.

Fig. 14.--View to east of fold illustrated in Fig. 13 showing development of structural terrace between two anticlinal axes derived from lower level single anticline to south (right). The more distant (eastern) anticlinal axis gradually dies northwards whereas the nearer (western) axis becomes a dominant structure (depicted in Fig. 10). Blue Creek Canyon Fault and U. S. Highway 58 to top right of picture.

Fig. 15.--Second order folds on northeastern limb of first order fold seen in Fig. 10. The folds are developed in a zone where there is rather abrupt change of dip on the major fold limb.

Fig. 16.--Pressure solution cleavage in hinge of plunging anticline 300 ft. west of Blue Creek Canyon Fault.

planes perpendicular to principal stress. Calcite crystals are oriented with C axes parallel to this cleavage.

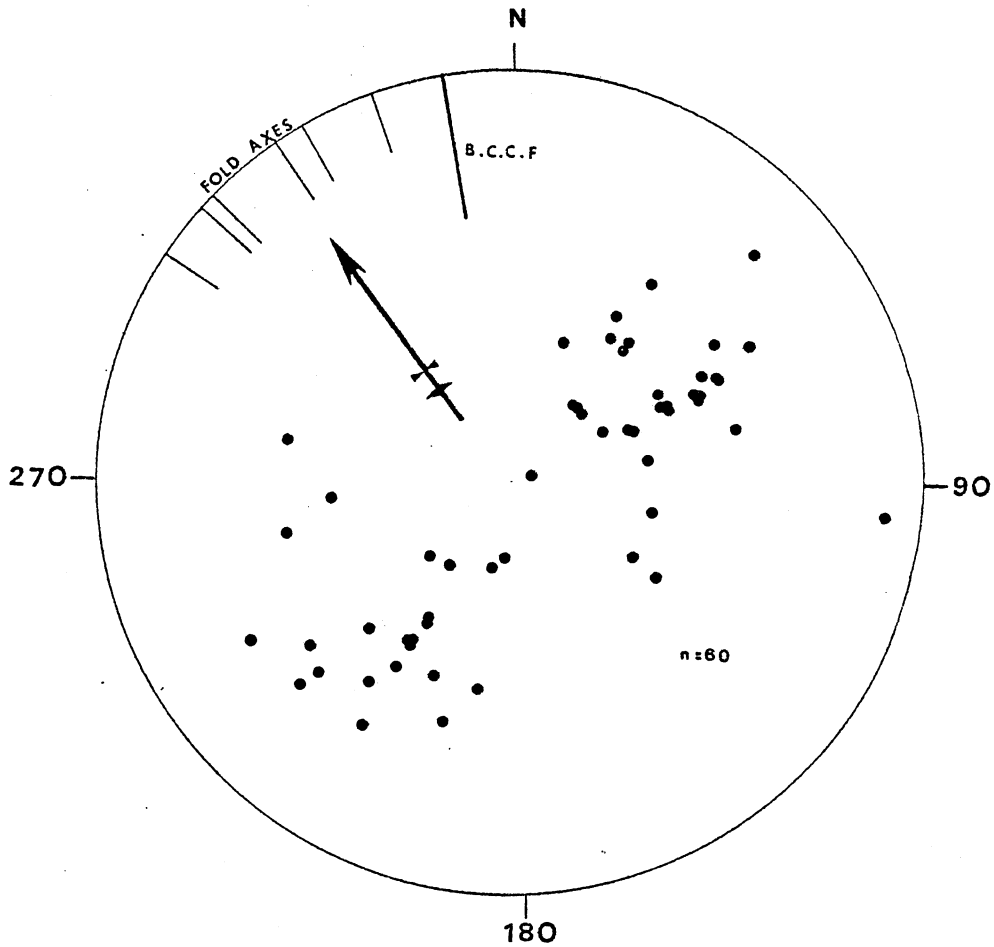


Fig. 17.--Stereogram showing bedding attitudes in the area adjacent to the Blue Creek Canyon Fault. The data plotted as poles to bedding, indicates folds oriented about northwest and consistently plunging in that direction. The local trend of the Blue Creek Canyon Fault and the trends of first order folds are also plotted.

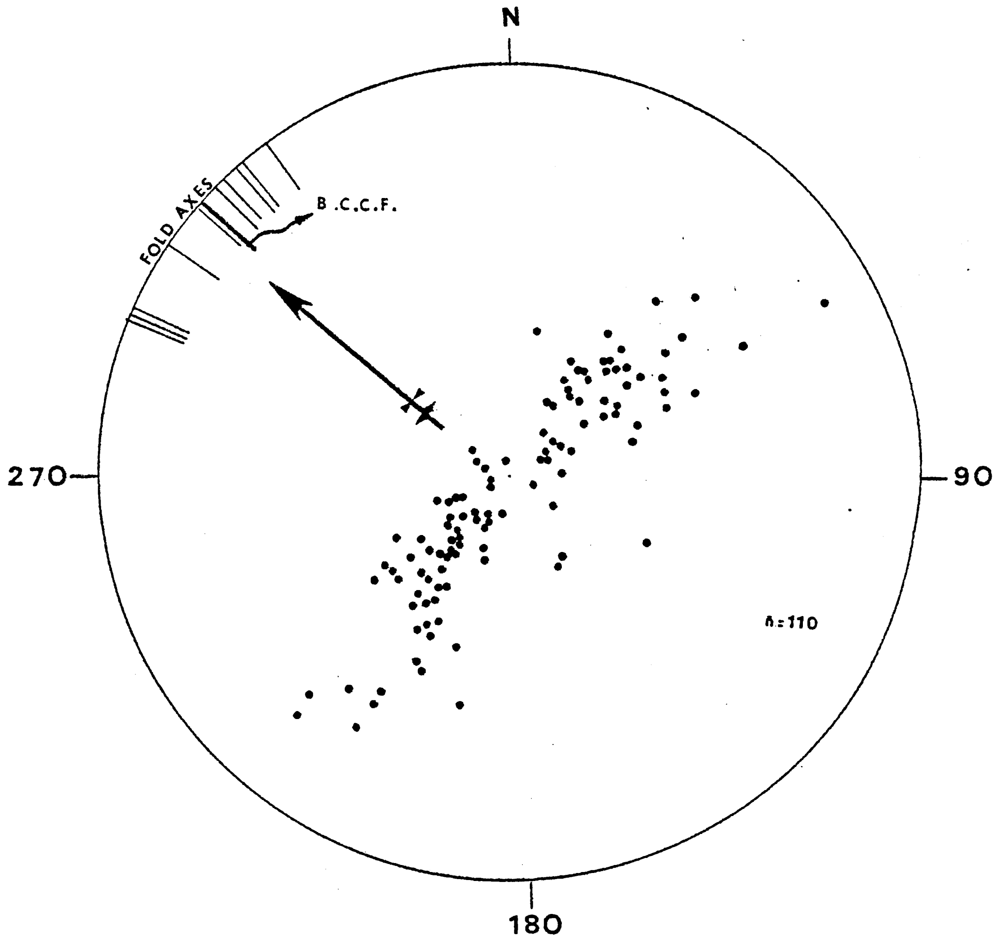


Fig. 18.--Stereogram showing bedding attitudes in the western part of the area. Bedding poles indicate folding about northwest axes and some plunge in that direction. The local trend of the Blue Creek Canyon Fault and the trends of the first order folds are also given. When compared with data in Fig. 17, the dip of fold limbs is more gentle and the plunge less emphatic.

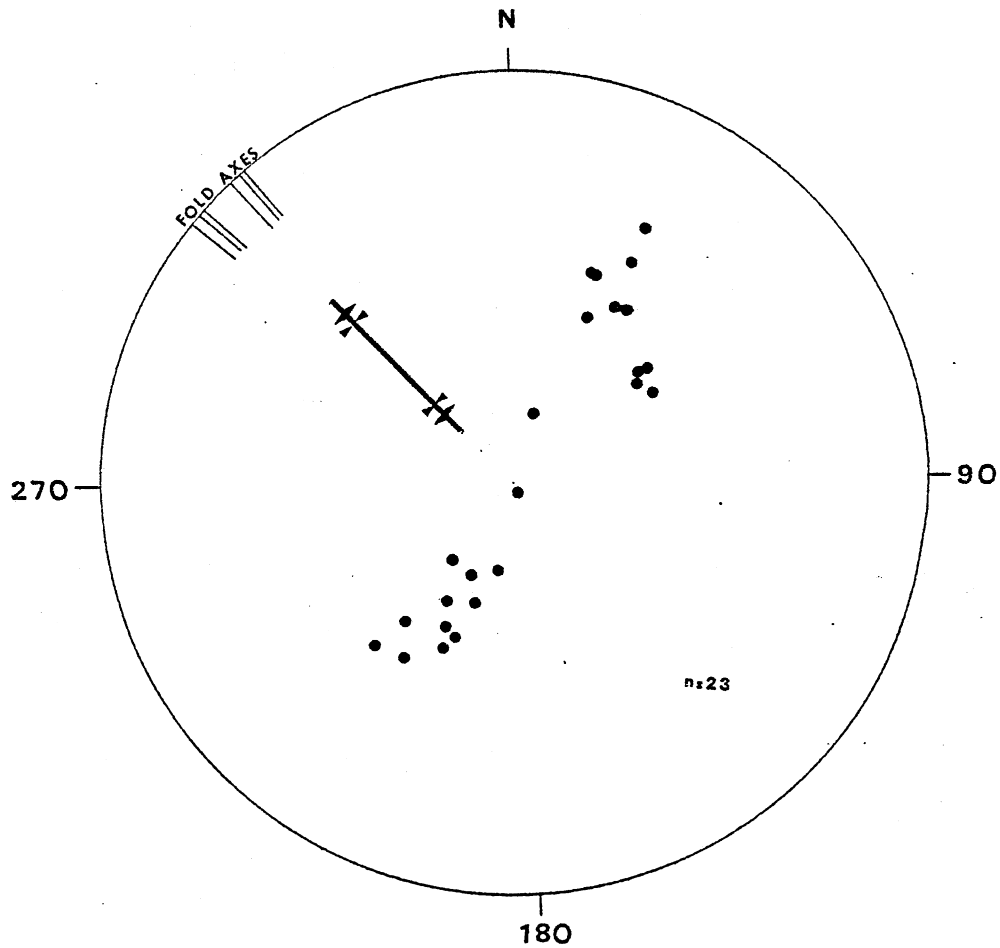


Fig. 19.--Data abstracted from Barthelman (1969) from the area of Saddle Mountain west of the area mapped indicates a general similarity with data in Fig. 18; no consistent direction of plunge is apparent.

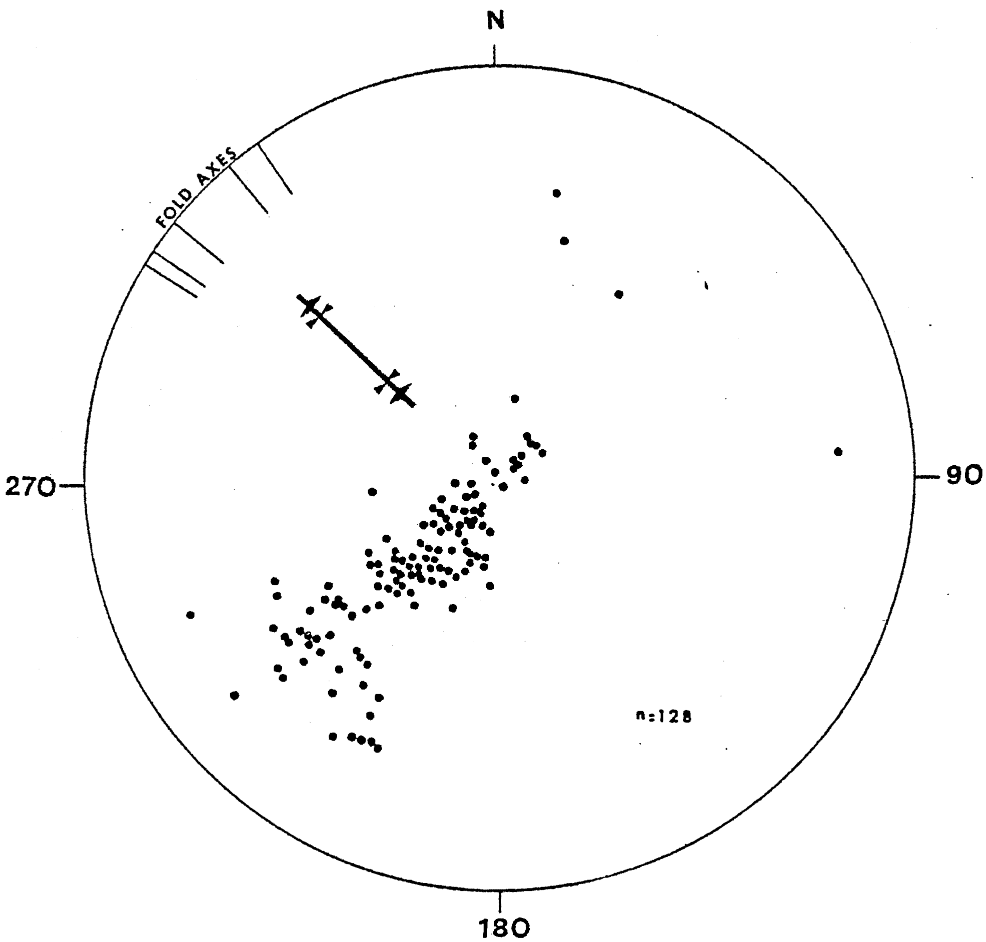


Fig. 20.--Data from Brookby (1969) from the area east of that mapped (and outside the Lawtonka "graben") illustrates that the same fold trend occurs as that in Fig. 18 and 19. The data is weighted as most of the fold exposures are northeasterly-dipping fold limbs.

CHAPTER VI

AN INTERPRETATION OF THE STRUCTURE OF THE AREA

Review of Principal Structural Features

The area studied is located in the eastern part of the Lawtonka graben, a complex structure bounded by the Meers and Blue Creek Canyon Faults (Figs. 3 and 23). The graben has a wedge shape in the area studied due to a divergence in trend between the bounding faults of about 15° (Fig. 21). Paleozoic limestones in the graben are comprehensively folded.

All major folds and faults trend between N5°W and N90°W; over most of the area the majority of folds trend N50°W (Figs. 18 and 21). This direction is parallel to that of the Blue Creek Canyon Fault in the west of the area mapped but is about 15° north of the trend of the Meers Fault.

In the east of the area studied the Blue Creek Canyon Fault complex has an overall trend of N5°W. Folds adjacent to the fault also show a more northerly attitude of approximately N30°W (Figs. 17, 21, and 23).

The attitude of folds in the west of the area mapped is continued both into the west of Saddle Mountain (Barthelman, 1969; Figs. 19 and 21) and in the Blue Creek Canyon horst to the east (Brookby, 1969; Figs. 20 and 21). The latter trend is important in demonstrating that the stress responsible for fold generation was effective outside the graben.

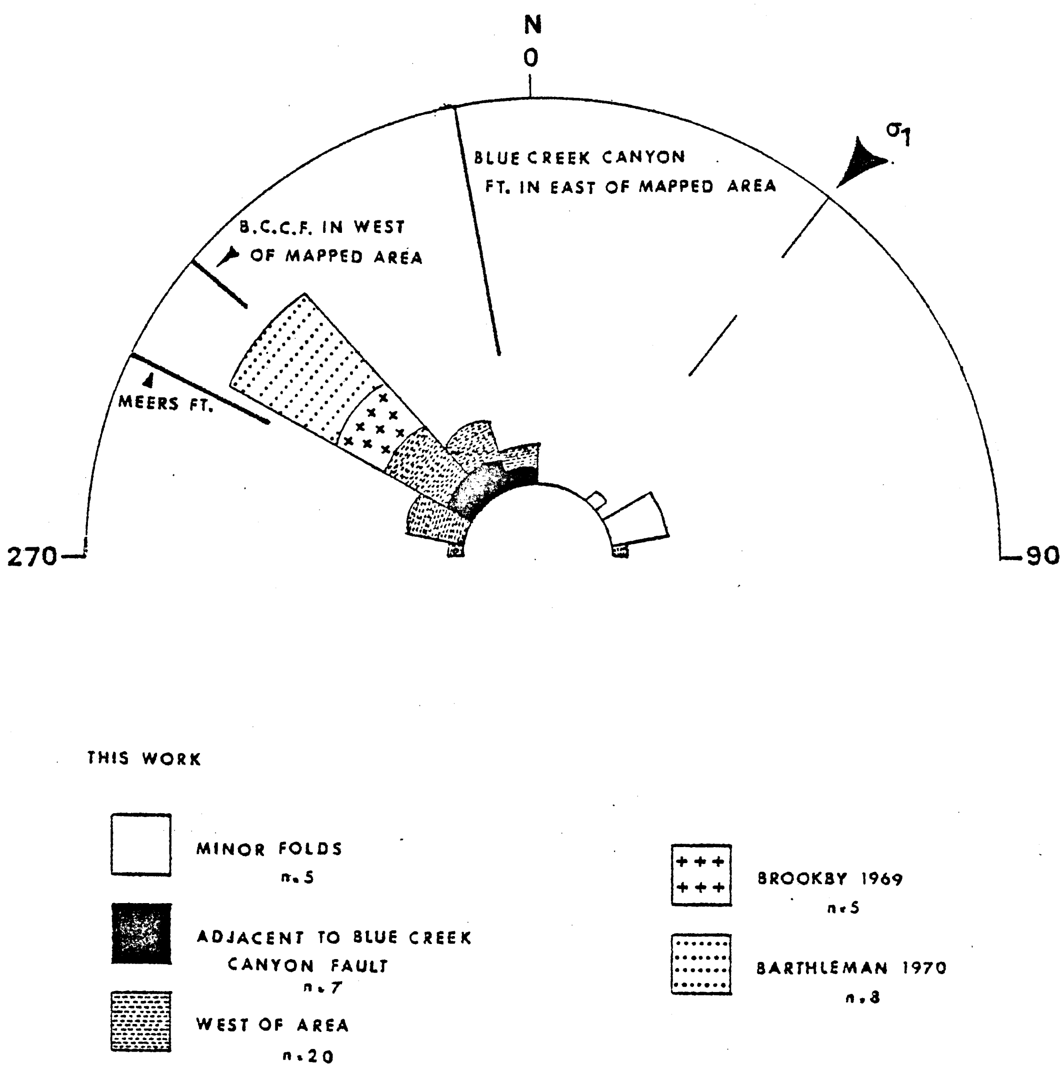


Fig. 21.--Synopsis of attitudes of major structural features in area mapped. Theoretical maximum stress is plotted at 90° to fold axes maxima.

The Anomalous Trend of the Blue Creek Canyon Fault

Sudden deflections in fault trend are usually of interest as they indicate reorientation of stress. In the Blue Creek Canyon Fault area the following departures from regional attitude are noted:

a. The fault trend changes from N50°W to N5°W.

b. Axes of first order folds trend N30°W as opposed to N50°W in the west of the area.

c. Fold limbs steepen towards the fault.

d. Fold plunge to the northwest is consistent close to the fault.

e. Pressure solution cleavage is more intense close to the fault.

In addition, fold limbs are truncated by the fault (Fig. 6), and field observation suggests that the fault is a high-angle reverse structure.

Fold Generation and Stress Orientation

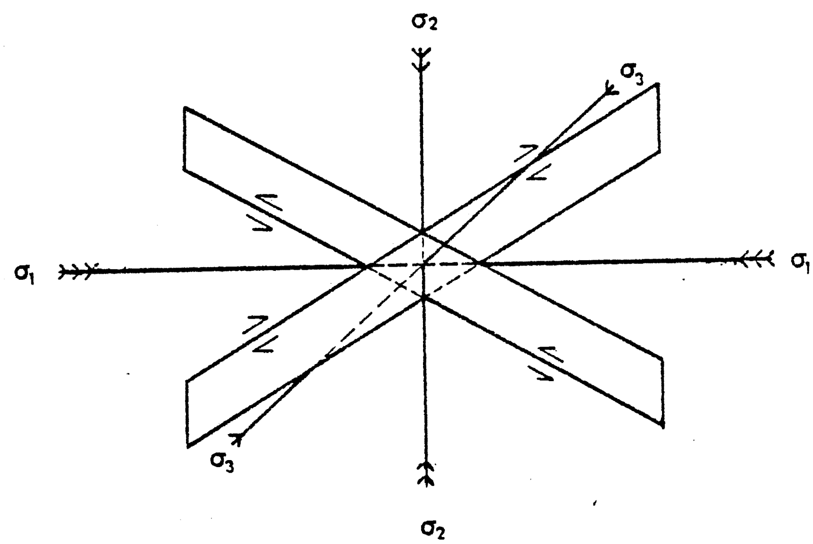
The most simple interpretation of the stress responsible for folding in the graben is that principal stress was oriented N40°E, perpendicular to the average fold axis trend. This stress is also perpendicular to the Blue Creek Canyon Fault trend in the west of the area and to other faults within the Lawtonka graben (as mapped in the study area and by Barthelman, 1969). Application of this stress could, therefore, be held to be responsible for both folding and reverse faulting in the area. In general terms, this stress could have been generated during closure of the southern Oklahoma aulacogen during Pennsylvanian times. Presumably, many of the faults are rejuvenated structures (many with reversed throw) which were initiated during early rifting.

However, as has been noted, the Lawtonka graben is wedge-shaped and both fold axes and the Blue Creek Canyon fault diverge by 15 to 20° from the Meers Fault to the south. The latter is a more substantial structure than the Blue Creek Canyon Fault and has a trend (N70°W) which is more characteristic of major faults elsewhere in southern Oklahoma. Thus it is probable that a N40°E principal stress is of local significance only. If the Meers Fault is considered as a high-angle reverse fault involving simple vertical displacement then a regional principal stress oriented N20°E is indicated.

An alternative model is one which involves left-lateral wrench movement on principal faults in the region (Walper, 1970; Prautt, 1975). If theoretical resolutions of stress are applied (Fig. 22) then the principal stress was oriented at about N80°E. Studies of major wrench fault zones (Wilcox et al., 1972) indicate that a common element of the basic wrench pattern is en echelon folds inclined at a low angle to the wrench zone. Thus if a large left-lateral movement on the Meers Fault is postulated, this could have resulted in the fold pattern within the Lawtonka graben.

It is now pertinent to discuss the anomalies in structural trend associated with the Blue Creek Canyon Fault (see above). The simplest interpretation of these anomalies is that in this area the fault is a high-angle reverse structure involving movement of the Blue Creek Canyon horst over the Lawtonka graben. This movement postdates folding in the graben and as a result folds adjacent to the fault have been distorted. In particular, fold limbs are truncated and steepen towards the fault and fold hinges show pressure solution cleavages. Also, a consistent northwestward plunge is a consequence of reorienting fold axis trend

(A)



(B)

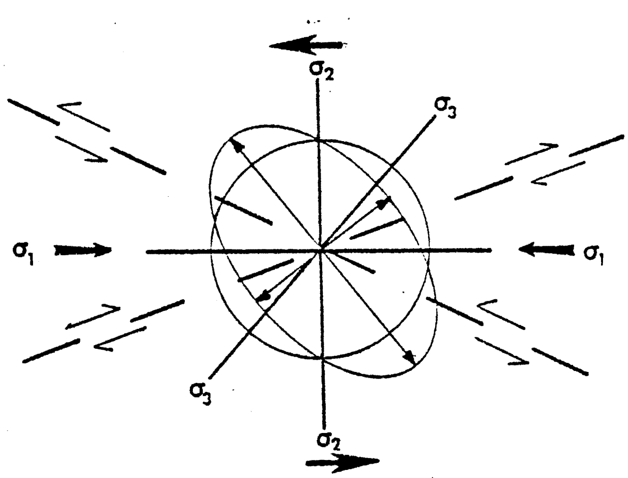


Fig. 22.--Compressional stress. (A) After Anderson (1972). (B) After Wilcox et al. (1972).

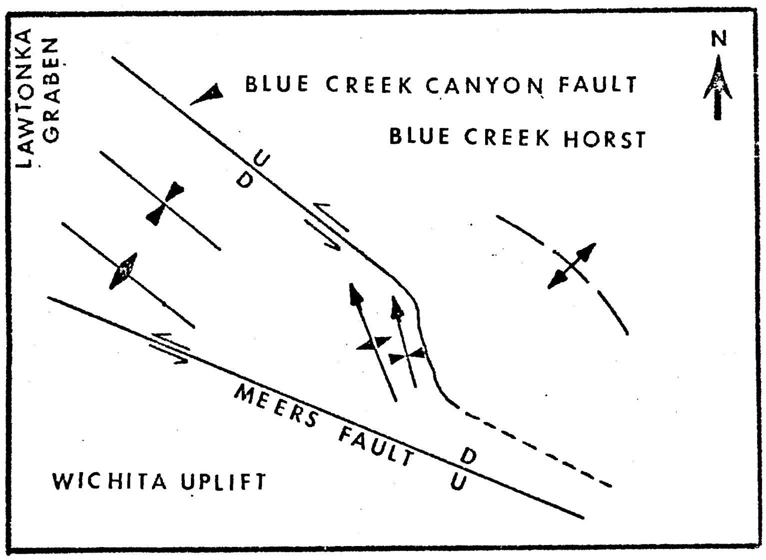


Fig. 23.--Principal structural features of the area. Scale 1:250,000.

from N50^{O}W to N30^{O}W. The principal stress required for this movement is a vector from approximately N80^{O}E. This stress would have induced left lateral wrench movement on both the Meers Fault and the Blue Creek Canyon Fault in the west of the area mapped.

Conclusion

Stress Orientation Models

The structure in the area studied can be interpreted in two ways. In the first model a principal stress oriented N40^{O}E could have initiated folds and high-angle reverse movements on structures oriented approximately N50^{O}W. Subsequently, a vector from N80^{O}E could have induced left-lateral wrench movement on faults trending N50^{O}W and high-angle reverse faulting on the Blue Creek Canyon Fault where it trends N5^{O}W. The second model invokes an initial N80^{O}E principal stress generating left-lateral wrench movement and en echelon folding oriented N50^{O}W, followed by a second deformation stressed similarly.

The first model is preferred as it accounts for the very great vertical displacements which have taken place on the major faults in the area. This model accords well with plate tectonic interpretation The first stress would have resulted from aulacogen closure and resulting compression of the supracrustal fill (in the Lawtonka graben this compression is approximately 80 percent at the present level of erosion). The second (N80^{O}E) stress would have resulted from closure of the "Ouachita Ocean" and overthrusting from the east of the Ouachita Fold Belt. This analysis of principal stress is simplistic in that it ignores the fact that rejuvenation of existing structures has taken place. Such rejuvenation could account for local discrepancies in structural attitudes.

Limitations of the Thesis

The thesis offers an interpretation of the structural features of a very small area in the southern Oklahoma aulacogen. Although the interpretation is in accord with plate tectonic theory there is an obvious risk that the data may have been overstretched. Furthermore, no subsurface data is available for the area; fault and fold behavior at depth is unknown.

Suggestions for Further Work

The value of this study is that it analyzes geological details and indicates that they can be related to regional interpretation. The study could be extended in area and an attempt made to integrate it with subsurface data. Detailed studies of joint pattern and cleavage/bedding relationships may define deformation phases more clearly.

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APPENDIXES

STRUCTURAL ATTITUDES

Fold Axes

A. Adjacent to Blue Creek Canyon Fault

1. $N20^{o}W$
2. $N9^{o}E$
3. $N57^{o}W$
4. $N35^{o}W$
5. $N31^{o}W$
6. $N49^{o}W$
7. $N47^{o}W$

B. West of Mapped Area

1. $N41^{o}W$
2. $N12^{o}W$
3. $N9^{o}W$
4. $N44^{o}W$
5. $N43^{o}W$
6. $N66^{o}W$
7. $N67^{o}W$
8. $N40^{o}W$
9. $N55^{o}W$
10. $N65^{o}W$
11. $N34^{o}W$
12. $N48^{o}W$
13. $N39^{o}W$
14. $N39^{o}W$
15. $N36^{o}W$
16. $N34^{o}W$
17. $N48^{o}W$
18. $N35^{o}W$
19. $N70^{o}E$
20. $N80^{o}E$

C. Kindblade Ranch - Richard Spur Area (Brookby, 1968)

1. $N40^{o}W$
2. $N56^{o}W$
3. $N35^{o}W$
4. $N58^{o}W$
5. $N51^{o}W$

D. Unap Mountain - Saddle Mountain (Barthleman, 1969)

1. N49°W
2. N43°W
3. N40°W
4. N42°W
5. N48°W
6. N51°W
7. N49°W
8. N23°W

Bedding Plane Attitudes

A. Adjacent to Blue Creek Canyon Fault

	Strike	Dip
1.	N60°W	38°NE
2.	N60°W	43°NE
3.	N52°W	20°SW
4.	N15°W	55°W
5.	N60°W	31°NE
6.	N70°W	41°NE
7.	N60°W	37°NE
8.	N10°W	28°SW
9.	N32°E	35°NW
10.	N30°W	65°NE
11.	N32°W	62°NE
12.	N10°E	45°SW
13.	N56°W	49°NE
14.	N45°W	55°NE
15.	N5°W	35°NE
16.	N82°W	42°NE
17.	N14°W	47°SW
18.	N40°W	51°NE
19.	N60°W	58°NE
20.	N25°W	41°SW
21.	N30°W	45°SW

	Strike	Dip
22.	N35°W	50°SW
23.	N28°W	47°SW
24.	N55°W	50°NE
25.	N20°W	45°SW
26.	N25°W	42°SW
27.	N25°W	35°SW
28.	N25°W	35°SW
29.	N30°E	29°NW
30.	N75°W	50°NE
31.	N60°W	32°NE
32.	N47°W	40°NE
33.	N80°W	17°NE
34.	N45°W	60°NE
35.	N55°W	35°SW
36.	N45°W	22°NE
37.	N70°W	30°SW
38.	N58°W	40°SW
39.	N27°W	33°SW
40.	N50°W	37°SW
41.	N44°W	70°SW
42.	N30°W	56°SW
43.	N23°W	27°SW
44.	N25°W	25°SW
45.	N60°W	37°NE
46.	N25°W	41°SW
47.	N20°W	47°SW
48.	N22°W	45°SW
49.	N40°E	80°NW

B. West of the Mapped Area

	Strike	Dip
1.	N40°W	34°NE
2.	N5°W	10°SW
3.	N45°W	30°SW

	Strike	Dip
4.	N45°W	30°SW
5.	N35°W	37°SW
6.	N25°W	12°NE
7.	N65°W	10°NE
8.	N40°W	30°NE
9.	N55°W	32°NE
10.	N55°W	30°NE
11.	N55°W	30°NE
12.	N62°W	30°NE
13.	N57°W	7°SW
14.	N62°W	17°SW
15.	N32°W	22°SW
16.	N50°W	25°NE
17.	N10°W	84°NE
18.	N75°E	3°NW
19.	N55°W	10°NE
20.	N55°W	10°NE
21.	N38°W	21°NE
22.	N52°W	15°NE
23.	N25°W	11°NE
24.	N3°E	7°NW
25.	N75°W	17°NE
26.	N62°W	9°NE
27.	N36°W	7°SW
28.	N37°W	30°NE
29.	N50°W	34°SW
30.	N60°W	22°SW
31.	N55°W	20°SW
32.	N52°W	11°SW
33.	N66°W	11°NE
34.	N72°W	15°NE
35.	N50°W	25°NE
36.	N52°W	20°NE
37.	N50°W	15°NE
38.	N52°W	18°NE

	Strike	Dip
39.	N50°W	17°NE
40.	N50°W	20°SW

C. Unap Mountain - Saddle Mountain (Barthleman, 1969)

	Strike	Dip
1.	N71°E	24°NW
2.	N71°E	23°NW
3.	N70°W	33°NE
4.	N83°W	23°NE
5.	N66°W	36°SW
6.	N72°W	25°NE
7.	N80°W	22°NE
8.	N33°W	33°SW
9.	N40°W	35°SW
10.	N42°W	33°SW
11.	N52°W	35°SW
12.	N52°W	20°NE
13.	N62°W	58°SW
14.	N50°W	43°NE
15.	N69°W	35°SW
16.	N69°W	45°SW
17.	N76°W	14°SW
18.	N59°W	29°NE
19.	N64°W	20°NE
20.	N65°W	32°NE
21.	N65°W	32°NE
22.	N66°W	26°NE
23.	N78°W	18°NE
24.	N78°W	16°NE
25.	N82°W	8°NE
26.	N38°W	31°SW

D. Kindblade Ranch - Richard Spur Area (Brookby, 1968)

	Strike	Dip
1.	N30^{o}W	70^{o}NE
2.	N32^{o}W	60^{o}NE
3.	N31^{o}W	52^{o}NE
4.	N22^{o}W	25^{o}NE
5.	N24^{o}W	80^{o}NE
6.	N60^{o}W	50^{o}NE
7.	N40^{o}W	50^{o}NE
8.	N5^{o}W	5^{o}NE
9.	N6^{o}W	8^{o}NE
10.	N-^{o}S	25^{o}NE
11.	N63^{o}W	60^{o}NE
12.	N40^{o}W	40^{o}NE
13.	N65^{o}W	60^{o}NE
14.	N46^{o}W	50^{o}NE
15.	N45^{o}W	40^{o}NE
16.	N35^{o}W	5^{o}NE
17.	N30^{o}W	17^{o}NE
18.	N30^{o}W	12^{o}NE
19.	N33^{o}W	9^{o}NE
20.	N26^{o}W	30^{o}NE
21.	N28^{o}W	30^{o}NE
22.	N31^{o}W	25^{o}NE
23.	N22^{o}W	14^{o}NE
24.	N24^{o}W	12^{o}NE
25.	N70^{o}E	13^{o}NW
26.	N68^{o}E	15^{o}NW
27.	N80^{o}E	15^{o}NW
28.	N65^{o}W	20^{o}NE

VITA

Abdolali Babaei

Candidate for the Degree of

Master of Science

Thesis: THE STRUCTURAL GEOLOGY OF PART OF THE LIMESTONE HILLS IN THE WICHITA MOUNTAINS, CADDO AND COMANCHE COUNTIES, OKLAHOMA

Major Field: Geology

Biographical:

Personal Data: Born in Khorramshahr, Iran, May 17, 1950, the son of Kazem and Khadijeh Babaei.

Education: Graduated from Hashtroodi High School, Khorramshahr, Iran, June, 1968; received Bachelor of Science degree in Geology from Pahlavi University, August, 1975; completed requirements for Master of Science degree in Geology, May, 1980.

Professional Experience: Scholarship for academic excellence, Pahlavi Foundation, Pahlavi University, Shiraz, Iran, 1971-1973; Natural Science teacher, Educational Ministry, Pahlavi University, Shiraz, Iran, 1972-1975; summer trainee, National Iranian Oil Companies, Tehran, Iran, 1974; geologist and geophysicist, D'Appolonia International Incorporation, Tehran, Iran, 1975-1977; teaching assistant, Oklahoma State University, Stillwater, Oklahoma, 1979.