OKLAHOMA GEOLOGY Notes

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On The Cover —

Acrocanthosaurus atokensis

A new OGS series of poster calendars premiers with "Oklahoma Dinosaur Days," featuring this painting of *Acrocanthosaurus.*

A resident of the southeastern Oklahoma area between 110 million and 100 million years ago, this meat-eating dinosaur was first described from two specimens found in 1940 in Oklahoma's Atoka County. Standing ~18 ft tall and measuring as much as 43 ft in length from head to tail, *Acrocanthosaurus* must have been a truly terrifying sight to the dinosaurs it preyed upon. It probably ate herbivores such as *Tenontosaurus,* using its powerful jaws to capture and dismember them.

The ridge along the dinosaur's backbone, visible in this portrait, is formed by bony spines extending upward from the vertebrae. The name *Acrocanthosaurus,* which means "high-spined lizard," comes from these extensions, whose function is uncertain.

Acrocanthosaurus lived during the Early Cretaceous Epoch, when the Gulf of Mexico extended much farther north. Southeastern Oklahoma was a coastal- and river-plains area with a subtropical climate, where areas of swampy brush mingled with dense forests of conifers, ferns, and palmlike trees called cycads. Dinosaurs ruled the land, but small, fur-covered insect-eaters—primitive mammals—had begun to emerge.

For more details on this Oklahoma Geocalendar 1996, see p. 189, this issue.

Tracy Peeters

Artist: *Karen Carr,* courtesy Fort Worth Museum of Science and History

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Cambrian Diabase and Gabbro in the Blue Creek Canyon Area, Wichita Mountains, Southwestern Oklahoma

Pamela J. DeGroat,[1] *R. Nowell Donovan,*[2] *Richard E. Hanson,*[2] *and Barry L. Weaver*[3]

Abstract

Several small mafic intrusions cut the Carlton Rhyolite in the Blue Creek Canyon area in the Slick Hills, north of the main mass of the Wichita Mountains in southwestern Oklahoma. The intrusions range in texture from basalt through diabase to medium-grained, ophitic gabbro. The gabbro forms a relatively large intrusion, >400 m across at the level of erosion, termed here the "Kimbell Gabbro." Primary igneous phases include plagioclase, olivine (now completely replaced by bowlingite), augite, and magnetite. Many of the major and trace elements have been affected by secondary alteration, but the more immobile elements show primary igneous trends on variation diagrams. Standard discrimination diagrams using the immobile trace elements show that the intrusions have affinities to other within-plate continental basalts. Clinopyroxene compositions and trace-element data indicate that the suite is transitional between tholeiitic and alkalic magma types. Contents of immobile trace elements are similar to those for previously analyzed late diabase dikes from other parts of the Wichita igneous province. The late diabases and Kimbell Gabbro appear to be geochemically indistinguishable from the Roosevelt Gabbros, which intrude the Glen Mountains Layered Complex in the main part of the Wichita Mountains and are generally believed to predate extrusion of the Carlton Rhyolite. Although the Roosevelt Gabbros are petrographically unlike the Kimbell Gabbro, the geochemical similarities raise the possibility that some of the Roosevelt Gabbros may relate to the late diabase suite rather than to a prerhyolite episode of mafic magmatism. Alternatively, both suites may have been emplaced during a single long-lasting period of mafic magmatism that overlapped the silicic episode.

Introduction

Late Precambrian to Cambrian igneous rocks in the Wichita Mountains of southwestern Oklahoma (Fig. 1) represent extension-related magmatism associated with initial stages in the development of the southern Oklahoma aulacogen (Gilbert, 1983; McConnell and Gilbert, 1990). The oldest igneous unit exposed in the Wichita Mountains is the Glen Mountains Layered Complex, a large, rhythmically layered body consisting predominantly of anorthositic gabbro, anorthosite, and troctolite. The complex is cut by a major unconformity representing an important episode of erosion. Silicic volcanic rocks of the Carlton Rhyolite Group are believed to have originally covered this unconformity, and sills of the related Wichita Granite Group were intruded along the contact between the eroded layered complex and the overlying rhyolites (Ham and others, 1964; Gilbert, 1982).

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The Roosevelt Gabbros form a suite of smaller, petrographically distinct intrusions that cut the Glen Mountains Layered Complex. They comprise four separate intrusions, the Glen Creek, Sandy Creek, Mount Sheridan, and Mount Baker Gabbros, together with numerous smaller dikes and pods (Powell and others, 1980; Powell, 1982,1986). The generally held view is that, although these gabbros are not

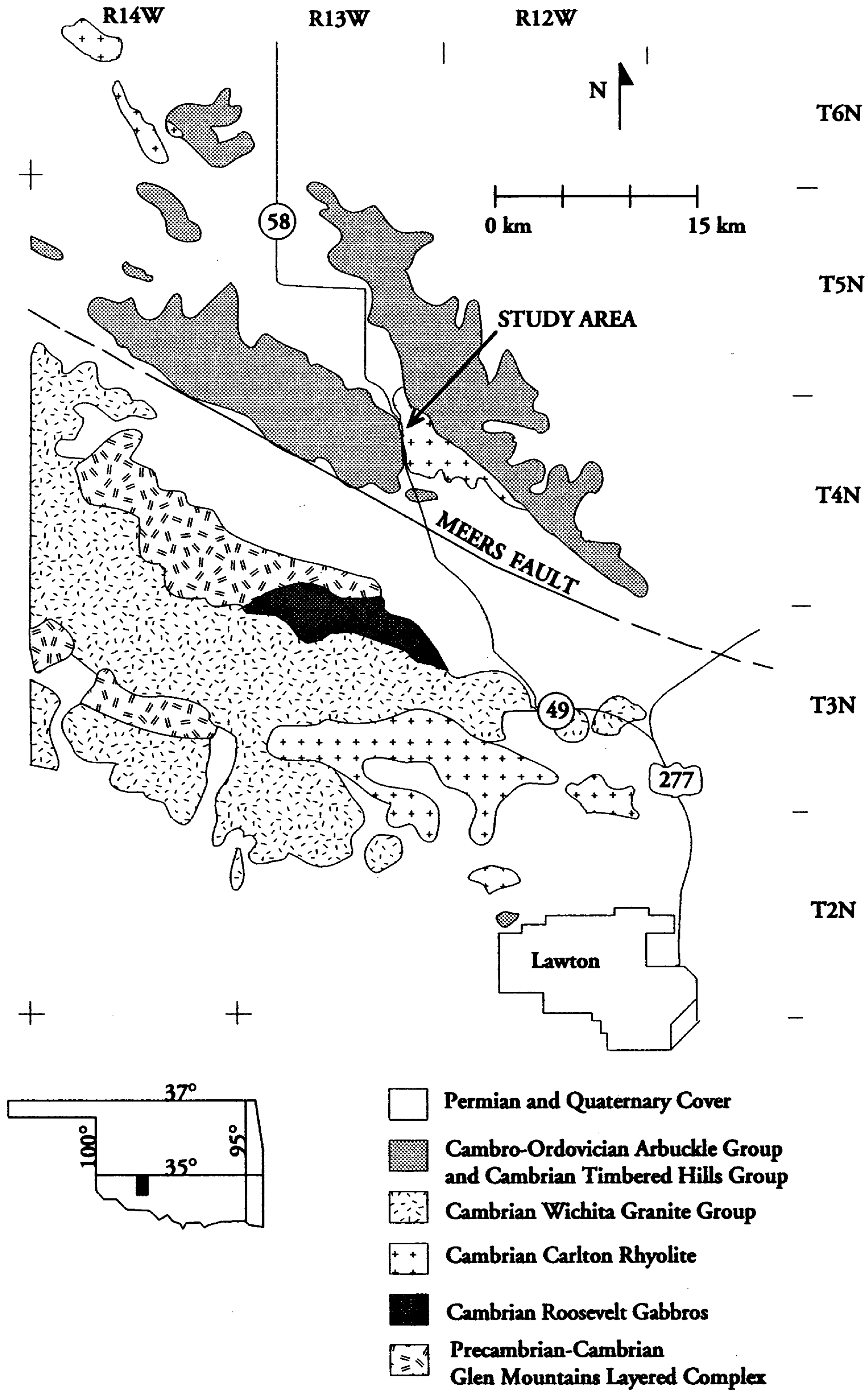

Figure 1. Geologic map of the Wichita Mountains, showing location of the study area in the Slick Hills. Modified from Powell and others (1980).

petrogenetically directly related to the layered complex, they were emplaced prior to development of the unconformity overlain by the Carlton Rhyolite and hence predate silicic magmatism in the Wichita province. Field evidence for this viewpoint has been noted specifically for the Sandy Creek Gabbro by Powell and others (1982). A younger phase of mafic magmatism affected the Wichita province following the voluminous silicic magmatism and is represented by a suite of basalt to diabase dikes termed "late diabase" (Gilbert, 1982; Gilbert and Hughes, 1986). These small intrusions cut all other igneous units of the province, including the Carlton Rhyolite (Powell and others, 1980; Gilbert, 1982).

In this paper, we discuss the petrology and geochemistry of several of these late mafic intrusions in the Blue Creek Canyon area of the Slick Hills (Fig. 2), to the north of the main mass of the Wichita Mountains. Of particular note is the discovery of a small but mappable body of gabbro in the area, which we term here the Kimbell Gabbro, named for the Kimbell ranch, where it crops out.

Kimbell Gabbro and Associated Mafic Intrusions in the Blue Creek Canyon Area

The mafic rocks of concern here intrude an extensive exposure of Carlton Rhyolite brought in contact with lower Paleozoic sedimentary rocks to the west by the Blue Creek Canyon fault (Fig. 2; Donovan, 1982). Locations of some of the mafic rocks cutting the rhyolite in this area were given by Donovan and others (1986); these and the locations of newly discovered occurrences, including the Kimbell Gabbro, are shown in Figure 2. Data presented in this paper come from 11 different samples collected from four mapped intrusions; sample localities are given in Figures 2 and 3. In the descriptions that follow, we use the term "gabbro" to refer to relatively coarse-grained mafic intrusive rocks. The term "basalt" refers to a mafic rock with an aphanitic groundmass, whether intrusive or extrusive. "Diabase" is a fine-grained, phaneritic, mafic rock texturally transitional between basalt and gabbro.

Kimbell Gabbro

At the present level of exposure, the Kimbell Gabbro forms an elongate, somewhat elliptical, discordant intrusive body in the northern part of the rhyolite outcrop (Figs. 2 and 3). Contacts with the host rhyolite generally are covered, but dense vegetation clearly delimits the extent of the gabbro; the surrounding rhyolite is fairly sparsely vegetated. The gabbro intruded to a high stratigraphic level in the Carlton Rhyolite, because the overlying unconformity between the rhyolite and the Upper Cambrian Timbered Hills Group is apparently only about 30 m above the contact between the gabbro and rhyolite. The outcrop of the gabbro is controlled by the incision of a small, intermittent stream that is cutting down from the rhyolite surface. As a result, the relationship of the mapped outcrop to the true form of the intrusion is not known.

In situ outcrops of the gabbro are rare, but, on the basis of the distribution of locally derived float, the intrusion appears to consist mainly of a medium-grained, ophitic phase displaying large clinopyroxene oikocrysts (samples 2P and 1C). Medium-grained gabbro also crops out along a low ridge to the east (sample EG). Gabbro with a somewhat finer grain size (sample FC) forms an *in situ* outcrop near the northern margin of the body, and this gabbro is intruded by a diabase sheet

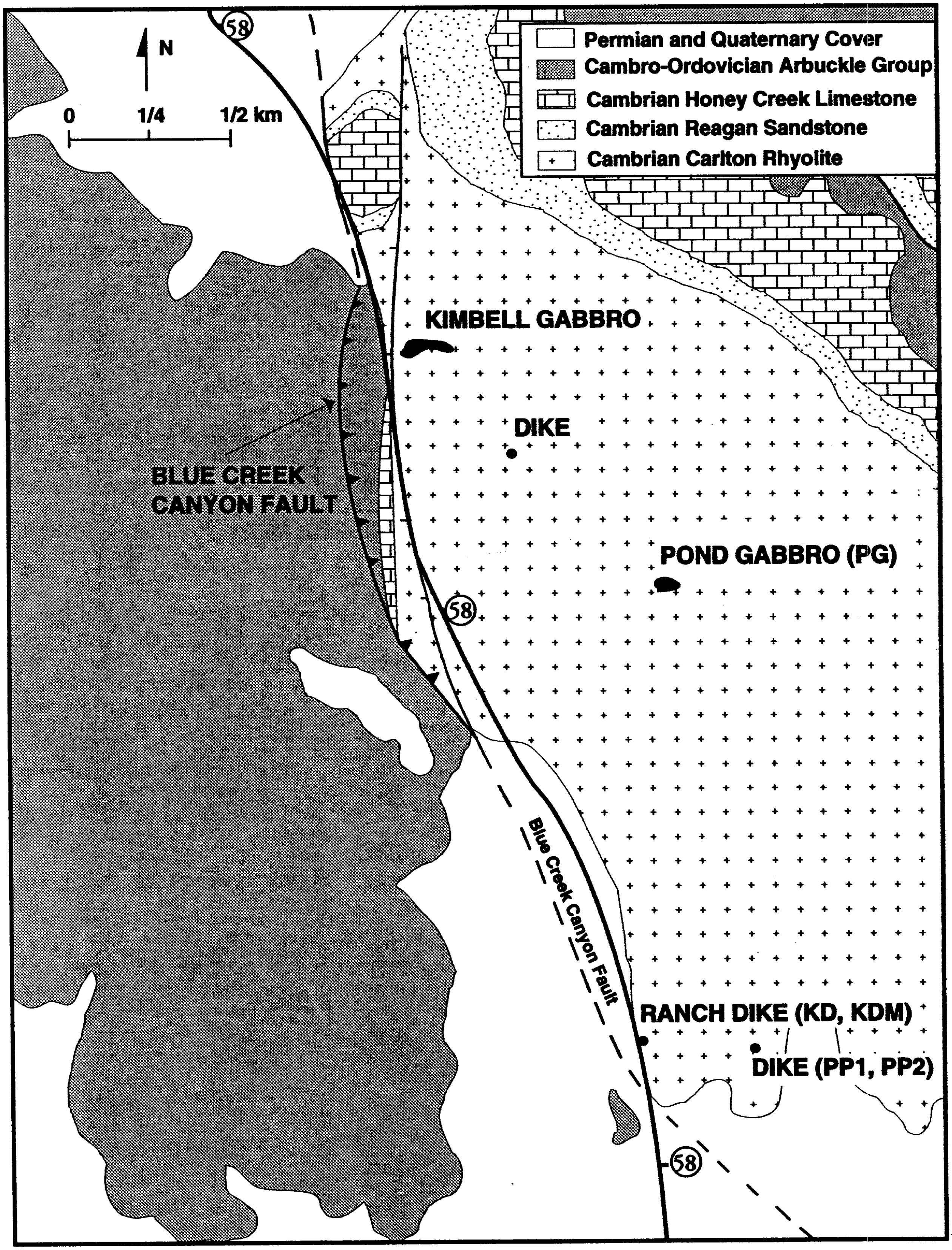

Figure 2. Geology of the Blue Creek Canyon area, modified from Donovan and others (1986). Location of the Kimbell Gabbro is shown, as well as sample localities (letters in parentheses) in other mafic intrusions.

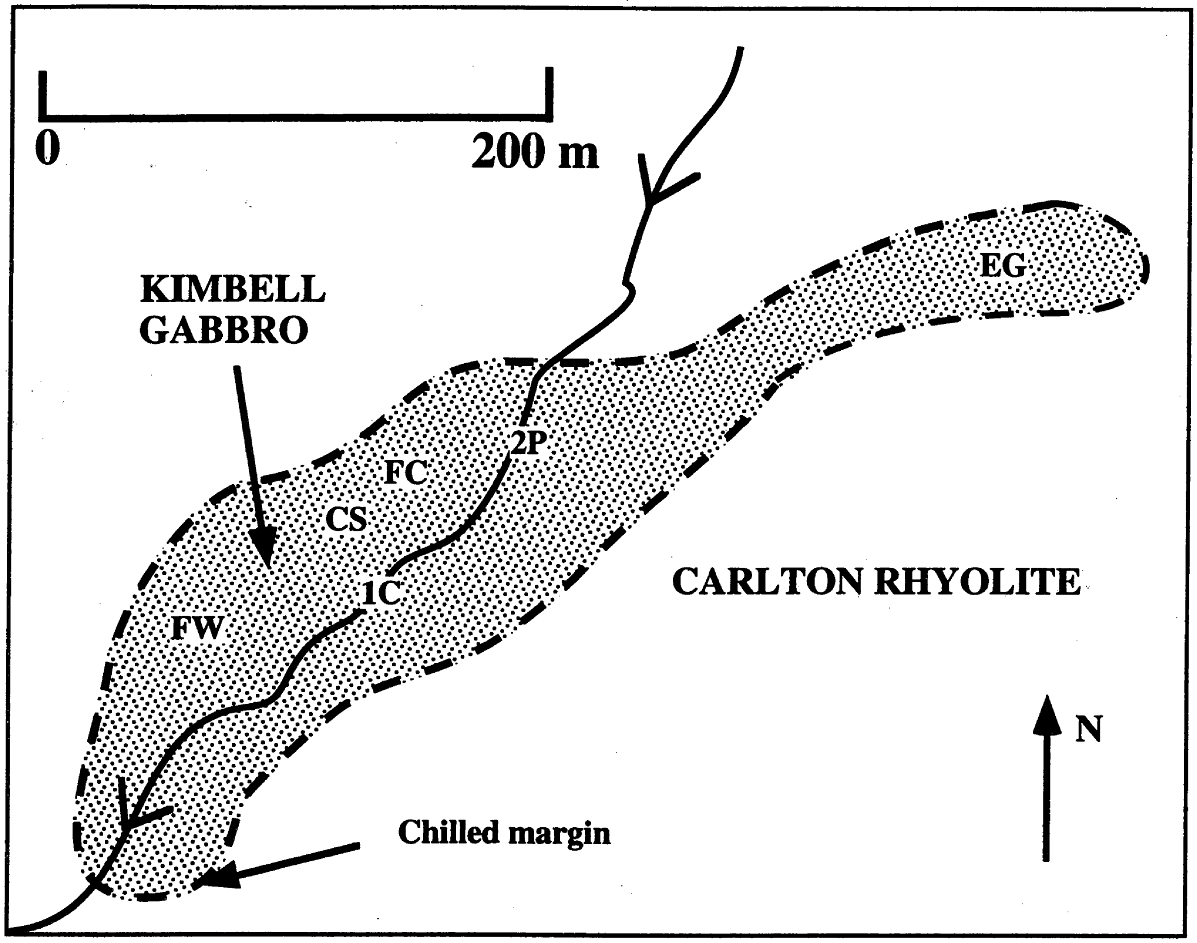

Figure 3. Generalized sketch map of the Kimbell Gabbro, showing sample locations (capital letters). The position of a creek flowing through the area is indicated. Approximate scale from aerial photograph.

several centimeters thick (sample CS), which dips slightly to the north. Similar relatively fine-grained gabbro forms locally derived float farther west (sample FW), and these rocks appear to represent a somewhat chilled marginal phase. A visible contact between rhyolite and aphanitic basalt occurs at the southwestern margin of the body and represents a distinct chilled margin (Fig. 3).

Other Mafic Intrusions

Other mafic intrusions cutting the rhyolite form small outcrops to the south of the Kimbell Gabbro (Fig. 2). Sample PG consists of spheroidally weathered boulders of medium-grained ophitic gabbro exhumed during construction of a cattle pond. These gabbros are texturally similar to the medium-grained phase of the Kimbell Gabbro. Two samples were collected from a 060°-trending dike that is ~1 m wide and is exposed in a road cut along Route 58, across from the Kimbell Ranch house. The contact between the dike (termed the "ranch dike" in Fig. 2) and the Carlton Rhyolite is sharp, and no xenoliths of the country rock are present within the dike. Texturally, the dike grades from a diabasic core (sample KD) into a basaltic chilled margin (sample KDM). Both samples display distinctive green amyg-

TABLE 1. — MODAL ANALYSES OF GABBROS (IN PERCENT)

Sample number	Plagioclase	Olivine (Bowlingite)	Clino-pyroxene	Magnetite	Other (>tr)
1C	50.2	10.5	23.0	13.5	Apatite 2.8
FC	54.3	4.6	27.4	11.3	Chilled* 2.4
2P	52.2	24.1	16.7	6.5	Biotite 0.5
EG	53.1	17.5	20.2	9.2	
FW	48.9	20.2	21.9	9.1	
PG	55.7	15.7	22.9	4.5	Calcite 1.2

*Refers to chilled interstitial areas described in text.

dules up to 1 cm in width. Finally, two samples were collected from two small, abandoned prospect pits a few meters apart and located east of the ranch dike. Sample PP1 is a nonvesicular diabase, whereas sample PP2 consists of very weathered, coarser-grained diabase displaying green amygdules. As shown later, the ranch dike differs markedly from these diabases (and from other mafic intrusions in the area) in trace-element content, and they cannot be part of the same intrusion, even though they appear to be approximately along strike in Figure 2.

Petrography

Texturally, the mafic intrusions in the Blue Creek Canyon area range from amygdaloidal basalt to diabase and gabbro. Modal analyses of the gabbros, based on counting 450–500 points per thin section, are presented in Table 1. The main magmatic phases are plagioclase, clinopyroxene, magnetite, and olivine. Apatite and ilmenite occur as accessories. Orthopyroxene, intersertal granophyre, and primary quartz are absent, in contrast to the Roosevelt Gabbros (cf. Powell, 1986). All of the rocks have been affected by relatively intense alteration that has produced variable amounts of prehnite, epidote, sericite, chlorite, smectite, leucoxene, pyrite, hematite, and calcite. Olivine has been completely replaced by bowlingite (Fig. 4), a secondary mineraloid defined by Deer and others (1992, p. 9) as an intergrowth of "smectite-chlorite together with serpentine and minor amounts of talc, mica, and quartz." In the present case, the bowlingite occurs as greenish-brown, birefringent, very fine grained masses of phyllosilicate material.

Intersertal texture occurs in the basaltic (i.e., aphanitic groundmass) chilled margin of the Kimbell Gabbro, in which original interstitial glass between plagioclase microlites is altered to smectite, chlorite, leucoxene, and hematite. The basaltic margin of the ranch dike (sample KDM) displays variolitic texture, consisting of radiating sheaves of plagioclase microlites, which reflects quenching of the magma at the margin. Amygdules in this dike and in diabase sample PP2 are filled with a mixture of chlorite and smectite. The diabases range from intergranular to subophitic in texture. All gabbroic samples display subophitic to ophitic texture, with clinopyroxene oikocrysts up to 2 cm in diameter surrounding smaller, randomly

Figure 4. Photomicrograph of Kimbell Gabbro, showing a bowlingite pseudomorph after olivine in the center of the view. Note that a very fine grained intergrowth of phyllosilicates is visible in the pseudomorph, which is surrounded by plagioclase; clinopyroxene is visible in the lower left and extreme right. Crossed polarizers; field of view is 1.3 mm across.

oriented plagioclase (Fig. 5). Small, sparse areas of interstitial material visible in thin section within some of the gabbros have the appearance of intersertal basalt with plagioclase microphenocrysts. Some of these areas are especially rich in apatite or in very fine grained magnetite. These interstitial areas appear to represent residual liquids that were suddenly quenched during the final stages of solidification. Why an intrusion that was cooling slowly enough to produce gabbroic texture would develop pockets of quenched interstitial material of this type is unclear. One possibility is that the quenching occurred when ground water contained in the host rocks gained entry into the nearly solid intrusion as it fractured during cooling. This scenario is consistent with the shallow depth of emplacement (see above).

Euhedral to subhedral plagioclase is the dominant mineral in all of the gabbros. In some cases it is heavily altered to sericite and prehnite $\pm$ epidote and calcite. Clinopyroxene is fresher than the other primary phases, displaying only limited alteration to calcite and leucoxene. Olivine, replaced by bowlingite, is present in all of the gabbros. Some of the replaced olivine crystals exhibit distinct, euhedral outlines (Fig. 4), but, in other cases, the bowlingite completely surrounds plagioclase crystals, implying that the olivine was poikilitic around plagioclase. Primary magmatic biotite, which was identified in only one of the samples (2P), is fine grained and red brown.

Figure 5. Photomicrograph of Kimbell Gabbro, showing ophitic clinopyroxene surrounding randomly oriented plagioclase laths and opaque magnetite. Gabbro matrix is visible to the left. Crossed polarizers; field of view is 3.3 mm across.

Clinopyroxene Compositions

Compositions of the clinopyroxenes were determined from four gabbros and one diabase by using the electron microprobe at the University of Oklahoma; analytical details and complete data are given in DeGroat (1994). The clinopyroxenes cluster in the augite field when plotted in the pyroxene quadrilateral (Fig. 6). Sample EG shows a limited trend toward more Fe-rich compositions, but the data in general indicate that only minor igneous zoning of the main pyroxene components is present in the crystals.

A plot of Al_z versus TiO_2 (LeBas, 1962) shows the clinopyroxene compositions to be transitional between nonalkalic and normal alkalic types (Fig. 7). As discussed below, this finding is consistent with other geochemical evidence.

Whole-Rock Compositions

Whole-rock major- and trace-element compositions were determined by X-ray fluorescence analysis at the University of Oklahoma. Results are presented in Table 2. CIPW norms are given in DeGroat (1994) but, because of the altered nature of the samples, the norms are extremely variable and undoubtedly do not represent pri-

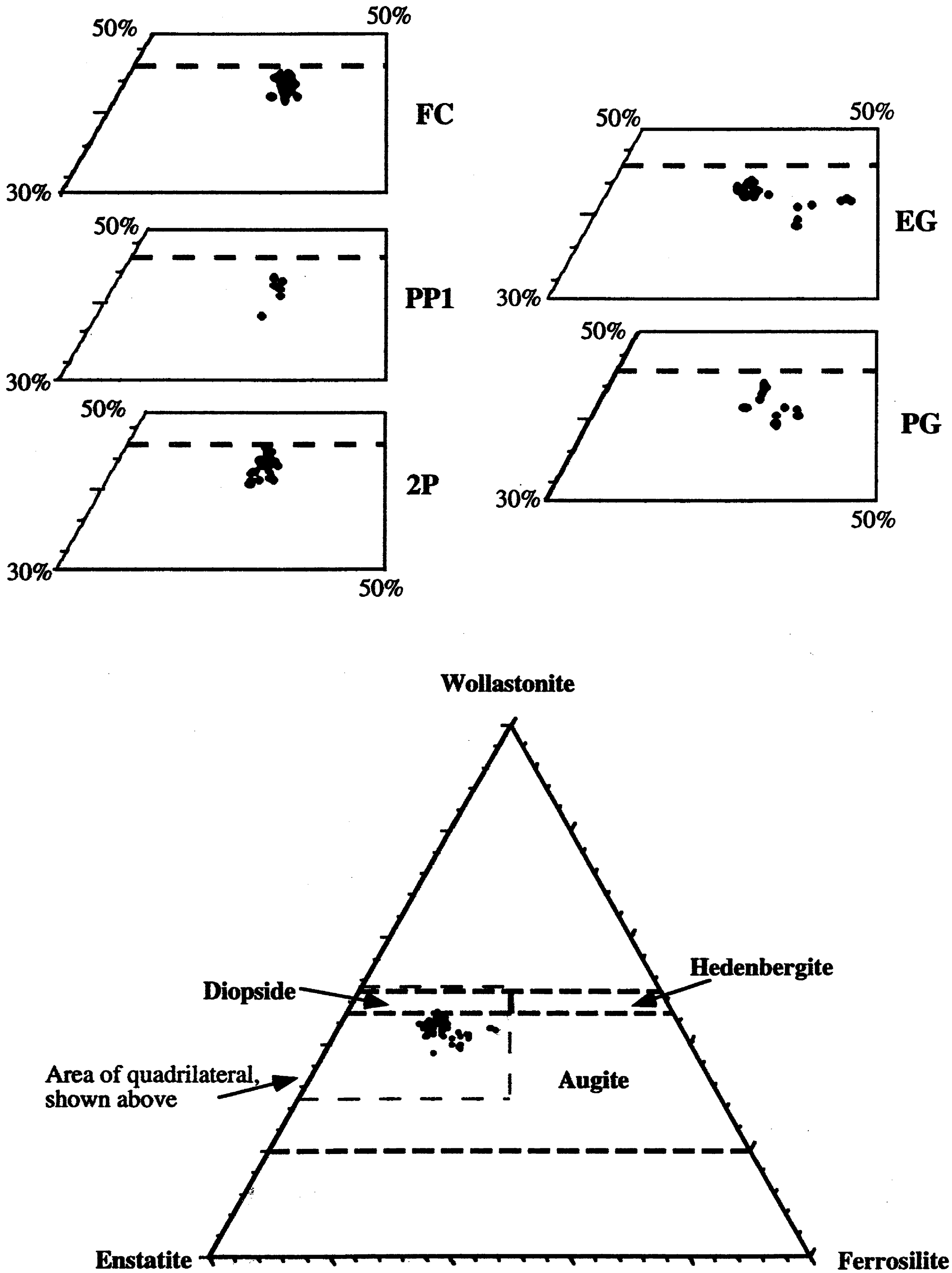

Figure 6. Clinopyroxene compositions from the Kimbell Gabbro (samples FC, 2P, EG) and from other mafic intrusions (gabbro sample PG and diabase sample PP1) in the Blue Creek Canyon area. Data for all samples are plotted on the pyroxene quadrilateral in the lower part of figure. Data for individual samples are separated in the upper part of the figure, where the outlined area of the quadrilateral is shown in more detail. Clinopyroxene compositional fields are from Morimoto (1988).

TABLE 2. — WHOLE-ROCK MAJOR-OXIDE AND TRACE-ELEMENT ANALYSES OF MAFIC INTRUSIONS IN THE BLUE CREEK CANYON AREA

	1C	FC	CS	2P	EG	FW	KD	KDM	PP1	PP2	PG
SiO_2	47.98	46.36	47.54	46.18	45.76	47.36	42.82	44.85	45.42	46.68	46.61
TiO_2	2.17	2.98	2.52	2.34	3.35	2.33	3.88	3.83	3.32	3.51	2.47
Al_2O_3	14.74	14.31	14.60	15.89	12.70	14.07	13.89	13.58	14.53	16.19	14.98
Fe_2O_3	15.30	17.60	15.98	15.62	19.07	15.64	19.36	18.89	18.03	16.81	16.42
MgO	6.24	6.93	6.96	7.16	6.21	7.38	5.90	5.04	5.00	4.73	6.43
CaO	8.47	6.29	6.94	9.44	7.86	8.05	6.40	5.99	7.67	5.53	9.51
Na_2O	4.45	3.48	3.85	2.47	4.01	3.84	2.70	3.06	3.95	4.94	2.54
K_2O	0.13	1.63	1.25	0.56	0.60	0.97	2.44	2.21	1.60	1.36	0.71
P_2O_5	0.52	0.42	0.36	0.34	0.44	0.36	2.61	2.55	0.48	0.53	0.33
Nb	18.9	17.0	15.3	13.5	14.6	12.0	76.4	76.9	20.6	21.9	15.6
Zr	174	159	134	112	150	117	552	554	143	150	139
Y	38	35	30	28	37	28	89	90	33	29	30
Sr	169	504	541	387	156	429	141	191	374	217	384
Rb	3	45	42	10	19	36	82	56	73	58	22
Th	2	< 2	< 2	< 2	< 2	< 2	3	2	< 2	2	< 2
Pb	< 2	< 2	< 2	< 2	< 2	< 2	13	24	4	5	< 2
Ga	23	23	21	23	24	19	38	35	22	28	24
Zn	85	75	101	65	71	80	455	466	400	272	92
Cu	98	153	117	107	202	90	< 2	37	177	176	119
Co	50	62	66	70	61	59	36	34	60	65	60
Ni	54	53	80	91	37	79	11	9	66	58	82

NOTE: Oxides in weight percent, normalized to 100%; trace elements in ppm.

mary igneous compositions. The two samples from the ranch dike (KD and KDM) show unusually low SiO_2 contents (Table 2). These samples contain abundant amygdules filled with smectite and chlorite and also contain extensive smectite in the groundmass. The low SiO_2 contents are therefore interpreted to reflect significant perturbation of the original igneous chemistry during secondary alteration.

Representative plots of the major oxides and trace elements versus Zr are shown in Figure 8. Zr is used as a differentiation index because of its wide range in the samples and its generally immobile nature during alteration (e.g., Pearce and Cann, 1973). Significant scatter of many of the major oxides and trace elements (e.g., Na_2O, K_2O, and Sr) is interpreted to at least partly reflect secondary disturbance of the primary igneous chemistry. The more immobile elements—P, Nb, and Y—display positive correlations with Zr that are considered to represent pri-

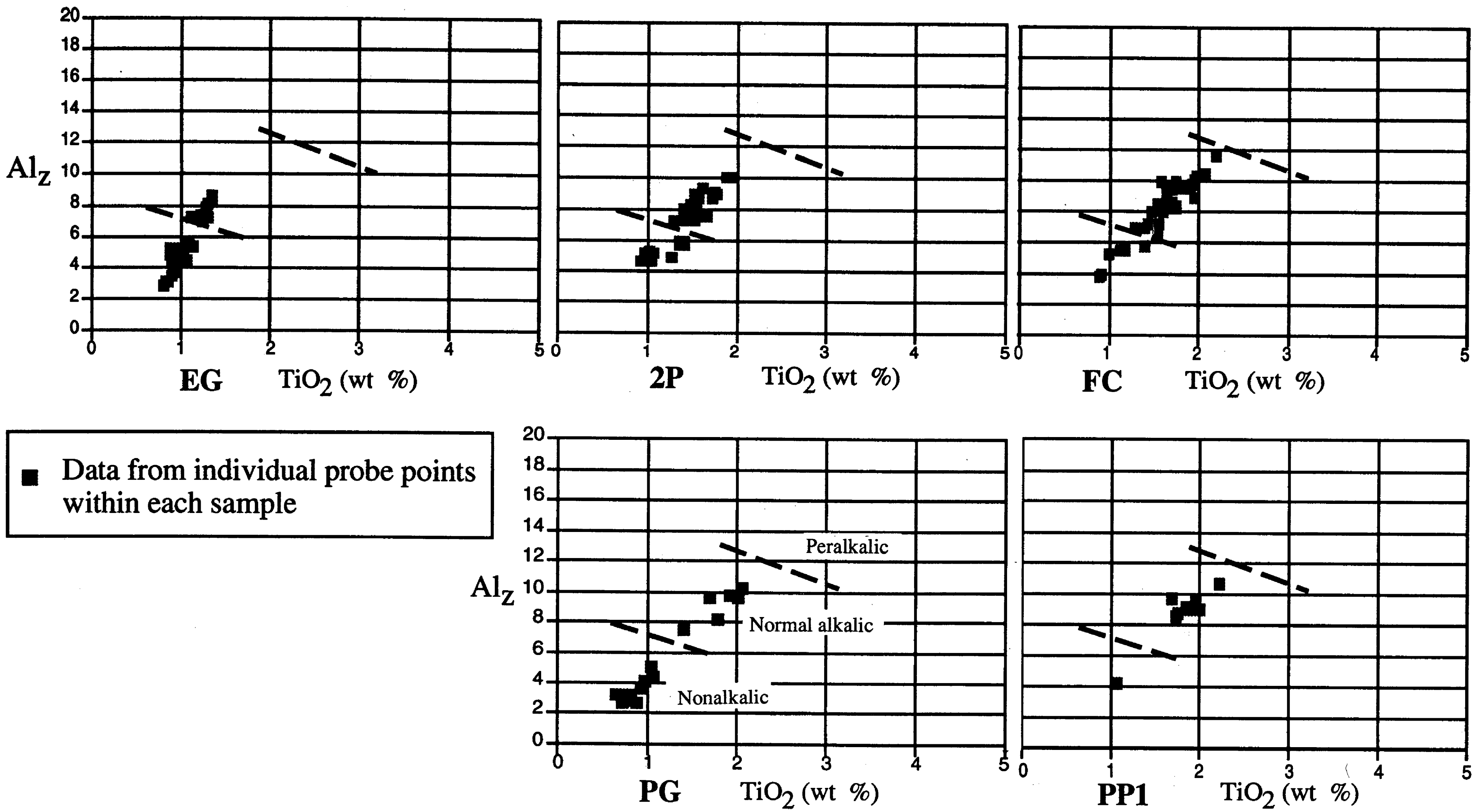

Figure 7. Clinopyroxene compositions plotted on the Al_z versus TiO_2 discrimination diagram of LeBas (1962). Boundaries separating nonalkalic, normal alkalic, and peralkalic fields are labeled on diagram for sample PG. Al_z refers to the amount of Al in the tetrahedral site in the crystal structure and was calculated following the technique of LeBas (1962).

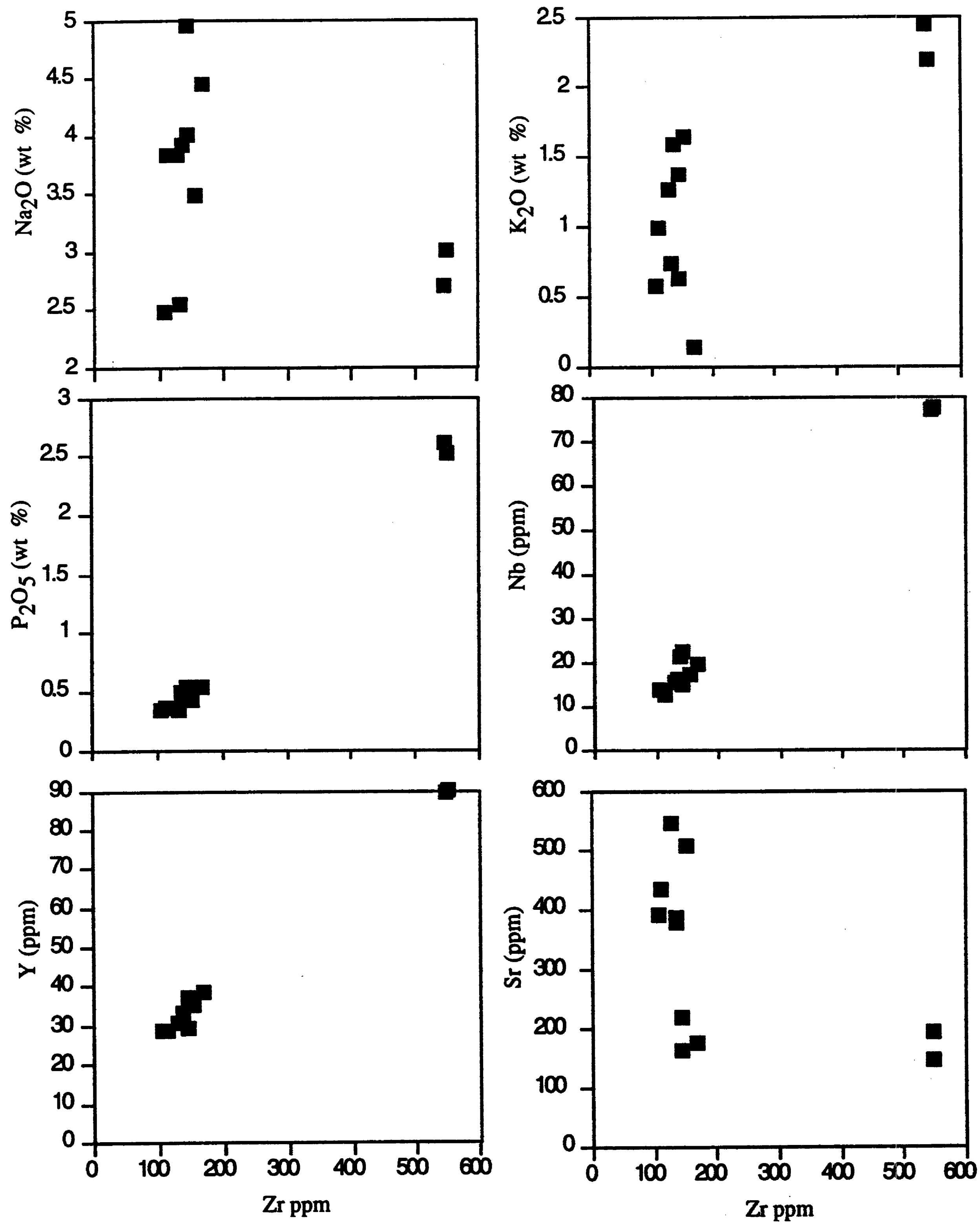

Figure 8. Na_2O, K_2O, and P_2O_5 (in wt %), and Nb, Y, and Sr (in ppm), plotted versus Zr for samples from mafic intrusions in the Blue Creek Canyon area.

mary igneous trends (Fig. 8). Note that Zr shows a significant range in the samples from the Kimbell Gabbro (Table 2), implying that this body was not intruded as a single, homogeneous mass of magma.

Fractionation of plagioclase, olivine, and clinopyroxene may explain the trends for Y and Nb versus Zr for most of the samples, based on comparison with fractionation vectors for these minerals from Pearce and Norry (1979). This interpretation is consistent with the observed igneous phases in the rocks.

The two samples of the ranch dike are extremely enriched in Zr (Fig. 8). The high Zr content of this dike relative to the other samples is difficult to explain by simple crystal/liquid fractionation processes operating in a closed system. Contamination of the magma does not seem to be a possibility because the dike contains no xenoliths or xenocrysts, nor does it show any other evidence of interaction with the country rock. The petrogenetic relations of this dike to the other mafic rocks are worthy of further study.

Trace-Element Discrimination Diagrams

Trace-element data for the Blue Creek Canyon samples have been plotted on a series of discrimination diagrams that employ elements generally believed to be immobile during low-grade alteration. These diagrams were developed for volcanic rocks, and caution should be used when applying them to plutonic rocks such as the Kimbell Gabbro, in which crystal accumulation may have occurred. However, the intrusive basalts and diabases analyzed in this study lack phenocrysts and therefore originally represented liquid compositions prior to alteration.

Some of the discrimination diagrams shown here commonly are used to infer the tectonic setting of eruption of ancient basalts. The diagrams are not presented here for that purpose, inasmuch as the setting of mafic magmatism in the southern Oklahoma aulacogen already is well established as involving rifting of older continental crust. The diagrams are used here simply to provide insight into the magmatic affinities of the mafic intrusions in the Blue Creek Canyon area, particularly with respect to other mafic rocks in the Wichita province. To that end, data from other late diabase dikes and from the Roosevelt Gabbros are also plotted (Weaver, unpublished data). On the basis of the analyzed elements, there is no clear difference between the Roosevelt Gabbros and the late diabase dikes in this data set (see also Gilbert and Hughes, 1986), and both suites are indicated by a single field in the following discrimination diagrams. Trace-element data presented by Cameron and others (1986) for the Roosevelt Gabbros and late diabase dikes also generally fall within the same field.

In the Ti-Y-Zr plot of Pearce and Cann (1973), the majority of the Blue Creek Canyon samples plot in the field for within-plate basalts (Fig. 9). The two samples from the ranch dike (KD and KDM) plot in the field for calc-alkalic basalts, away from the other Blue Creek Canyon data, whereas sample 1C from the Kimbell Gabbro plots in the field for calc-alkalic basalts and ocean-floor basalts. Weaver's larger data set from the Roosevelt Gabbros and late diabase dikes also extends into the ocean-floor and calc-alkalic basalt fields, and all of the Blue Creek Canyon samples plot within the area defined by that larger data set.

Wang and Glover (1992) questioned the applicability of the Ti-Y-Zr diagram to discriminate within-plate, continental-rift basalts, based on the fact that many samples from continental basalts plot outside the within-plate basalt field and in-

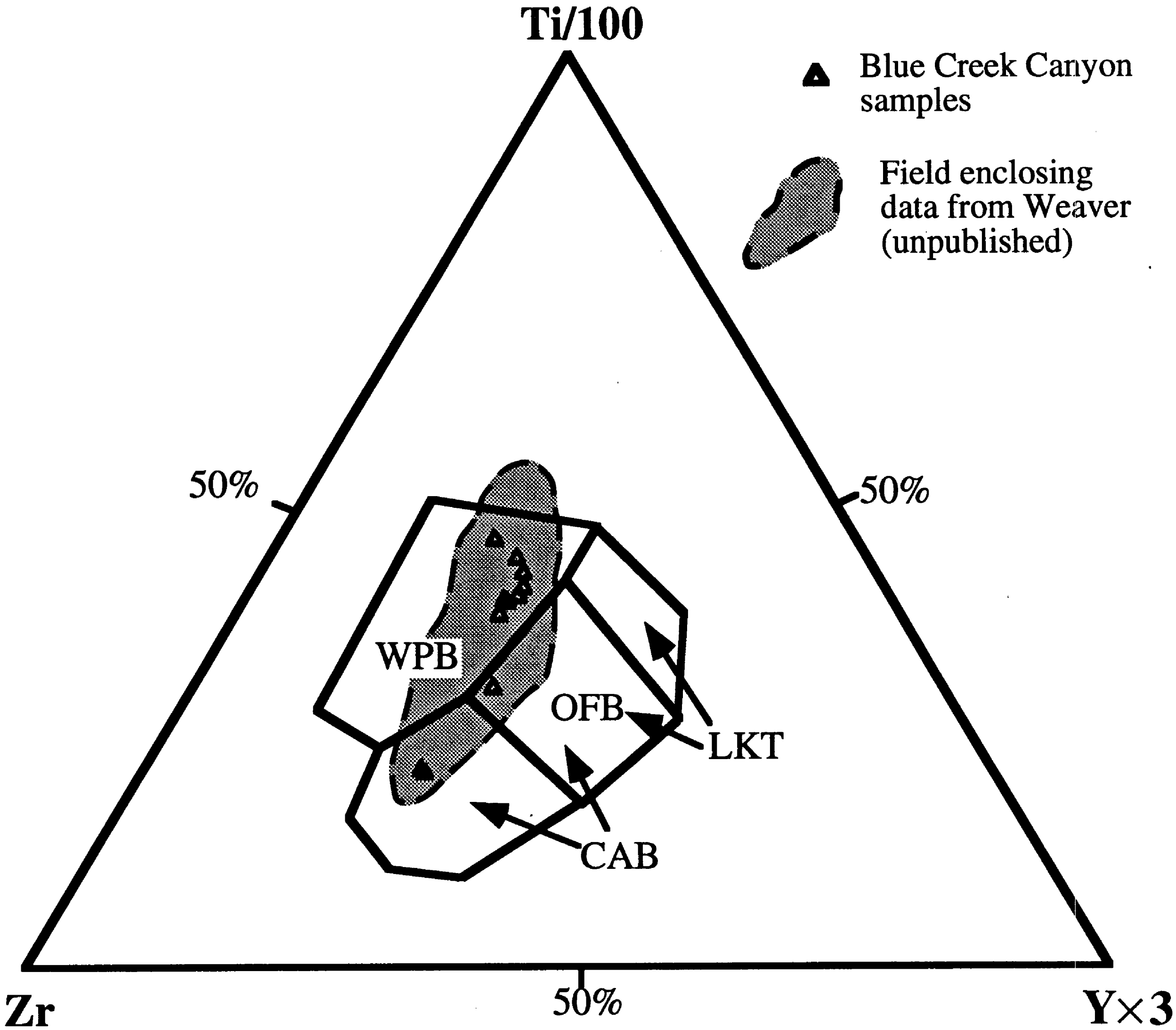

Figure 9. Data from mafic intrusions in the Blue Creek Canyon area plotted on the Ti-Y-Zr diagram of Pearce and Cann (1973). Field enclosing data from other late diabase dikes and Roosevelt Gabbros (Weaver, unpublished data) also is plotted. WPB = within-plate basalts; CAB = calc-alkalic basalts; OFB = ocean-floor basalts; LKT = low-K island-arc tholeiites.

side either the ocean-floor or calc-alkalic basalt fields on this diagram. Wang and Glover (1992) believed this situation reflects a variety of complex processes involved in the petrogenesis of continental basalts, including contamination by continental crust and/or lithosphere. Other workers also have shown that the diagram may produce erroneous conclusions with regard to tectonic setting (e.g., Arculus, 1987). Therefore, we attach no significance to the fact that some of the Wichita mafic igneous rocks plot in the calc-alkalic and ocean-floor basalt fields in Figure 9.

The data are plotted on the Ti/Y versus Nb/Y differentiation diagram of Pearce (1982) in Figure 10. As in the last diagram, the Blue Creek Canyon samples fall within the field for within-plate basalts, except for the three anomalous samples noted above. Again, the field for Weaver's data encompasses all of the Blue Creek Canyon sample points. Note that the data spread across the boundary for tholeiitic versus transitional basalt types.

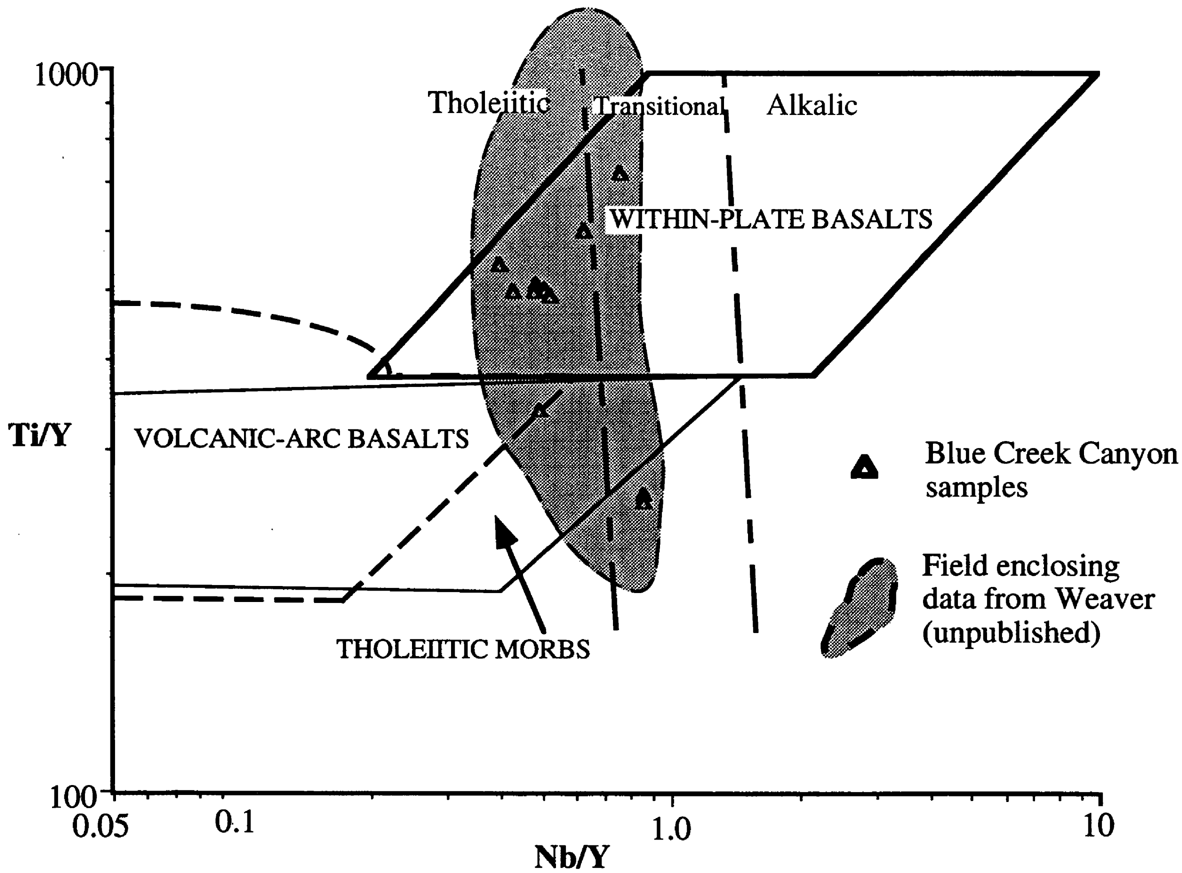

Figure 10. Data from mafic intrusions in the Blue Creek Canyon area plotted on the Ti/Y versus Nb/Y diagram of Pearce (1982). Field enclosing data from other late diabase dikes and Roosevelt Gabbros (Weaver, unpublished data) also is plotted.

The Nb/Y versus Zr/P_2O_5 discrimination diagram of Floyd and Winchester (1975) and Winchester and Floyd (1976) is displayed in Figure 11. On this diagram, the Blue Creek Canyon samples define a very rough vertical trend in the direction of the two anomalous dike samples (KD and KDM), which plot well within the alkali basalt field. However, the majority of the samples plot as tholeiites. The spread in the data across the tholeiitic versus alkalic boundary implies that the suite as a whole is transitional in nature. These results are in keeping with those given in Figure 10 and with the clinopyroxene data discussed above. Cameron and others (1986) also concluded that their data indicated transitional affinities for the Roosevelt Gabbros and late diabases.

The samples were also plotted on the TiO_2 versus Zr/P_2O_5 and TiO_2 versus Y/Nb discrimination diagrams of Floyd and Winchester (1975), although these diagrams are not shown here. The samples generally plot within the continental-tholeiite field on both diagrams and display trends of a transitional nature.

Figure 12 shows the Zr/TiO_2 versus Nb/Y discrimination diagram of Winchester and Floyd (1977). The majority of the Blue Creek Canyon samples plot within the subalkalic basalt field, whereas the two anomalous dike samples and sample 1C plot within the alkali basalt field, again indicating the transitional nature of the suite as a whole. The area defined by Weaver's data also crosses the boundary between subalkalic and alkalic basalts.

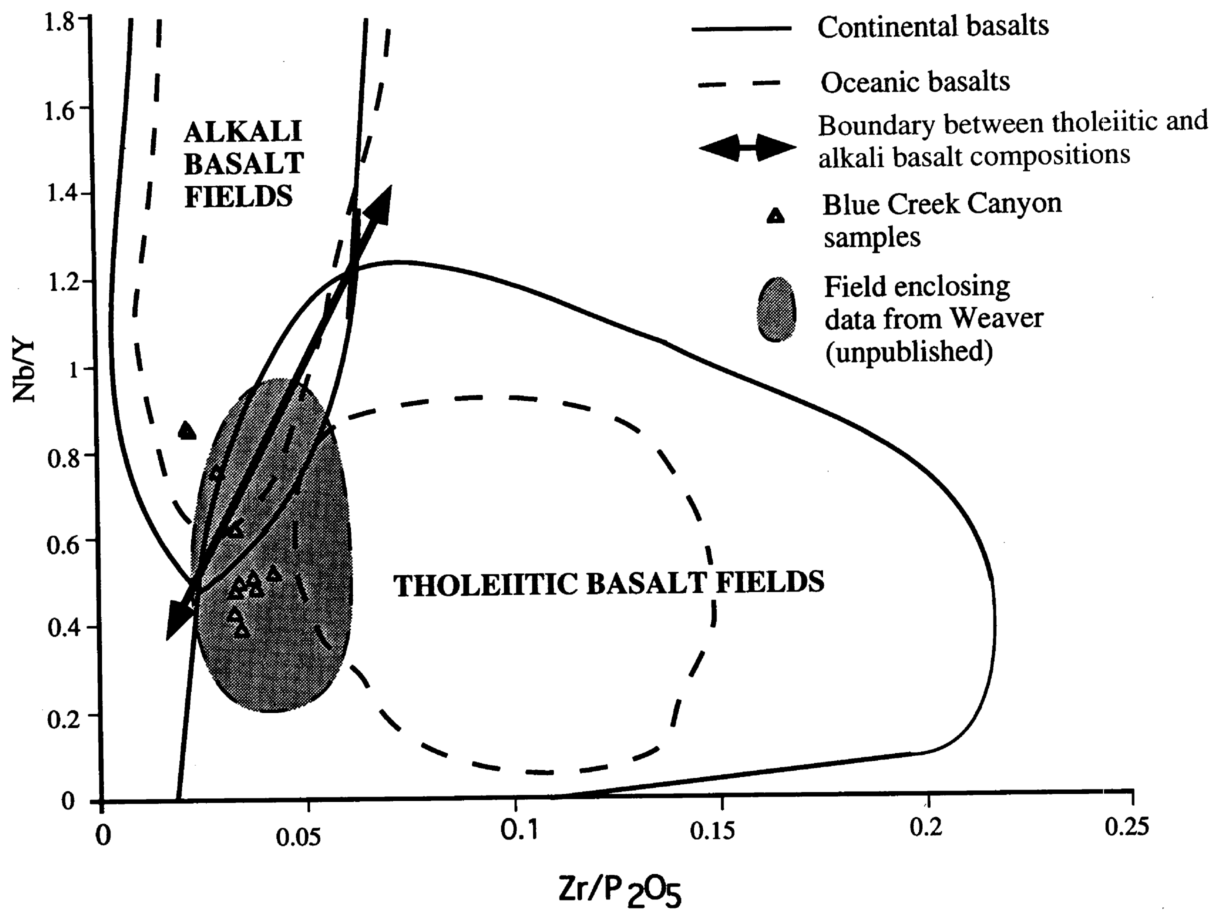

Figure 11. Data from mafic intrusions in the Blue Creek Canyon area plotted on the Nb/Y versus Zr/P_2O_5 diagram of Floyd and Winchester (1975). In calculating the Zr/P_2O_5 values, P_2O_5 has been multiplied by 10^4, following Floyd and Winchester (1975). Boundary between tholeiitic and alkali basalt compositions is from Winchester and Floyd (1976). Field enclosing data from other late diabase dikes and Roosevelt Gabbros (Weaver, unpublished data) also is plotted.

Discussion

Clinopyroxene compositions and immobile trace-element contents of Cambrian mafic intrusions cutting the Carlton Rhyolite in the Blue Creek Canyon area indicate that the mafic rocks have transitional affinities between tholeiitic and alkalic magma types and are compositionally similar to other late diabases in the Wichita province. Although the relatively coarse grain size of the Kimbell Gabbro distinguishes it texturally from most examples of the late diabases, this feature is clearly a function of this intrusion's slower cooling rate.

The absence of orthopyroxene and the general lack of primary hydrous minerals in the Kimbell Gabbro make it petrographically unlike the Roosevelt Gabbros, which are characterized by two pyroxenes and relatively abundant primary biotite (or phlogopite) and amphibole (Powell, 1986). However, the similarity in trace-element signatures between the Roosevelt Gabbros and the late diabase dikes and Kimbell Gabbro means that these two different mafic intrusive suites cannot be

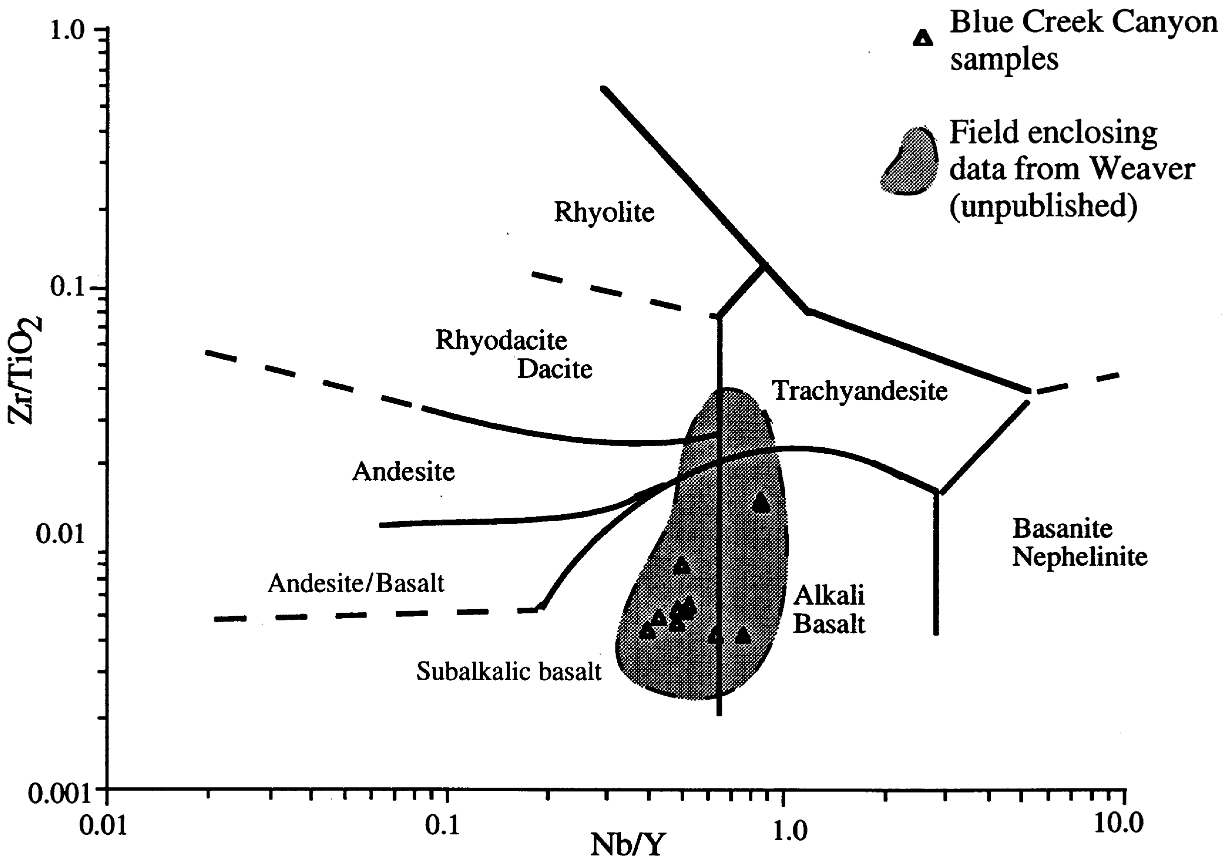

Figure 12. Data from mafic intrusions in the Blue Creek Canyon area plotted on the Zr/TiO_2 versus Nb/Y diagram of Winchester and Floyd (1977). Field enclosing data from other late diabase dikes and Roosevelt Gabbros (Weaver, unpublished data) also is plotted.

distinguished on the basis of currently available geochemical data (Figs. 9–12). The generally held view, which is supported in some cases by field relations, is that the Roosevelt Gabbros predate the unconformity developed prior to extrusion of the Carlton Rhyolite (Gilbert, 1982; Powell, 1986) and therefore represent a distinctly older phase of mafic magmatism than the late diabases (and Kimbell Gabbro). Given the geochemical similarities between these various mafic rocks, perhaps the possibility should be considered that some of the intrusions mapped as Roosevelt Gabbro in the Wichita Mountains are significantly younger than previously thought and are directly related to the late diabase dikes. Alternatively, both suites may relate to a single period of mafic magmatism that overlapped the silicic episode and was characterized by fairly uniform trace-element compositions.

Finally, the relatively intense alteration exhibited by the mafic intrusions in the Blue Creek Canyon area deserves some comment. Possibly the alteration reflects intrusion of these bodies into the Carlton Rhyolite during or only shortly after the volcanic activity, so that hydrothermal fluids circulating through the rhyolitic pile were available to alter the mafic rocks. Alternatively, a low-temperature component of the alteration may reflect sea-floor alteration during the Late Cambrian transgression over the eroded surface of the Carlton Rhyolite.

Acknowledgments

We are grateful to John Hogan, Charles Gilbert, and David London for their help in planning the lab work at the University of Oklahoma and to George Morgan III for assistance in operation of the electron microprobe. We also thank Arthur Busbey for sharing his computer expertise with us, Van Lohuisen for preparing the thin sections, and the Kimbell family for allowing access to the study area. Funding for the study was provided by the Moncrief Chair endowment, Texas Christian University. The manuscript was significantly improved by reviews by Rodger Denison, Edward Lidiak, and Kenneth Johnson.

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NEW OGS *Publications*

CIRCULAR 97. ***Structural Styles in the Southern Midcontinent, 1992 Symposium,*** edited by Kenneth S. Johnson. 300 pages, 34 contributions. Price: Paperbound, $10.

From the editor's preface:

The transfer of technical information will aid in the search for, and production of, our oil and gas resources. To facilitate this technology transfer, the Oklahoma Geological Survey (OGS) and the Bartlesville Project Office of the U.S. Department of Energy (BPO-DOE) co-sponsored a symposium dealing with structural geology, petroleum geology, and reservoir characterization in the southern Midcontinent. The symposium was held on March 31–April 1, 1992, at the Oklahoma Center for Continuing Education, The University of Oklahoma, Norman. This volume contains the proceedings of that symposium.

Research reported upon at the symposium focused on structural geology, tectonic evolution, petroleum reservoirs in various structural settings, development of oil and gas resources, geophysics, and neotectonics. In describing the various structural styles and related petroleum reservoirs in the southern Midcontinent, the researchers have increased our understanding of how the tectonic history of an area can affect reservoir heterogeneity and our ability to efficiently recover the hydrocarbons they contain. We hope that the symposium and these proceedings will bring such research to the attention of the geoscience and energy-research community, and will help foster exchange of information and increased research interest among industry, university, and government workers.

Twenty papers were presented orally at the symposium, and they are presented as full papers or abstracts. An additional 14 reports were given as posters, and they are presented as short reports or abstracts. About 260 persons attended the symposium.

This is the fifth symposium in as many years dealing with topics of major interest to geologists and others involved in petroleum-resource development in Oklahoma and adjacent states. These symposia are intended to foster the exchange of information that will improve our ability to find and recover our nation's oil and gas resources. Earlier symposia subjects were: the Anadarko basin (published as OGS Circular 90); Late Cambrian–Ordovician geology of the southern Midcontinent (Circular 92); source rocks in the southern Midcontinent (Circular 93); and petroleum-reservoir geology in the southern Midcontinent (Circular 95).

SPECIAL PUBLICATION 95-2. ***Oklahoma Oil and Gas Production by Field, 1991–94.*** 440 pages. Price: $12.

This annual publication provides data on reported oil and gas production and related information for each formally recognized field in the State. The volume contains the following types of field data:

- Field name
- County or counties in which the field is located
- Total acreage of the field

- Date the Oklahoma Nomenclature Committee named the field and date of the last revision of field boundaries
- Annual production from 1991 through 1994 by type of product: oil, condensate, total liquids, associated gas, natural gas, and total gas
- Cumulative production from 1979 through 1994 by type of product

Part 1 of this publication includes oil and gas production by county; Part 2 is a summary of production within each county that is not assigned to any formally recognized field. Part 3 is an alphabetical list of all fields, districts, and gas areas that have been formally recognized by the Oklahoma Nomenclature Committee. Part 4 is a listing of discontinued field names.

This publication has been developed from data contained in the Natural Resources Information System (NRIS), a computerized data base of oil and gas information for the State of Oklahoma. NRIS currently contains data files of monthly oil and gas production by lease that can be aggregated by such categories as field, producing interval, geologic play, petroleum province, and political area (e.g., county). NRIS also contains digitized records for almost 40,000 well completions and recompletions dating from statehood (1907) to present. The well records include latitude/longitude coordinates that permit plotting and use in a GIS system.

SPECIAL PUBLICATION 95-3. ***Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Booch Play,*** by Robert A. Northcutt, Kurt Rottman, and others. 67 pages, 5 plates. Price: $6.

The second in a series of publications addressing fluvial-dominated deltaic (FDD) light-oil reservoirs in Oklahoma, this volume presents the material covered in the Booch play workshop held in September 1995.

In Part I of this publication, Richard D. Andrews, Jock A. Campbell, and Robert A. Northcutt explain the scope of the FDD project and describe the significant features of the depositional setting of an FDD reservoir system to provide an understanding of the properties of the individual FDD reservoirs identified in the project.

In Part II, Robert A. Northcutt gives an overview of Booch FDD areas in Oklahoma. Booch fluvial systems are found in the Cherokee Platform in northeastern Oklahoma and extend southward beyond the hinge line of the McAlester Formation into the Arkoma basin. This section of the book presents studies of three areas within the Booch play: the Hawkins pool area, Wewoka N.W. Booch sand unit (contributed by Kurt Rottmann), and Greasy Creek field, including stratigraphy, structure, isopach mapping, reservoir characteristics, and oil and gas production.

The results of a reservoir simulation of a Booch oil reservoir in the Greasy Creek field, Hughes County, Oklahoma, are presented in Part III, by R. M. Knapp and X. H. Yang. The simulation included a forecast of expected waterflood performance.

The book also includes a list of selected references and a glossary of terms. Plates included with the publication are a map of the Booch sandstone play area, stratigraphic cross sections of the study area, a production map of the Booch FDD area, a map of Booch oil and gas fields, and an index to selected Booch references used for Booch sandstone mapping.

Booch play authors Robert A. Northcutt and Kurt Rottmann are consulting geologists in Oklahoma City. Richard D. Andrews, exploration and development geologist with the University of Oklahoma's Geo Information Systems (GeoSystems) unit, and Jock A. Campbell, OGS geologist, are the other two lead geologists on the FDD project team. R. M. Knapp is the petroleum engineer for the FDD project and a professor in the OU School of Petroleum and Geological Engineering. X. H. Yang is a graduate student in the OU School of Petroleum and Geological Engineering. The next publication to be released in this series will be on the Layton/ Osage-Layton play.

OKLAHOMA GEOCALENDAR 1996. ***Oklahoma Dinosaur Days—Acrocanthosaurus.*** Price: $4, rolled in tube.

The first in a new series, this 1996 calendar features Karen Carr's dramatic full-color rendering of *Acrocanthosaurus atokensis,* a dinosaur first described from two specimens found in 1940 in the Antlers Formation of Atoka County, Oklahoma (see front cover, this issue). Nearly the size of *Tyrannosaurus rex, Acrocanthosaurus* was one of the largest carnivores that lived during the Early Cretaceous. The poster-size calendar measures 24 × 36 inches and is accompanied by a color-illustrated pamphlet describing *Acrocanthosaurus* as well as the geological and biological environment he inhabited. The pamphlet can be purchased separately for $1 each. A special 20% volume discount applies for orders of 25 or more calendars or pamphlets. Science advisors for the text were Richard L. Cifelli, associate curator of vertebrate paleontology at the Oklahoma Museum of Natural History, and Kenneth S. Johnson, OGS associate director.

OGS Circular 97, SP 95-2, SP 95-3, and Geocalendar 1996 can be purchased over the counter or by mail from the Survey at 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031 *or* (800) 330-3996, fax 405-325-7069. To mail order books, add 20% to the cost, with a minimum of $1 per order. To mail order 1–10 calendars, add $2, for 11–25 calendars, add $3 to the cost for postage.

AGI Solicits Input for New Directory

The American Geological Institute is asking for help in identifying geoscience data repositories to include in a new National Geoscience Data Repository System (NGDRS). This directory of data repositories will serve as an important source of information for the entire geoscience community for a variety of applications, including environmental protection, water resource management, global change studies, reducing risks from earthquakes and other geologic hazards, and basic and applied research. The repository system would also contain critical data that would enable domestic energy and minerals companies to expand their exploration and production programs in the United States for improved recovery of domestic oil, gas, and mineral resources.

The AGI plans to include in the new directory all public and private (membership/other commercial) repositories. If you are aware of a data repository that has not been contacted by AGI, please write or call the American Geophysical Institute, 4220 King Street, Alexandria, VA 22302-1502; (703) 379-2480, fax (703) 379-7563.

Oklahoma Geological Survey

UPCOMING WORKSHOPS AND EVENTS RELATED TO OIL & GAS IN OKLAHOMA

1995

December	PTTC Arkansas Problem-Identification Workshop

1996

January 16	PTTC/FDD Reservoir Class Workshop *Bartlesville*
February 1 & 2	FDD Workshop: Layton/Osage-Layton Play *Oklahoma City*
February 13	PTTC/FDD Reservoir Class Workshop *Oklahoma City*
February	PTTC Focused-Technology Workshop
March 26–27	Platform Carbonates in the Southern Midcontinent *Norman*
April	FDD Workshop: Prue and Skinner Plays
September	FDD Workshop: Cleveland and Peru Plays

1997

January	FDD Workshop: Red Fork Play
April	FDD Workshop: Tonkawa Play
July	FDD Workshop: Bartlesville Play

FDD = Fluvial-Dominated Deltaic (U.S. Department of Energy Class I Reservoirs)
PTTC = Petroleum Technology Transfer Council

UPCOMING *Meetings*

SEPM, Gulf Coast Section Annual Research Conference, "Salt, Sediment, and Hydrocarbons," December 3–6, 1995, Houston, Texas. Information: GCS, SEPM Foundation, 165 Pinehurst Road, West Hartland, CT 06091; (203) 738-1068 *or* (800) 436-1424.

Tailings and Mine Waste '96, January 16–19, 1996, Fort Collins, Colorado. Information: Linda Hinshaw, Dept. of Civil Engineering, Colorado State University, Fort Collins, CO 80523; (303) 491-6081, fax 303-491-7727.

North American Energy Summit '96, February 4–7, 1996, Houston, Texas. Information: Conference Coordinator, Institute for International Research, 708 Third Ave., 4th Floor, New York, NY 10017; (800) 999-3123, fax (800) 959-9644.

AAPG, Southwest Section Convention, March 10–12, 1996, El Paso, Texas. *Abstracts due November 1, 1995.* Information: G. Randy Keller, Dept. of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968; E-mail: aapgsw96@geo.utep.edu.

Geological Society of America, South-Central Section Annual Meeting, March 11–12, 1996, Austin, Texas. *Abstracts due November 20, 1995.* Information: William F. Mullican, Bureau of Economic Geology, University of Texas, University Station Box X, Austin, TX 78712; (512) 471-1534; E-mail: mullicanb@begv.beg.utexas.edu.

Geological Society of America, Southeastern Section Annual Meeting, March 14–15, 1996, Jackson, Mississippi. *Abstracts due November 15, 1995.* Information: Darrel Schmitz, Dept. of Geosciences, P.O. Box 5448, Mississippi State University, Mississippi State, MS 39762; (601) 325-2904.

Geological Society of America, Northeastern Section Annual Meeting, March 21–23, 1996, Buffalo, New York. *Abstracts due November 20, 1995.* Information: Parker E. Calkin, Dept. of Geology, SUNY at Buffalo, 876 NSM, Buffalo, NY 14260; (716) 645-6800, ext. 3985, fax 716-645-3999; E-mail: glgparker@ubvms.cc.buffalo.edu.

Geological Society of America, Rocky Mountain Section Annual Meeting, April 18–19, 1996, Rapid City, South Dakota. *Abstracts due January 5, 1996.* Information: Alvis L. Lisenbee, Dept. of Geology and Geological Engineering, South Dakota School of Mines and Technology, 501 E. St. Joseph St., Rapid City, SD 57701; (605) 394-2463.

Geological Society of America, Cordilleran Section Annual Meeting, April 22–24, 1996, Portland, Oregon. *Abstracts due December 28, 1995.* Information: Richard Thoms, Dept. of Geology, Portland State University, P.O. Box 751, Portland, OR 97207; (503) 725-3379.

Geological Society of America, North-Central Section Annual Meeting, May 2–3, 1996, Ames, Iowa. *Abstracts due January 17, 1996.* Information: Kenneth E. Windom, Dept. of Geological and Atmospheric Sciences, Iowa State University, 253 Science I Bldg., Ames, IA 50011; (515) 294-2430.

North American Paleontological Convention, June 9–12, 1996, Washington, D.C. *Abstracts due January 19, 1996.* Information: NAPC-96, c/o Dept. of Paleobiology, National Museum of Natural History, Mail Stop 121, Smithsonian Institution, Washington, DC 20560.

Water Resources Data for Oklahoma, Water Year 1994

Records on both surface water and ground water in Oklahoma are contained in this two-volume annual report by R. L. Blazs, D. M. Walters, T. E. Coffey, D. K. White, D. L. Boyle, and J. F. Kerestes. The report consists of discharge records for 118 gaging stations; stage and contents for eight lakes or reservoirs; water quality for 47 gaging stations; 21 partial-record or miscellaneous streamflow stations and 28 ground-water sites. Also included are lists of discontinued surface-water discharge and water-quality sites. Data for the Arkansas River basin are given in volume 1 (461 pages), and data for the Red River basin are given in volume 2 (212 pages). The data in this report represent the part of the National Water Data System collected by the U.S. Geological Survey and cooperating State and federal agencies in Oklahoma.

Order Water-Data Report OK-94 from: U.S. Geological Survey, Water Resources Division, 202 N.W. 66th St., Bldg. 7, Oklahoma City, OK 73116; phone (405) 843-7570, fax 405-843-7712. A limited number of copies are available free of charge.

Industrial Minerals of the Midcontinent—Proceedings of the Midcontinent Industrial Minerals Workshop

The Midcontinent industrial minerals workshop brought together about 100 industry, government, and academic personnel to discuss the problems, options, and opportunities facing the conservation and utilization of industrial nonmetallic minerals and rocks. Edited and compiled by A. L. Bush and T. S. Hayes, this proceedings report combines verbatim transcripts of the discussions with a summation by the editors of the issues and options for action. The single most important issue and need was overwhelmingly deemed to be education—of the lay public, of the regulators, and of the environmental community. This 126-page USGS bulletin was prepared in cooperation with the U.S. Bureau of Mines and the state geological surveys of Arkansas, Illinois, Kansas, Kentucky, Missouri, Nebraska, and Oklahoma.

Order B-2111 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225. The price is $9; add 25% to the price for foreign shipment.

Historical Land-Use Changes and Potential Effects on Stream Disturbance in the Ozark Plateaus, Missouri

Prepared in cooperation with the Missouri Department of Conservation, this 95-page USGS open-file report was written by R. B. Jacobson and A. T. Primm.

Order OF 94-0333 from: U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225. The price is $4 for microfiche and $15.25 for a paper copy; add 25% to the price for foreign shipment.

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists and the Geological Society of America for permission to reprint the following abstracts of interest to Oklahoma geologists.

Late Paleozoic Migration of Basinal Fluids in the Basal Cambrian Aquifer, Arbuckle Mountains, Southern Oklahoma

TEREE CAMPBELL, GLENN BIXLER, ADITYA KAR, and *R. DOUGLAS ELMORE,* School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

Models for basinwide flow of orogenic/basinal fluids commonly relay on basal aquifers in the sedimentary section as important fluid pathways. Paleomagnetic and geochemical results from the Reagan Sandstone (Late Cambrian), the basal aquifer in the Paleozoic section, and the underlying Middle Cambrian Colbert Rhyolite Porphyry (525 Ma) provide information on the fluid pathways, the nature of the fluids, and the timing of migration in the Arbuckle Mountains. Samples of relatively unaltered Colbert rhyolite contain a magnetization that resides in magnetite and a fold test suggests the magnetization could be primary. The pole position for this magnetization plots close to poles from other units of similar age. In contrast, an altered zone at the top of the rhyolite and rhyolite clasts in the Reagan Sandstone contain a magnetization that resides in hematite. A conglomerate test indicates that this magnetization is secondary and a fold test suggests that it is synfolding and Late Paleozoic in age. This magnetization is interpreted as chemical in origin and related to migration of fluids which altered the conglomerate as well as the top of the rhyolite. Geochemical investigations are currently underway to determine the nature of the fluids and if they are related to basinal fluids which moved through the overlying Ordovician carbonates and caused geochemical alteration as well as acquisition of Late Paleozoic chemical magnetizations around the conduits for flow.

Reprinted as published in the American Association of Petroleum Geologists *1995 Annual Convention Official Program,* v. 4, p. 14A.

Basin-Wide Fluid Flow at Plate Boundaries, Major Fault Zones, and Thrust-Loading Settings: What Do the Data Tell Us

GERALD M. FRIEDMAN, Brooklyn College and Graduate School of the City University of New York, and Northeastern Science Foundation affiliated with Brooklyn College, CUNY, 15 Third St., Troy, NY 12181

Along plate boundaries, such as the Dead Sea transform, hydrothermal fluids form carbonates and evaporites. Modern dolomite from this boundary has a strontium-isotopic signature signifying that it derived from a volcanic mantle source. The extrusive magmatic subsurface source which provides on surface the heat (60°C) and saline fluids to form the dolomite also makes the Mg^{2+} available. The apparent age of the dolomite is >40,770 C-14 years. The dated carbon of the dolomite is inherited and much older than the dolomite which currently forms where the springs extrude. In the rock record near

major fault zones, such as in the Ordovician Arbuckle Group of Oklahoma, dolomitization of limestone occurs with enrichment in heavier carbon and oxygen isotopes. Hydrothermal fluids once again were responsible for dolomite formation.

Current concepts of basin-wide fluid flow still need to be tested. As an example, foreland basins are said to create favorable conditions for the migration of mineralizing fluids. In the northern Appalachians four thrust-loading episodes of deformation occurred which may have generated multiple brine migration. MVT mineralization and authigenic feldspar are considered diagenetic products of this migration. Yet if hot brines carried concentrations of elements that generate MVT minerals, like barite, then barium should be present in authigenic feldspar. Yet microprobe analysis shows the presence of barium in the cores of the detrital K-feldspar crystals and its absence in the authigenic overgrowths suggesting that the fluids responsible for authigenic K-feldspar may not have been the same that produced MVT mineralization; otherwise, enrichment in barium would have been expected in the overgrowths.

Brine-migration diagenesis is not well understood.

Reprinted as published in the American Association of Petroleum Geologists *1995 Annual Convention Official Program*, v. 4, p. 30A.

Clarifying Gabbro-Granite Relationships in the Wichita Mountains, Oklahoma

M. C. GILBERT and *J. P. HOGAN*, School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019

The eastern Wichita Mountains is a bimodal igneous terrane commonly displaying enigmatic relationships between gabbro and granite. Present structural-stratigraphic models show an older gabbroic substrate, consisting of a host Glen Mountains Layered Complex (GMLC) intruded by younger Roosevelt Gabbros, overlain by younger sheet granites (dominantly Mount Scott and Quanah). The Central Lowland, both a Quaternary and a Permian valley, is underlain by the GMLC. The eastern end of the Central Lowland is covered by Holocene sediments which obscure contact relations among the three closest outcrop units: Mount Scott Granite, Quanah Granite, and GMLC. This covered area is a geomorphic yoke between the Central Lowland and the Eastern Lowland. The Eastern Lowland is underlain by Carlton Rhyolite. Thus, spatial contact relations among key stratigraphic units are hidden in an area crucial to unraveling the magmatic relations. This area, incidently, is the location for a new Visitors' Center and Museum of the Wichita Mountains Wildlife Refuge.

Our proposal is to drill a core hole 100 m deep in this covered area of the "yoke" (sec. 24, T3N, R14W) for the purpose of (1) determining bedrock; (2) establishing contact relations; (3) relating valley morphology to bedrock (Permian and Quaternary effects); and (4) obtaining core for chemical and isotopic studies.

Reprinted as published in the Geological Society of America *1995 Abstracts with Programs*, v. 27, no. 3, p. 51.

Oxide Mineralogy of the Mount Scott Granite Drill Core, OK

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About 300 ft of continuous drill core was retrieved from the Cambrian Mount Scott Granite of the Southern Oklahoma Aulacogen. A magnetic susceptibility survey of the core revealed an order of magnitude increase in readings between 70 and 100 ft. This interval was isolated for detailed study including: (1) texture, (2) color, (3) fracture density, (4) magnetic susceptibility readings at 0.5 ft intervals, and (5) detailed petrography.

Fracture density, secondary mineralization, and alteration of primary magnetite to hematite are negatively correlated with magnetic susceptibility as a function of depth. Within the interval of 70–100 ft below the surface, magnetic susceptibility gradually increases from 2–5 mT to 25–28 mT and then remains relatively constant with depth. Exsolved primary titanomagnetite has been replaced by hematite and ilmentite (e.g., martite) between 0–75 ft. Between 75–95 ft the abundance of secondary hematite decreases, and its occurrence is restricted to magnetite grain boundaries and edges of fractures penetrating magnetite grains. Below 95 ft fracture density decrease markedly, magnetite exhibits minimal alteration, secondary hematite is scarce, and magnetic susceptibility readings are high (~28 mT) and stable.

The order of magnitude decrease in magnetic susceptibility of Mount Scott Granite reflects oxidation of primary titanomagnetite to secondary hematite as a result of fluid-rock interaction. Circulation of meteoric waters through this crystalline basement was controlled by brittle fractures and appears to have been restricted to depths less than 90 ft below the present erosional surface. The timing and extent of fluid movement remains to be determined.

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Petrology and Geochemistry of Cambrian Diabase and Gabbro in the Blue Creek Canyon Area, Wichita Mountains, Oklahoma

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Upper Precambrian–Cambrian igneous rocks in southwestern Oklahoma formed during initial stages in the development of the Southern Oklahoma aulacogen. The oldest igneous rocks are part of a layered mafic/ultramafic complex, which is intruded by a number of smaller, petrogenetically unrelated gabbros (Roosevelt Gabbros), These rocks are believed to predate emplacement of voluminous granites and rhyolites, which in turn are cut by widespread late diabase dikes. Several of these dikes cut rhyolite in the Blue Creek Canyon area, north of the main igneous exposures in the Wichita Mountains, and are associated with a hitherto unrecognized intrusion of medium-grained, ophitic, magnetite-bearing gabbro (Kimbell Gabbro) that is >400 m across. The gabbro contains large oikocrysts of fresh augite, but most of the igneous phases are heavily altered to prehnite, epidote, sericite, and other secondary minerals; olivine is pseudomorphed by bowlingite.

Major and some trace elements in the diabases and gabbro have been perturbed by the alteration, but immobile elements (e.g., Ti, Zr, Y, Nb, P) preserve igneous trends. Trace-element discrimination diagrams indicate affinities to other within-plate continental basalts. Augite compositions and the trace-element data show that the suite is transitional between tholeiitic and alkaline magma types and is similar to other late diabases from the Wichita province. The rocks are geochemically indistinguishable from the Roosevelt Gabbros, and the possibility should be considered that some of the latter may relate to the late diabases rather than to a pre-rhyolite episode of basic magmatism. Alternatively, both suites may reflect a single long-lasting period of basic magmatism that overlapped the acidic episode.

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Surface Exposures of the Blue Creek Canyon Fault, Slick Hills, Southern Oklahoma

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The Blue Creek Canyon fault (BCCf) is an oblique left lateral high angle reverse fault that forms part of the WNW-ESE trending Frontal fault zone, an area of transpressive Pennsylvanian deformation which separates the Wichita uplift and Anadarko basin in southwestern Oklahoma. The stratigraphic throw of the fault, to the southwest, means that the structure acts as an oblique back-thrust within the zone. The fault is only exposed in Blue Creek Canyon where it trends approximately north-south, a ~40° clockwise rotation from the regional subsurface trends seen to north and south of the canyon.

In Blue Creek Canyon the BCCf is a braided fault complex composed of four major faults that have a combined stratigraphic throw to the west of ~3,000 ft (915 m). Signature indicators of a reverse component and an east-west compression include associated approximately N-S trending fold axes: the Blue Creek Canyon syncline, Blue Creek anticline, Paradox anticline. Other indicators include a reverse dip on fault planes and the orientation of minor normal faults in the hanging wall of the BCCf. A component of left-lateral displacement is suggested by the following kinematic indicators: drag features in the bedding of Cambro–Ordovician carbonates within the fault zone; sigmoidal sheer arrays; slickensides and gouges in exposed fault planes.

In a regional context, most structures in the Slick Hills trend N40°–N60°W. These N40°–N60°W trends have been interpreted as a response to a regional N50°E compressive stress (e.g., Donovan, R. N., 1986). The anomalous trend of a variety of strain indicators within Blue Creek Canyon implies a local reorientation of stress. A possible reason for this is the Pennsylvanian rejuvenation of a pre-existing zone of weakness. Evidence for the existence of such a weakness is not conclusive but includes the occurrence of approximately north-south pre–upper Cambrian faults and fractures in the basement of the Wichita uplift and geomorphology of the upper Cambrian landsurface in Blue Creek Canyon which shows a gorge that may record Cambrian erosion along a preexisting fault line.

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The Structural Geology of an Unnamed Hill South of Bally Mountain, Western Slick Hills, Southwest Oklahoma

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The Slick Hills of southern Oklahoma are the exposed portion of the WNW-ESE trending Frontal fault zone, an area of transpressive Pennsylvanian deformation which separates the Wichita uplift and Anadarko basin in southwestern Oklahoma. The Blue Creek Canyon fault, an oblique left lateral high angle reverse fault, separates the Slick Hills into eastern and western portions. The stratigraphic downthrow of the fault, from ~1,500–8,000 ft to the southwest, means that the structure acts as an oblique back-thrust within the zone. The Slick Hills are geologically recently exhumed relief of Permian age, presently consisting of deformed Cambro–Ordovician carbonates and underlying late Cambrian igneous basement, surrounded by a veneer of relatively undeformed Permian sedimentary rocks. Here we describe the structural geology of an

isolated and unnamed hill that is located at the northwestern periphery of the western Slick Hills immediately south of the subsurface trace of the Blue Creek Canyon fault. The results of our study are presented as a reconnaissance structure map on an air photograph base at a scale of 1:2,400, accompanied by cross sections. Data collected in the field include the orientations of numerous fold axes, bedding surfaces, fractures, stylolites, veins, and faults. Field-collected fracture data are compared with lineament data derived from air photographs. The air photographs were analyzed by the use of integrated computer graphics software. These data are compared with similar data for other parts of the Slick Hills.

The structures exposed on the unnamed hill are essentially similar in both style and orientation to those found elsewhere in the Slick Hills. In a regional context, most compressive structures in the Slick Hills trend N40°–N60°W. These N40°–N60°W trends have been interpreted as a response to a regional N50°E compressive stress (e.g., Donovan, R. N., 1986). The Lower Ordovician carbonates (Arbuckle Group) exposed on the unnamed hill appear to have deformed under a similar stress regime. The most obvious features are parallel folds, reflecting the basic anisotrophy of this thick sequence of thinly bedded carbonates. Most folds are upright, exhibiting smi-chevron profiles. Space problems in the folds are accommodated by extensive bedding-parallel faulting as well as pressure solution cleavage. Fracture patterns reflect local fracturing, related to fold bends as well as a regional pattern of extension, as suggested by tension fractures oriented ~040–050.

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Structural Controls of Holocene Reactivation of the Meers Fault, Southwestern Oklahoma, from Magnetic Studies

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Holocene reactivation of the aseismic Meers fault in southwestern Oklahoma illustrates the limitation of using the historical seismic record for identifying hazardous faults in the central United States. The 26- to 37-km-long fault scarp is one of the few known scarps recording Holocene movement in the central and eastern United States. Two documented late Holocene slip events, each with about 2.5 m of net slip and estimated M. ranging from 6¾ to 7¼, identify the Meers fault as a potentially hazardous fault.

During Carboniferous and Early Permian tectonism, the Meers fault displaced rocks of sharply contrasting magnetic properties. Analysis of aeromagnetic data and twelve ground-magnetic profiles provides a detailed look at the fault within the magnetic basement. Because subsequent reactivation has been minor and of an opposite sense, the pronounced magnetic anomaly associated with the Meers fault reflects Paleozoic structures in the magnetic basement. The location of the Holocene fault scarp corresponds to the strong horizontal magnetic gradient caused by Paleozoic offset of magnetic basement, indicating that the Paleozoic fault controlled Holocene displacement. Two features apparent in both sets of magnetic data are splays of the Meers fault northwest of the Holocene scarp and dikelike bodies immediately south of the fault.

Magnetic susceptibility measurements and rock magnetic data from unoriented core penetrating a dikelike body were incorporated into models of the ground-magnetic profiles. In most cases, secondary faults mapped or visible on low-sun-angle photographs correspond to faults modeled from magnetic data. This correlation shows that preexisting structures probably controlled secondary faulting. However, secondary faults at the southeastern end of the 26-km long continuous fault scarp, previously interpreted from low-sun-angle photography, are not apparent in the magnetic data.

Of importance to seismic hazard evaluation, the magnetic models show that the northwestern splays probably begin at the northwestern end of the reactivated segment and may indicate a persistent rupture propagation barrier to the west. In addition, the models show the dip of the Meers fault to be nearly vertical to about 0.5 km depth. This dip is consistent with the nearly straight fault trace, results of trenching studies, interpretation of shallow seismic-reflection data, and regional gravity and aeromagnetic models. In the present-day strike-slip regional stress field, the observed up-to-the-north Holocene displacement suggests that either the fault continues to dip steeply at depth or the regional stress field is approaching a normal-faulting stress regime. If the former is true, the scarcity of near-vertical faults with similar orientation within the area of the southern Oklahoma aulacogen implies that few are likely candidates for reactivation.

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Hydrocarbon-Induced Diagenetic Aureoles (HIDA): Indicators of Deeper Leaky Reservoirs

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The Permian redbeds that overlie some giant oil fields in southwestern and south-central Oklahoma have undergone extensive mineralogical and chemical diagenesis. The diagenetic minerals occur within a distinctly zoned aureole that delineates the position of the oil field. The geometries of the aureoles strongly reflect the major structural elements that controlled emplacement of hydrocarbons in the underlying rocks. Calcite, ferroan calcite, manganese-rich calcite, dolomite, ankerite, pyrite, and native sulfur are the major diagenetic minerals. The innermost zone of the aureole (zone 1) is characterized by abundant carbonate cementation and generally coincides with a major fault system. Zone 2 is composed of altered (bleached) redbeds with minimal calcite cement. Pyrite cement (zone 3) is commonly associated with the carbonate-cemented zones and is disseminated in some bleached sandstones. Zone 4 represents the unaltered redbeds.

δC^{13} values of carbonate cements indicate 3 major sources of carbon: (1) an organic source with δC^{13} values approximately −32‰ vs. PDB, (2) a freshwater source with an average δC^{13} value of −8 ± 3‰, and (3) a hybrid source (freshwater and organic). A mixing model was developed to calculate the proportion of organic carbon in carbonate cement.

δS^{34} values of pyrite average 6.1‰ and range from −9‰ to +16‰. The isotopic composition of sulfides is similar to that of oil in the underlying reservoirs. Formation of diagenetic pyrite is explained by reduction of iron oxides in redbeds by hydrogen sulfide or other organic material associated with hydrocarbons.

Gas chromatography and isotopic analysis suggests oils in the shallow Permian sandstones in Cement field located from deeper Pennsylvanian reservoirs. Leakage from deeper hydrocarbon-bearing reservoirs formed shallow petroleum accumulations and contributed to the alteration of the redbeds. Faults were the likely conduits that carried leaked hydrocarbons to the shallow rocks.

The development of the oil fields with alteration halos indicate that the HIDA can be used to identify potential shallow oil and deep gas accumulations. Therefore, the HIDA concept can be used in the exploration for oil and gas, especially in faulted structural settings.

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Early Pennsylvanian Wrenching Along the Red River–Matador Arch: Formation of a Pull-Apart Basin, Depocenter for Atokan to Lower Des Moines (Bend) Clastics, Cottle County, Texas

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Early Pennsylvanian wrenching along the Red River–Matador Arch (Tectonic Zone) created a braided series of en echelon faults and folds with associated pop-up structures and pull-apart basins. Local extension, or overstepping, in southeast Cottle County, Texas, has produced the deepest pull-apart basin along the arch with over 10,000 ft of structural relief. The emerging Wichita-Amarillo Uplift, to the north, provided an abundant sediment source, which prograded rapidly southward as an alluvial fan-braided river complex. Exposure of basement rocks and lower Paleozoic sediments along the Red River–Matador Arch also contributed to the basin fill.

Syntectonic sedimentation led to the accumulation of over 6,000 ft of Bend (Atoka–lower Des Moines) sediments within the basin. Deposition was dominated initially by alluvial fan to fluvial siliciclastics. As basin subsidence was further amplified by sediment loading, accommodation exceeded sedimentation capturing a large segment of the southward prograding Wichita-Amarillo derived clastic wedge. Encroachment of the late Atoka to lower Des Moines epeiric sea promoted further evolution of depositional environments to fan deltas, marine dominated clastics and, later, localized carbonate development. Type III kerogen rich organic shales produced abundant gas prone source rocks. The extreme depth of the basin combined with the local geothermal gradient provided for significant hydrocarbon generation.

By early 1988 new well control helped revise previous stratigraphic correlation demonstrating a rapidly expanding lower Des Moines to Atokan section. The drilling of the Gunn Oil Company–Brothers #1 to a total depth of 10,301 ft in the Mississippian Chappel Limestone, encountered 2,025 ft of Bend sediments, with 279 ft of gross Bend Conglomerate (162 ft of net pay). The Brothers #1 was potentialled on 11/19/89 with a CAOF of 6.0 MMCFD and filed as the field discovery for the Broken Bone (Bend Conglomerate) field.

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Project CRATON: A Multi-Discipline Study of the U.S. Continental Interior

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COCORP, Lithoprobe, and other deep reflection profiles over the past several years have explored significant parts of the Cordillerian and Appalachian orogenic belts of North America, and have made important contributions to understanding crustal evolution and the architecture of these Phanerozoic orogens. In contrast, large parts of the U.S. midcontinent basement remain unexplored beneath the masking veneer of Phanerozoic strata. Some features of the midcontinent have locally been studied intently, such as the Keweenawan Rift beneath Lake Superior as revealed on GLIMPCE profiles; however, the basement structures associated with accretion and stabilization of Precambrian continental crust, as well as the structural underpinnings of the Phanerozoic intra-cratonic basins and their fundamental mechanisms of formation, are not known.

The role of basement reactivation, if any, in the formation and evolution of intracratonic basins and other structures in the Phanerozoic rocks is commonly debated; but, without substantive information about the structure and evolution of the continental crust beneath, such debate is largely pedantic. Project CRATON addresses this fundamental lack of knowledge by both compiling/reanalyzing existing data sets and collecting new geological and geophysical data along strategic transects of the U.S. midcontinent, cored by new deep seismic profiles.

COCORP profiles, together with reprocessed industrial reflection data, already have begun to reveal important structural features that lie hidden beneath the midcontinent. Large parts of the midcontinent (i.e., southern Indiana and Illinois, southwestern Ohio, and southwest Oklahoma and adjacent Texas) are underlain by layered Precambrian rocks that represent unexplored sedimentary/volcanic sequences. The extent, nature, and correlation of these sequences, however, remains to be resolved. Also, existing data reveal the clear potential for identifying and mapping major crustal structures and tectonic boundaries across the region. The Grenville Front and its characteristic deeply penetrating zone of dipping reflections can be correlated over 100's of kilometers on COCORP and GLIMPCE data. COCORP profiles in eastern Montana and North Dakota across the Williston Basin and the underlying early Proterozoic Trans-Hudson orogen reveal a crustal-scale structure that is remarkably similar to that observed across this orogen farther north in Canada on LITHOPROBE profiles.

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