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Petroleum Migration Through Basement in Southwest Oklahoma, U.S.A.

ABSTRACT

Hydrocarbon occurrences hosted both in Cambrian igneous rocks and in Lower Permian clastic sedimentary rocks surrounding the Wichita Mountains are anomalous for lack of obvious local hydrocarbon source rocks. Study of the petrology and geochemistry of three occurrences, one newly established, shows that they have similar sources which are likely linked to the well-known Late Devonian–Early Mississippian Woodford Shale of the Anadarko Basin. Consideration of the structural setting of the Wichita Mountains area indicates where the source Woodford Shale must be located. The location suggests that vertical oil migration pathways would have to traverse through kilometers of igneous rock. Available evidence indicates some of this migration is Quaternary and still occurring.

INTRODUCTION

Oil seeps are common in Oklahoma (Jordan, 1964). Most seem to have had flow paths from sources to the surface through sedimentary rock sections. Southwestern Oklahoma has many small oil fields producing from thin Permian reservoirs overlying parts of the Ancestral Rockies Wichita Uplift (Boyd, 2002). This Uplift includes parts of the igneous basement represented by the Cambrian Southern Oklahoma Aulacogen (Campbell et al., 1988). In this report, we discuss the connections among an active oil seep on the Fort Sill Military Reservation, oil being produced from the nearby shallow Lawton oil field, and a recently recognized paleoseep along Oklahoma Highway 49 in fractured Mount Scott Granite (Figure 1). These hydrocarbon occurrences likely have a common origin in source regions in the deeper parts of the adjacent Anadarko Basin. What is particularly fascinating is that the hydrocarbons characterizing these occurrences in the Wichita Mountains area must have traveled kilometers from their sources in order to exit at the surface at their present locations (Campbell et al., 1988; Campbell, 2007). Various organic geochemical tracers are used to suggest probable hydrocarbon sources and relationships.

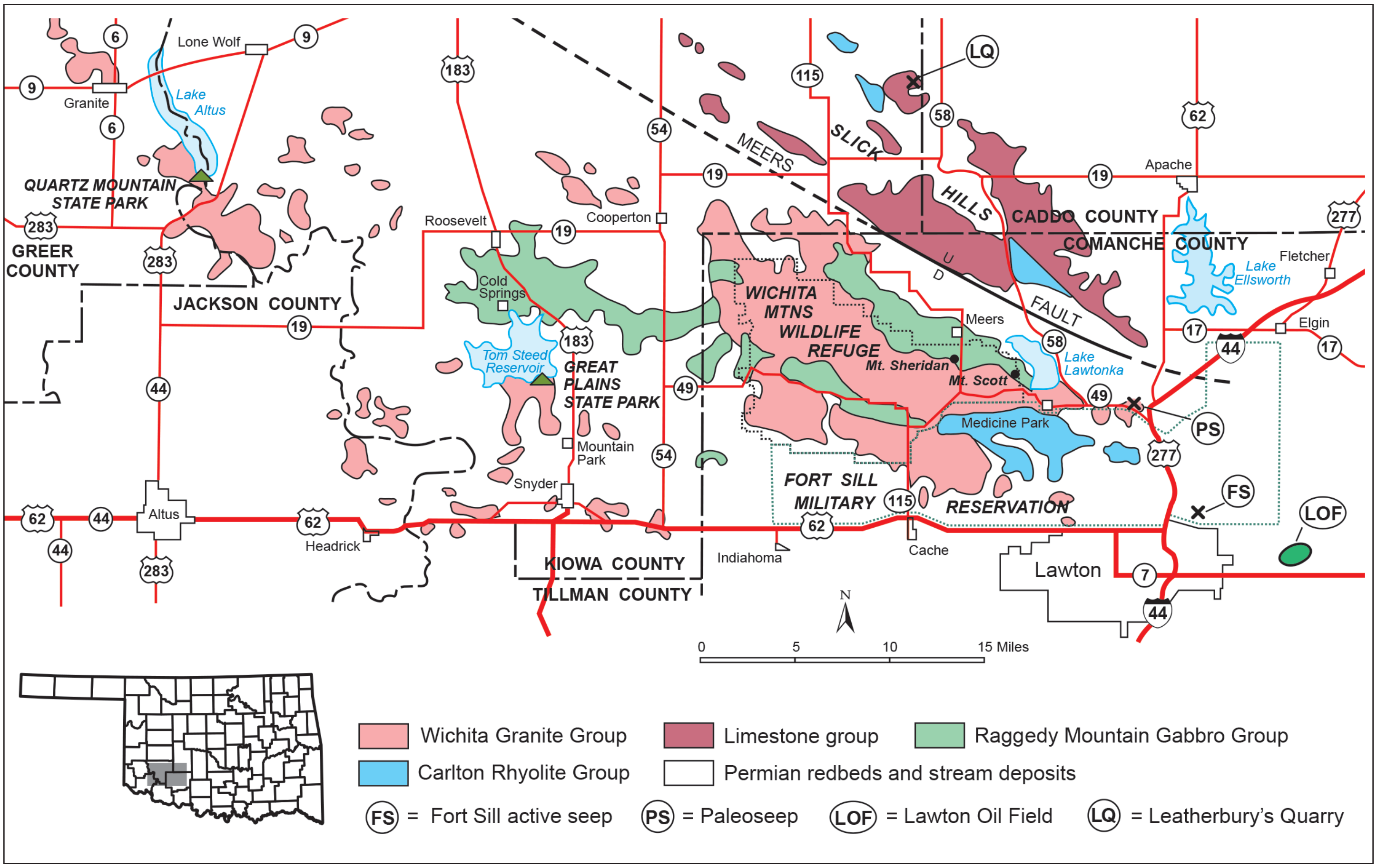


Figure 1: Map of the Wichita Mountains area with locations of sites referenced in the text. Diagram modified from Powell et al. (1980).

GEOLOGIC SETTING

A rift zone developed in southern Laurentia in the late Neo-Proterozoic-Early Cambrian. During this time, the previously existing supercontinent, Rodinia, was in the process of being dismembered. A large chunk of the Laurentian portion of this supercontinent was separated and rifted away, and is now found in the Precordillera of Argentina (Thomas et al., 2004). Two primary models exist for the rift zone, known as the Southern Oklahoma Aulacogen (SOA): one which treats the rift as an aulacogen (Hoffman et al., 1974), where the rift extends from a Dallas triple junction inward, and one which treats the rift as an inland extension of a transform (Thomas, 2011) as part of the plate breakup process. In any case, recent work (e.g., Larson et al., 1985; Keller and Stephenson, 2007; Soreghan et al., 2012) justifies carrying the rift zone continent-ward from about the Dallas area to the Uncompahgre Plateau, Colorado, area (Figure 2). The exposed eastern upper parts of this rift are in the Wichita Mountains, dominantly Cambrian volcanic and shallowly emplaced gabbros and granites (Ham et al., 1964; Gilbert and Donovan, 1982).

The area over the rift (SOA) in Oklahoma accumulated a substantial (4-5 km) thickness of sediments during subsequent continental plate marine transgressions from the Late Cambrian to the Mississippian. The Early Paleozoic units thicken regionally toward the rift axis, demonstrating that the rift area had become a basin axis. The resulting basinal section is known variously as the Oklahoma Basin, or proto-Anadarko (Johnson et al., 1988; Gilbert, 1992). The rift zone structure was inverted during the Pennsylvanian Wichita orogeny and became the pronounced uplifts of the easternmost Ancestral Rockies, dismembering the older, large, shallow intracontinental basin into a series of areally smaller basins, but with one deeper basin. This is the present Anadarko Basin. It became the deepest interior basin in the U.S. by the addition of about 7 km of Pennsylvanian and Permian sediments onto the middle and older Paleozoic units of the pre-existing Oklahoma Basin (Johnson et al., 1988). The old rift was thrust northward in the Pennsylvanian into the deepening Anadarko Basin (Brewer et al., 1983; Perry, 1989; McConnell, 1989).

Some of the deeply buried units, such as the Viola and Woodford, became principal sources of petroleum generation in Oklahoma (Johnson and Cardott, 1992; Wavrek, 1992). Petroleum generation has occurred since the late Pennsylvanian and seemingly throughout subsequent time. Hydrocarbon leakage to the surface in the Anadarko Basin has resulted in the famous Cement anomaly. There, in an area about 1½ by 4 km, the ferric iron coloring the redbeds at the surface has been reduced, yielding distinctly tan-gray shales, and gypsum beds converted to limestones (Donovan, 1974; Al-Shaieb, 1988).

Because of the strong Pennsylvanian rift inversion, the northern edge of the Wichita Uplift, which is also the southern edge of the Anadarko Basin, is marked by the dramatic Frontal Fault Zone (Figure 3) with over 12 km of vertical displacement (Ham et al., 1964; McConnell, 1989). Here, public records show that the Frontal Fault Zone, with the dominant feature being the Mountain View Fault, dips ~25-40° south, to a possible depth of 25 km, and thus basement is thrust north over Anadarko sedimentary units (Brewer et al., 1983; Campbell, 2007; Keller and Stephenson, 2007). This basement is the Cambrian igneous rocks of the rift, known in outcrop as the Wichita Igneous Province described by Powell et al. (1980).

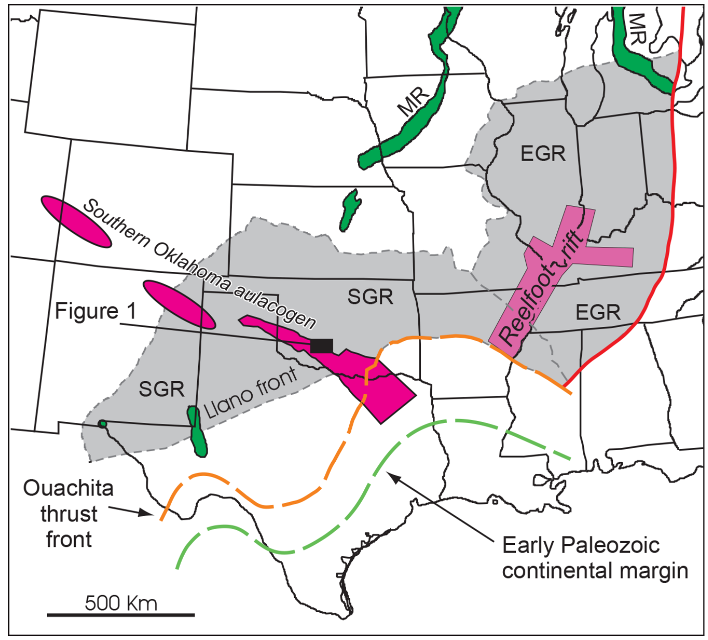


Figure 2: Prominent basement features of the Midcontinent United States. Extent and setting of the Cambrian Southern Oklahoma Aulacogen showing location of this study. MR is the 1.1Ga Midcontinent Rift; SGR and EGR are the southern and eastern Granite-Rhyolite Terranes. Diagram after Keller and Stephenson (2007).

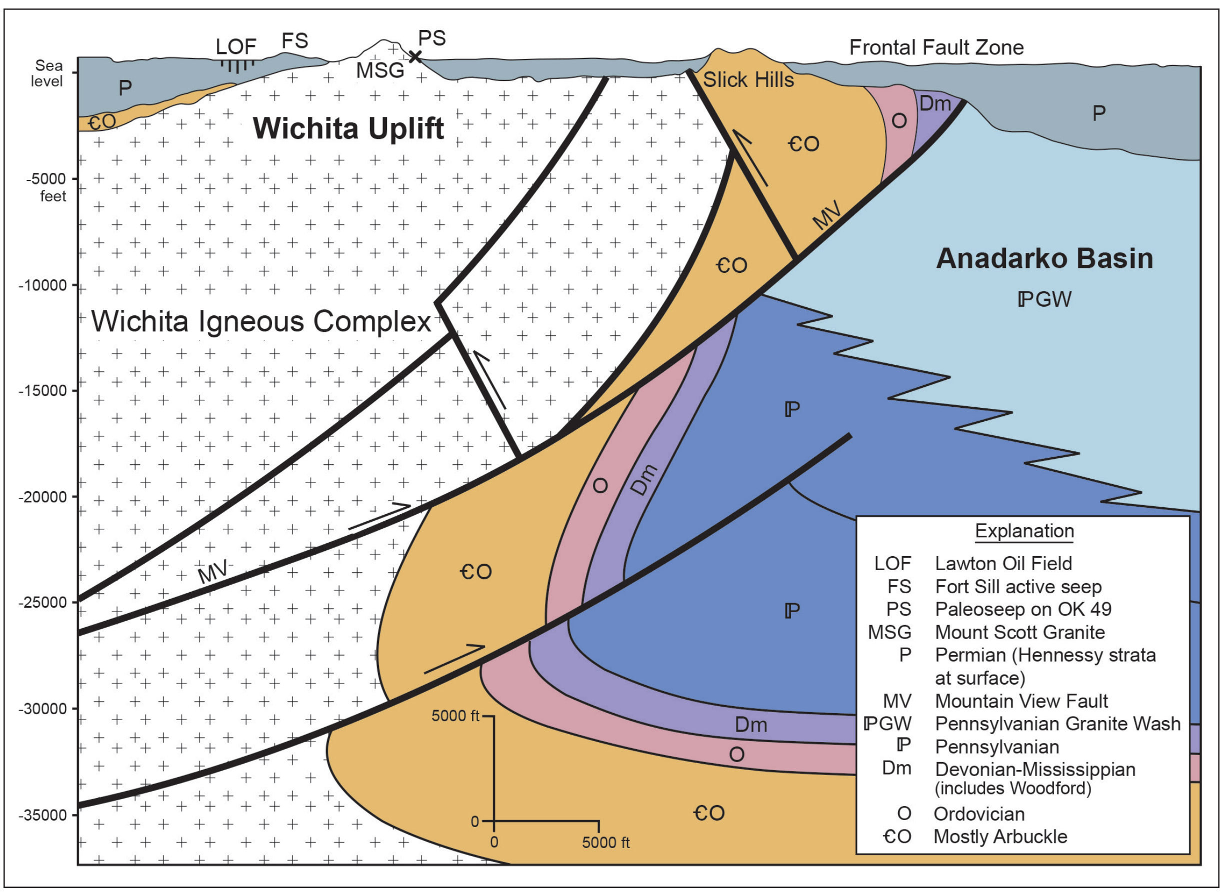


Figure 3: Generalized structure section nearest the study sites based on nearby sections of McConnell (1989) and Saxon (1998), geological reasoning in Coffman et al. (1986), and discussions with Andrew Cullen. The section is along a SSW-NNE line passing through the Fort Sill seep, with the Lawton oil field projected westerly to it, and the paleoseep projected easterly to it. Vertical and horizontal scales are equal.

By the early Permian, the Wichita uplifted blocks were deeply eroded, exposing the Cambrian igneous core of the rift and the Cambro-Ordovician Arbuckle Group limestones. In the later Permian, the Anadarko Basin, as well as the rift core, subsided (Soreghan et al., 2012). The Permian section continued to thicken with sediments derived outside this region, such as from the east (Ouachitas and Appalachians), burying the eroded Ancestral Rockies topography (Johnson et al., 1988; Soreghan et al., 2012; Templet, 2011). By middle Permian, Anadarko basinal sections had developed which covered and thinned over the rift zone's uplifted areas (Johnson et al., 1988).

The Permian units were deposited under arid conditions and are highly oxidized, yielding what are now called "Permian Redbeds". Perhaps ½ km of Permian strata were removed from the Wichita paleotopography in the late Cenozoic, leaving about ½ km or less still covering much of the rift core area (Campbell et al., 1988; for a somewhat different estimate of past covering thicknesses, see Winkler et al., 1999). The present Lawton oil reservoirs and the Fort Sill oil seep are in this thin Permian clastic section.

This Permian does not contain a significant potential petroleum source rock. Hydrocarbons that are being produced from the shallow Permian fields overlying Wichita basement, as well as the oil seeps/shows which exist or once existed, would seem to have had to originate in source rocks in the adjoining basins, especially the Anadarko Basin (Liu et al., 2016). Our study in the eastern Wichita Uplift area will concentrate on linking three sites: an existing oil seep (Fort Sill Military Reservation), the present nearby shallow Lawton oil field, and evidence of a past seep in the Cambrian igneous rock of the basement. Finally, what this likely means for the ultimate source of these signals and their migration paths will be discussed.

FORT SILL OIL SEEP

The Fort Sill oil seep has been known for some time (Wegemann and Howell, 1915) but had not been adequately characterized. The seep (Figures 4a,b) occurs on the top of Adams Hill on Fort Sill's east range about 3-4 miles (6 km) NW of the Lawton field. Fort Sill was established in 1869 and over time the site was extensively modified by the Army and probably by locals after settlement of this area in 1901. Consequently, how the seep appeared to Native Americans in its pristine natural state is unknown.

The bedrock for the Fort Sill seep and Lawton oil reservoirs is the Permian Hennessey Group (Leonardian) siltstones, shales and very local sandstones, commonly called Garber-Hennessey (Stanley and Miller, 2005; Havens, 1977). Interestingly, at the seep site, there are some thin layers of coal (Figure 5), unusual in the Permian of Oklahoma, with 24.4% ash and huminite reflectance of 0.28% Ro, suggesting a lignite. The sedimentary section at the seep only has about 150 m (approximately 500 feet) of Permian strata and possibly some Upper Cambrian Arbuckle Group limestone sitting on top of Lower Cambrian Wichita Carlton Rhyolite basement (Ham et al., 1964). Because the seep is at the top of a hill, it is clear that hydrologic conditions related to present topography do not determine its location. The pathway to the near surface is controlled by a deeper source, in this case, basement characteristics, the top of which is just about 500 feet below the surface.

The Hennessey surrounding the oil seep for several hundred meters is discolored, similar to the previously mentioned Cement anomaly, suggesting the hydrocarbon leakage is larger than just the oil seep itself and includes gas. Moreover there are numerous hydrocarbon shows scattered over the Lawton-Fort Sill area

Figure 4a: Drainage channel from the Fort Sill oil seep.

Figure 4b: Fort Sill oil seep.

Figure 5: Thin unnamed lignite bed along the side of the Fort Sill oil seep drainage channel.

showing that hydrocarbon leakage has been pervasive during the Quaternary (Wegemann and Howell, 1915).

From the seep, the basement surface (Cambrian-Permian unconformity) slopes southeast so that its depth under the Lawton field is ~400-500 m (1200-1500 feet) (Ham et al., 1964). The clastic reservoir depths of the field vary between 150-900 feet (45-275 m). The oils from the seep and from the Lawton oil field have now been studied and linked (Liu et al., 2016).

Geochemical characterization of the seep oil shows that it is very heavily biodegraded (Liu et al., 2016). All of the n-alkanes and isoprenoids have been removed, but the more resistant biomarkers, namely steranes and terpanes, are still present. Distribution of various sterane and terpane biomarkers, typically used for maturity measurements, suggest that the oil has been sourced from the Late Devonian–Early Mississippian Woodford Shale. The nearest location of this source is in the adjacent, deeper Anadarko Basin (Cardott, 1989).

LAWTON OIL FIELD

Oil and gas fields occur south, east, and north around the Wichita Uplift (Pritchett, 2015). The Lawton oil field (Lawton District in Pritchett, 2015) is an example of these and is the first studied geochemically (Liu et al., 2016). Boyd (2002) and Campbell et al. (1988) thought that many of these reservoirs were of Permian age. They wondered if there were mature hydrocarbon source rocks contained in the Permian sections. However, geological history and geochemistry indicate this could not be the case as will be argued shortly.

Liu et al. (2016) used Carbon isotopic data to demonstrate source similarity for these Lawton oil field oils with the Woodford Shale. The n-alkane distributions from reservoir oils are compatible with a marine origin, as are the steranes, and show minor biodegradation. Other markers such as dibenzothiophene/phenanthrene and pristane/phytane also eliminate other common potential source rocks. Hopane characteristics indicate that the oil seep and the

Lawton oils have a common source, and that the source was shale rather than carbonate. Thus, all data point to a Woodford source for the Lawton oil field oils, as well as for the active seep.

PALEOSEEPS IN THE WICHITA MOUNTAINS

Several earlier reports of paleoseeps in the Wichita basement have been briefly noted (Wegemann and Howell, 1915; Anderson, 1946; Merritt, 1958). These seep occurrences were either in the eastern Wichitas, or in granite quarried areas about 80 km west. The organic materials in the west were termed "asphaltite" and were recognized in miarolitic cavities in granite exposed during the quarrying operations. Miarolitic cavities are formed from gas exsolution during crystallization of magma. In granite systems, this is typically in the range of ~700-800°C, far above the stability of most hydrocarbons. Thus, these hydrocarbon occurrences must be secondary and reflect movement of hydrocarbons long after the emplacement and crystallization of the granites during the Early Cambrian. "Asphaltite" was also seen along fractures in the miarolitic granite. From this we can conclude that the petroleum migrated into the granite at a much later geologic time after the Cambrian emplacement and after the Pennsylvanian uplift when at least some of the fractures formed.

Donovan and Busbey (1991) described a small Permian cave with hydrocarbon deposits in the Ordovician Arbuckle limestone in the Slick Hills area of the eastern Wichita Uplift (Leatherbury Quarry). This area is about 28 km NW of the paleoseep discussed here (Figure 1). While in limestone, this section overlies the Cambrian igneous basement. This crustal block is on a Pennsylvanian thrust block of the Frontal Fault Zone (Figure 3). Donovan (1986) had earlier speculated that brine and hydrocarbons migrated into these Permian features from the Anadarko Basin. Donovan et al. (1992) have given a full report of the site's geology.

The newly recognized paleoseep occurrence is displayed on the north-facing rock wall along the south lane of the recently expanded State Highway 49 (Figure 6), just west of the intersection of OK 49 and I-44, often called the Medicine Park "Y". The excavation is in the Cambrian Mount Scott Granite. The granite from the nearby older, smaller, two-lane OK 49 roadcut was described in Gilbert and Donovan (1982, Stop 9). No evidence of the paleoseep was seen in the smaller, earlier roadcut at that time. However, that original roadcut must have been over 60 years old, and evidence for the seep, if it once existed there, would have been weathered (oxidized) away.

The paleoseep was recognized both from a mass of shiny bitumen filling a fracture cavity exposed by the recent excavation and by the dark coatings on the fracture surfaces of Mount Scott Granite over a distance of about 100 m along the roadcut face (Figures 6, 7, 8). The upper part of the granite roadcut, which is next to the modern landscape surface, has the "normal" yellow-red color of oxidized and exposed Wichita granites (Figure 6). The lower 2/3 of the outcrop face appears dark due to the thin films of chlorite (?) and organic material coating the fractured surfaces. It would appear that the upper part of the roadcut, which once must have been coated with bitumen, has had the organics weathered away, suggesting that evidence for hydrocarbon leakages might not last long once migration ceases.

Figure 6: Photo of the main roadcut in Cambrian Mount Scott Granite along OK 49 displaying the dark coatings on the fracture surfaces and a large mass of bitumen.

Interestingly, the roadcut face also exposes two highly altered mafic dikes: a vertical one near the east end of the face and a subhorizontal, bigger one to the west of the main darkened area. No evidence of these dikes existed in the old roadcut either. There is no evidence of magmatism after the Early Cambrian, so it is worth noting that these dikes are part of the Cambrian Wichita

Figure 7: Photo of the larger bitumen mass in Figure 7 as originally uncovered in 2001.

igneous event. Whether the dike conduits could have provided part of the pathway for the migration of the hydrocarbons to this level in the granites is unclear.

PETROLOGIC CHARACTERIZATION OF THIS PALEO-SEEP OCCURRENCE

The solid hydrocarbon masses first extracted from the new road-cut were shiny black bitumen. Bitumen is classified as organic matter that is soluble in organic solvents such as carbon disulphide. Bitumen that is insoluble in organic solvents is classified as pyrobitumen (Abraham, 1960). The terms solid bitumen (Curiale, 1986), solid hydrocarbon (Landis and Castano, 1994), and migrabitumen (Jacob, 1989) have been used to describe solidified bitumens, based on chemistry and petrography.

Under reflected white light in oil immersion at high magnification (500x), the mean random bitumen reflectance of the Mount Scott Granite bitumen is 0.05% Ro based on 10 measurements from 0.04-0.06% Ro. The sample has weak fluorescence and is partially soluble in immersion oil. According to the generic classification of Jacob (1989), the sample is classified as asphalt (random bitumen reflectance of 0.02-0.07% Ro) being the least mature solid hydrocarbon. According to the genetic classification of Curiale (1986), the sample is classified as a post-oil solid bitumen formed from the near-surface, low-temperature alteration of a once-liquid crude oil by biodegradation, water-washing and devolatilization.

GEOCHEMICAL COMPARISON OF THESE HYDROCARBON OCCURRENCES AND PROBABLE SOURCE

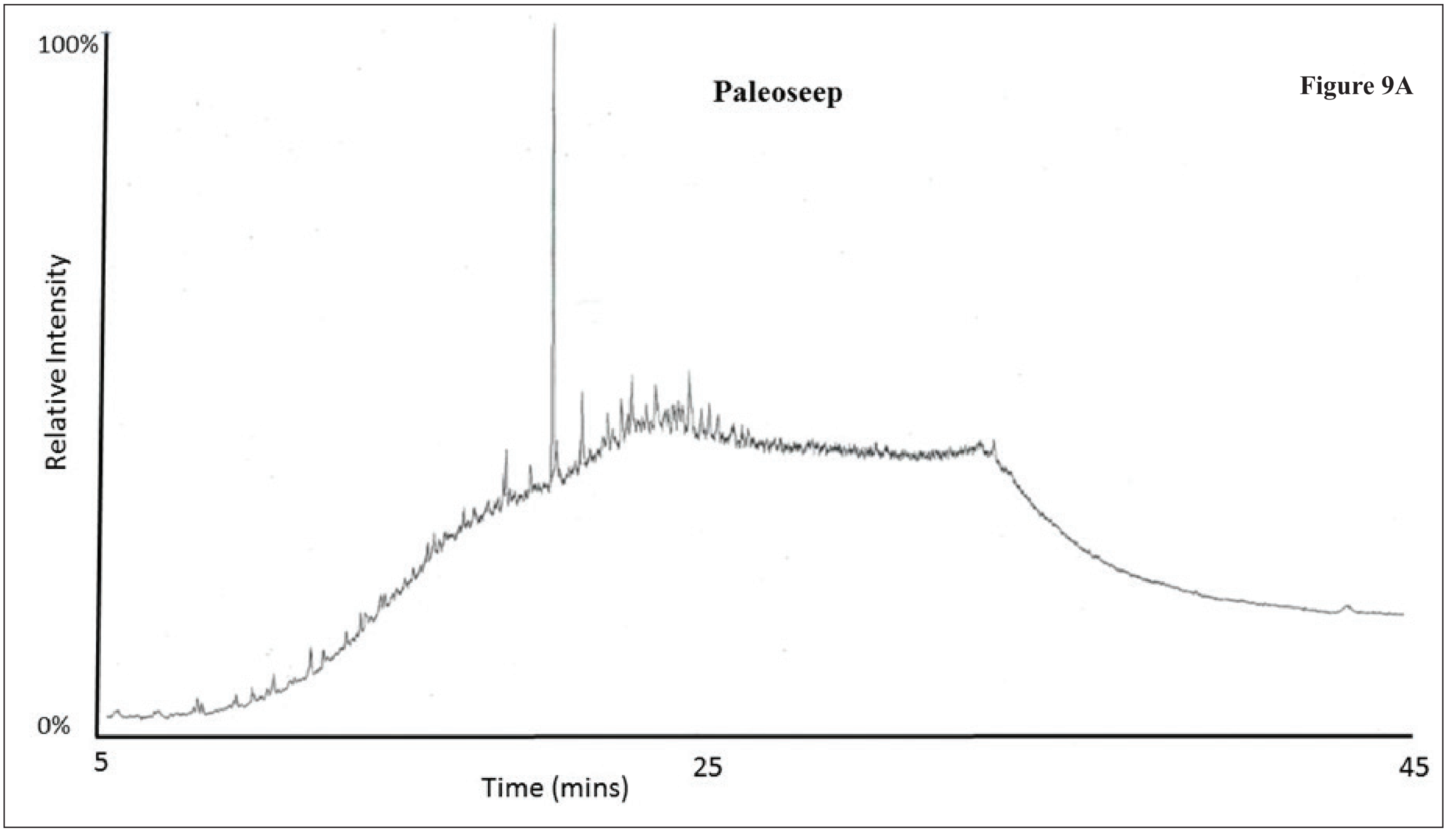
The Lawton oil field, Fort Sill seep, and the Highway 49 paleoseep show strong geochemical similarities after alteration effects are considered and removed. Liu et al. (2016) have argued convincingly that the hydrocarbons of the oil field and Fort Sill seep were generated from a similar source. Detailed geochemical characterization shows that the likely source was the Woodford Shale. The link of the paleoseep to the active Fort Sill seep and the

Figure 8: Bitumen along fractured surfaces of the Cambrian Mount Scott Granite.

Lawton oil field is discussed below.

The gas chromatogram of the paleoseep is shown in Figure 9A and, as anticipated, the paleoseep is biodegraded with a few of the more resistant biomarkers evident along the classic unresolved complex mixture (UCM) characteristic of a degraded sample. Chromatograms for the Fort Sill seep and an oil from the Lawton oil field are shown in Figure 9B. As described in Liu et al. (2016) the Fort Sill seep is heavily biodegraded and the Lawton oil shows only slight signs of degradation. The fact that two of these samples are degraded makes it futile to draw any conclusions about their relationship based simply on these chromatograms. More detailed examination of these three locations is necessary. The task is difficult because of the impact of biodegradation, not only on the n-alkanes but also on commonly used biomarkers such as steranes and terpanes.

The m/z 217 chromatograms that illustrate the distribution of steranes in the three samples are shown in Figure 10. Steranes in the Fort Sill seep have undergone extensive alteration and the major components are the more resistant diasteranes, along with the C30 regular steranes which have been shown in previous papers to be more resistant to biodegradation. The paleoseep signal might have been anticipated to be similar to the active seep, but is not; the steranes do not show signs of alteration. However, the paleoseep sample was recovered from a recent roadcut, so it



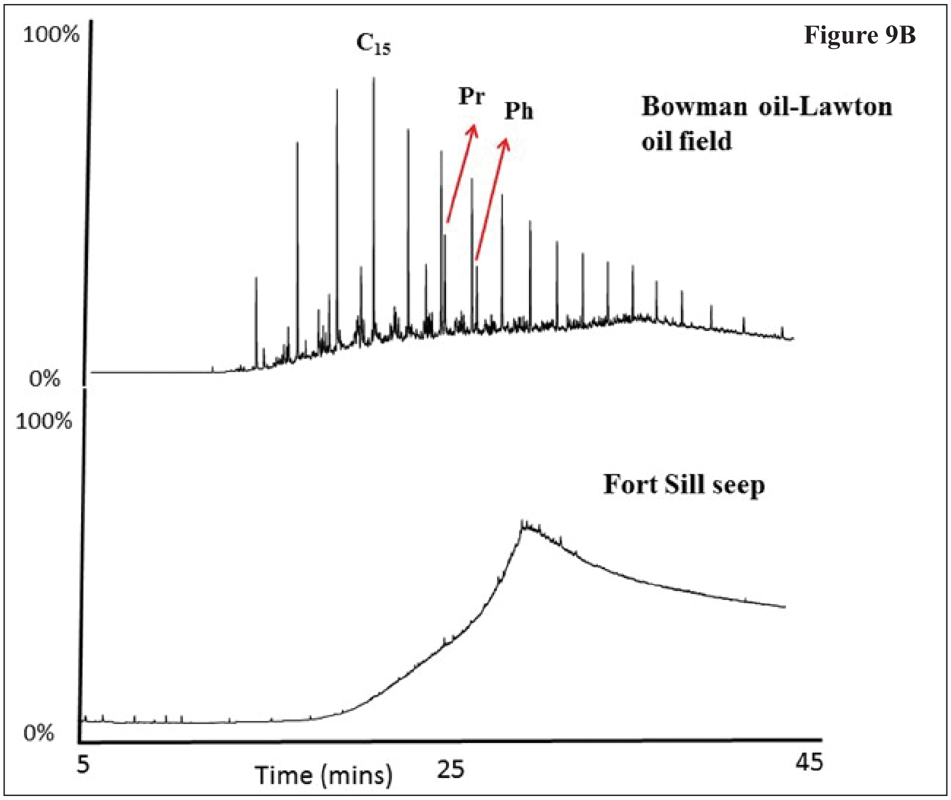


Figure 9: A. Gas chromatogram of the extract from the granite paleoseep. As expected the sample is heavily weathered and the chromatogram shows the absence of the readily degraded n-alkanes and isoprenoids; B. Gas chromatograms of a typical oil from the Lawton oil field and the Fort Sill seep. The oil is only lightly degraded and shows an abundance of n-alkanes and isoprenoids. The Fort Sill seep is extensively weathered and like the paleoseep all the n-alkanes and isoprenoids have been removed.

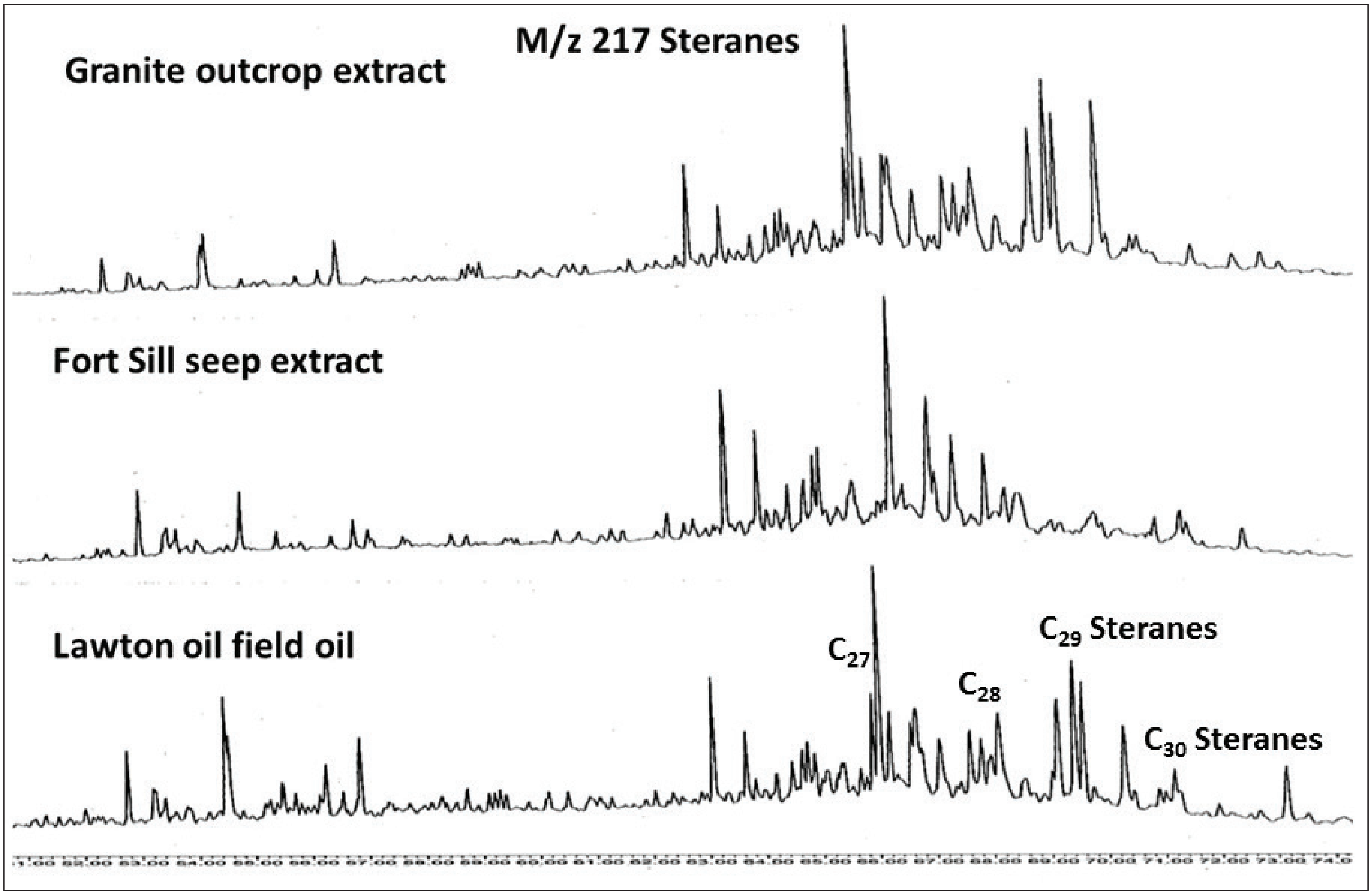


Figure 10: Chromatograms are shown here for the sterane distributions in three samples, the granite outcrop sample, the Fort Sill seep extract and an oil from the Lawton oil field. These distributions are determined by gas chromatography/mass spectrometry (GCMS) and single ion monitoring the ion at m/z 217. Some of the major compounds are identified but more importantly the distributions of the granite outcrop sample and the Lawton oil field sample are virtually identical, suggesting they are from the same source. The Fort Sill sample is heavily degraded and a number of the regular steranes have been removed following biodegradation.

is possible that prior to the excavation of the roadcut the sample was well preserved and there has not been sufficient time since the roadcut was exposed for alteration of the more resistant biomarkers to have taken place. This is different from the Fort Sill seep sample that has been exposed at the surface for a significant period of time, undergoing continuous degradation. The steranes of the paleoseep and Lawton oil field show a strong similarity. Steranes are basically source indicators and their similarity supports the fact that these samples are probably derived from the same or similar sources. Liu et al. (2016) previously established a relationship between the Lawton oil and the Fort Sill seep, and now this relationship can be extended to include the paleoseep. Further detailed examination of the relationships among these three occurrences follows.

Jiang et al. (1988) demonstrated that there are a series of degraded steranes present in many oils that are resistant to biodegradation and increase in relative concentration as oils are biodegraded. It is not clear whether these compounds are formed during early digenesis, or are a direct source input. However it does appear unlikely that they are products of biodegradation as discussed in the original paper (Jiang et al., 1988). However, these compounds are useful for correlation purposes. Figure 11 shows the distribution of one of the series of these degraded steranes for each location. Comparisons among these three chromatograms suggest fairly strong similarity, further strengthening the argument that these three samples are derived from the same source.

Further evidence for the same or similar sources of these three samples comes from the mono- and triaromatic steroid hydrocarbons shown in Figures 12 and 13 respectively. Aromatized steranes are far more resistant to biodegradation than the regular steranes and terpanes. When the chromatograms showing the distribution of these two classes of compounds are compared, the

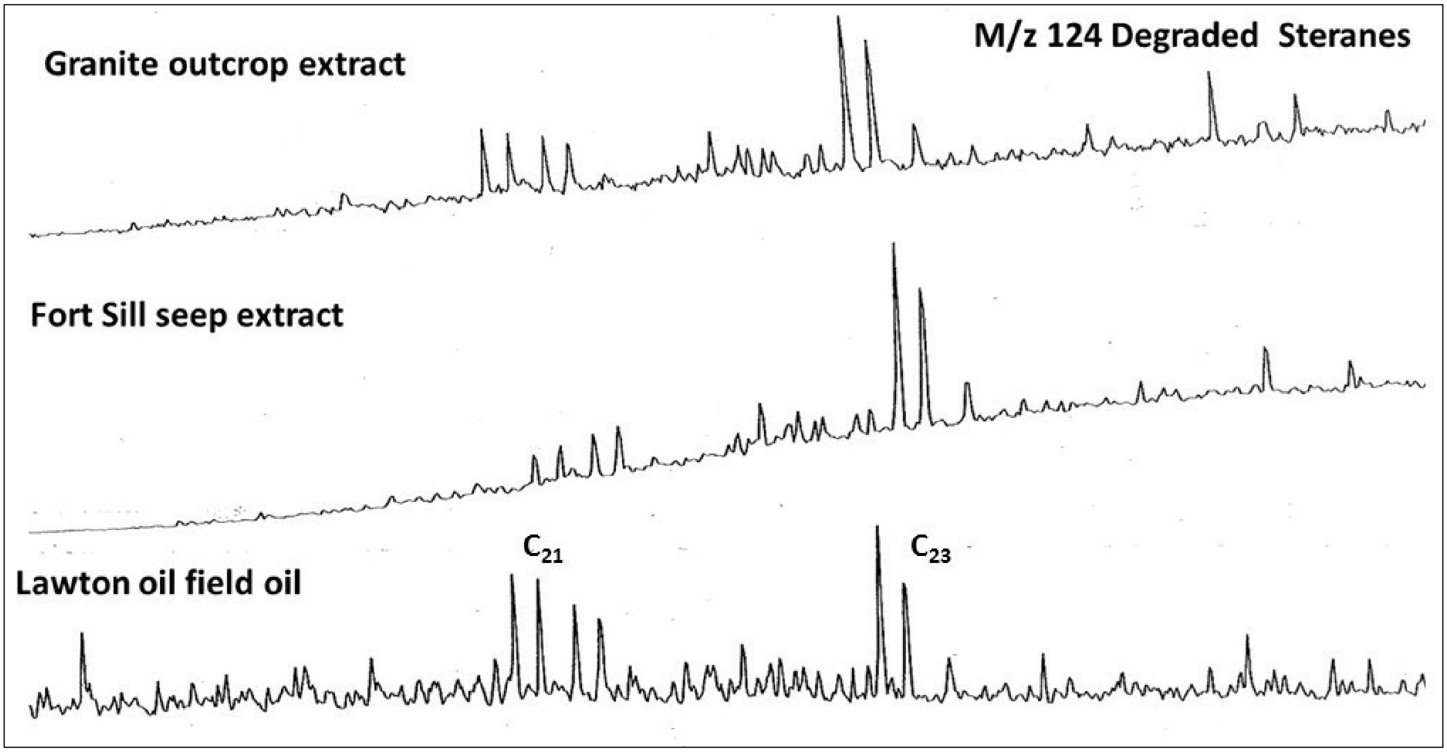


Figure 11. The chromatograms in this figure are from the same samples shown in Figure 10. The distributions here are of a family of degraded steranes that have not been unequivocally identified but their distributions are the same or very similar in all three samples. This supports the fact that all of these samples are derived from a similar source.

similarity between all three samples is clearly evident.

Another common class of compounds used for correlation purposes is the terpanes, comprised of both tricyclic and pentacyclic terpanes as shown in Figure 14. These compounds are also susceptible to biodegradation over the long term and the Liu et al. (2016) paper discusses the impact of biodegradation and mixing on the Lawton oils. In the Lawton oil and the Fort Sill samples, the hopanes have been altered and produced 25-norhopanes. These are also present in the paleoseep but in very low concentrations, again suggesting a lower level of degradation for the paleoseep for reasons given above. Alteration of the hopanes in all three samples makes it difficult to use them for correlation purposes, but despite the alteration, nothing in these chromatograms suggests that all three samples are not from the same or similar source.

Liu et al. (2016) showed that the Lawton oil field and the Fort Sill seep hydrocarbons are most typical of those from the Woodford Shale. Because the paleoseep hydrocarbons can be shown linked to these two active occurrences, it follows that Woodford Shale is also the likely source of the paleoseep hydrocarbons. Since the paleoseep occurrence is in fractured Cambrian Mount Scott Granite, and the other two occurrences are in thin stratigraphic sections of Permian lying unconformably on Cambrian igneous rocks, where is this probable Woodford Shale source located? Where could any source be located? We return to the structural setting of this area for the answer.

PROBABLE MIGRATION PATHWAYS

A somewhat diagrammatic structural cross-section was shown in Figure 3. The cross-section has been constructed to show the physical relations between the near-surface (LOF) and surface hydrocarbons (FS, PS) and possible source rock units, such as the Woodford. The Woodford Shale is not present in the Hollis Basin south of the Wichita Mountains (Amsden, 1975; Campbell and Northcutt, 2001). The Woodford and other possible sources are all buried beneath the Frontal Fault Zone, the leading edge of which is the Mountain View Fault. What is immediately clear is that there are no reasonable migration routes from the sources to these surface locales except through the overthrust block. The hydrocarbons must have passed through 4-8 km of igneous rock to reach their destinations. As depicted on Figure 3, the Woodford is in the gas window in thrust sheets below the Wichita Uplift. In addition, the Woodford could be in the oil window in shallower thrust sheets (see Cullen (2016) for compatible structural interpretations). The hydrocarbons may be using various pathways which would transect the igneous block, such as fractures and cross-faults generated during the Pennsylvanian thrusting, or perhaps

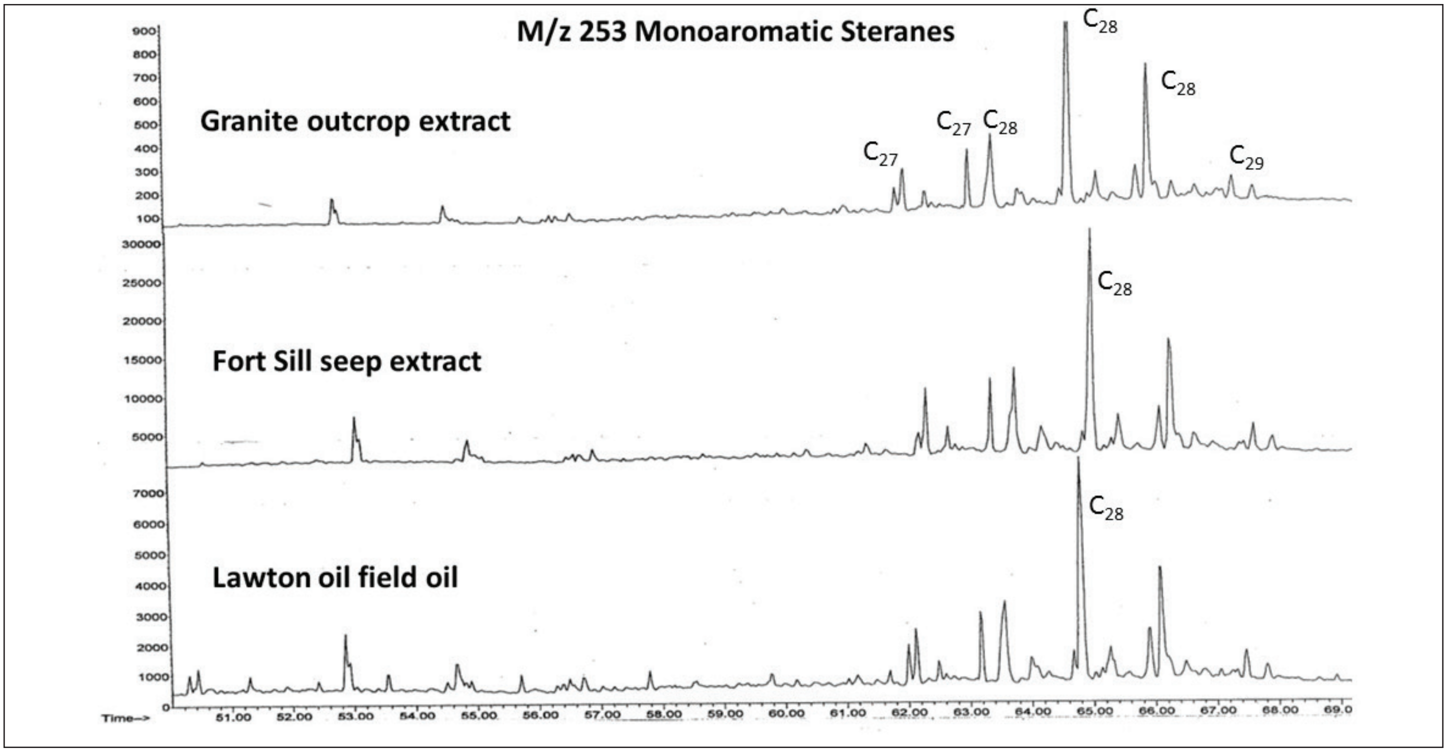


Figure 12. Monoaromatic steranes can be determined by GCMS and single ion monitoring of the ion at m/z 253. These compounds are resistant to biodegradation and when the three samples shown in Figure 10 are analyzed the distributions are again all very similar suggesting all three samples are derived from a similar source. Selected compounds are identified on the basis of their carbon numbers as indicated.

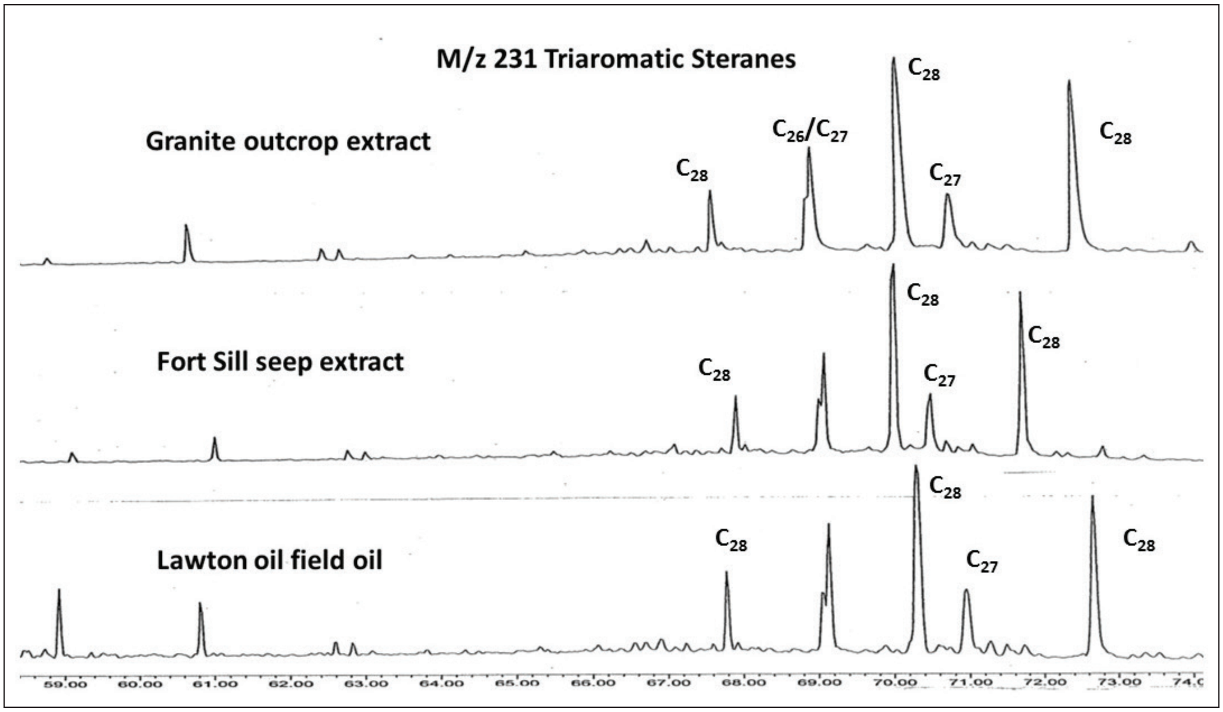
even older various cross-cutting Cambrian igneous intrusions as well as secondary igneous units, such as dikes. Reasoning from the Cement anomaly, where hydrocarbon leakage is directly over the reservoir and source rocks, we would expect our described locations to essentially be over their sources. Figure 15 shows the distribution of Permian hydrocarbon occurrences (seeps and fields) in Permian strata around the Wichitas. Those that are set back from the Frontal Fault Zone area potentially tracked source rocks buried beneath the thrust. Presumably, other occurrences not described here have similar sources and similar migration pathways.

It is also clear that hydrocarbon migration along the Permian unconformity from the subcrop edge of the buried Frontal Fault Zone, to these seeps and shallow fields, is not feasible. This unconformity surface is at a very low angle to the horizontal. There is no driving force for such a lateral migration. Finally, the Permian strata are too thin and permeable to hold fluid down for such a long lateral travel.

Lastly, what is also interesting is that there is no obvious chemical signal generated from the travel of hydrocarbons through the conduit igneous material. The igneous units are known from nearby outcrops to be gabbroic, granitic, and rhyolitic (Powell et al., 1980; Gilbert and Donovan, 1982). Hydrocarbons likely traveled through compositions ranging from mafic (~50 wt %SiO_2) to silicic (~70-75 wt % SiO_2). The dominant mineral group in these rocks is feldspar, Ca-rich plagioclase to K+Na-rich orthoclase. It was a "clean" travel path that did not directly contaminate the hydrocarbons.

Finally, how old is the paleoseep? The hydrocarbons are situated on the granite fractures which are mostly due to the Pennsylvanian tectonism. So the occurrence is younger than the fractures. Figure 6 shows the bitumen and hydrocarbon staining of the fractures does not now reach the ground surface, indicating that the seep has been inactive long enough for modern weathering to oxidize the very near surface hydrocarbons. But the topographic surface has a complicated history. General features of the regional topography are a paleotopography generated in the Permian as it was being buried in the Permian. The Permian cover is now being stripped away, and this process has been going on for about the last 20 Ma (Johnson, 1989; Gilbert, 2014). Nevertheless, the immediate ground surface and thin soil above the paleoseep is essentially Quaternary. The deposit conforms to the Quaternary features of the outcrop. Thus the paleoseep is not geologically old, but probably Quaternary. This is consistent with Liu et al. (2016) who show that the Lawton oil field is currently being recharged. Hydrocarbons have moved up, and are moving up from their sources.

Figure 13. Triaromatic steranes can be determined by GCMS and single ion monitoring of the ion at m/z 231. These compounds are also resistant to biodegradation and when the three samples shown in Figure 10 are analyzed for triaromatic steranes the distributions are again all very similar suggesting all three samples are derived from a similar source. Selected compounds are identified on the basis of their carbon numbers as indicated.



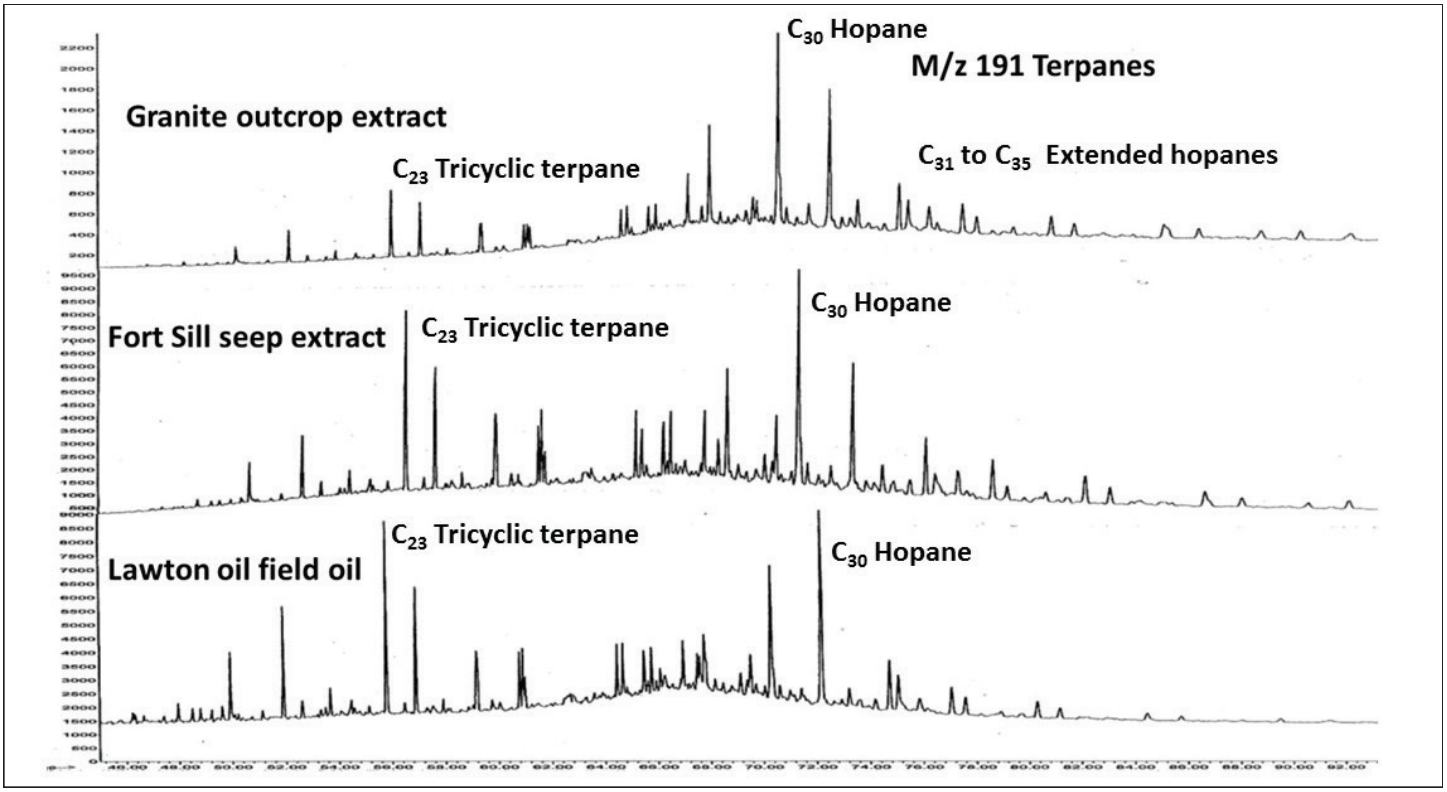


Figure 14. The chromatograms show the terpane distributions for the same three samples as shown in Figure 10. Selected compounds are identified with their carbon numbers. There are small differences in these chromatograms as a result of biodegradation and weathering, particularly in the case of the Fort Sill seep sample; however, in general these three chromatograms are all very similar, again supporting a common origin for all three samples.

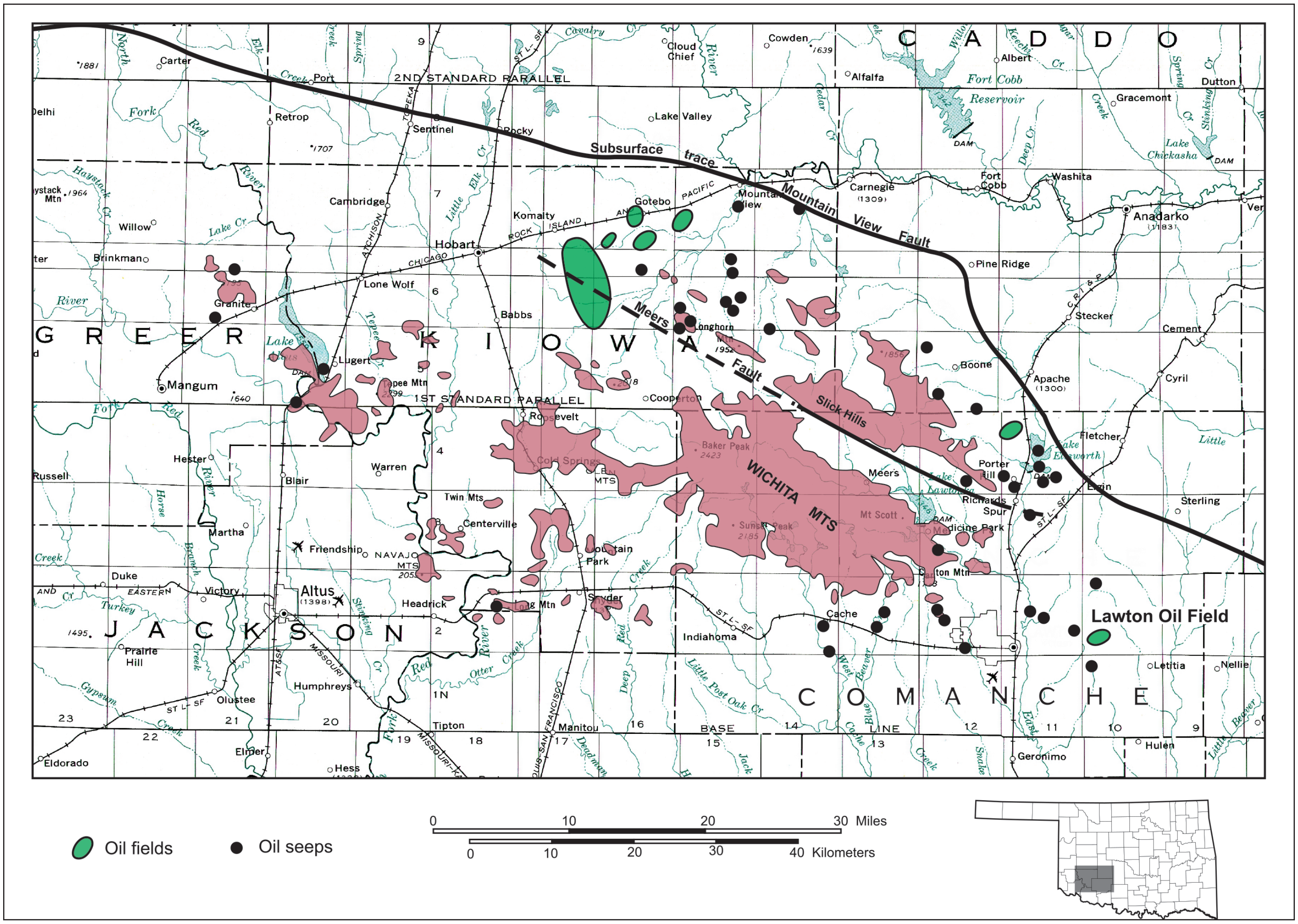


Figure 15: Distribution of hydrocarbon occurrences (seeps and small oil fields) around the eastern Wichitas from Jordan (1964).

CONCLUSIONS

The Lawton oil field hydrocarbons, the active Fort Sill seep, and the inactive paleoseep are genetically related, as indicated by their similar geochemistries. The most likely source is the Late Devonian-Early Mississippian Woodford Shale. The probable location of the Woodford is beneath the block of Cambrian Wichita Igneous Complex rocks thrust north over the Anadarko Basin and its stratigraphy in the Pennsylvanian.

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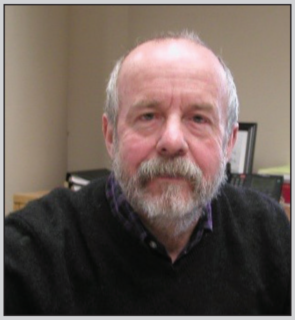
M. Charles Gilbert

Biographical Sketch

M. Charles Gilbert grew up in Lawton, OK, near the Wichita Mountains. His love of geology was nurtured by a Lawton High School geology class and by climbing around in the Wichitas. He graduated from OU with a B.S. in Geology in 1958 and an M.S. in 1960. The M.S. was a field study of the mafic igneous rocks near Roosevelt, OK, under Hugh Hunter. Graduate student colleagues in the study of these gabbroic rocks were Bill Hiss, Burke Spencer, and Dick Frech. Tim Denison provided a lot of useful interaction on the igneous relations. Subsequently, Gilbert went to UCLA for a Ph.D. (1965) under Gary Ernst with a lab-oriented experimental dissertation on hornblende stability and geochemistry. He also worked with Ernst on the Franciscan mélange of the California Coast Ranges and the Sanbagawa terrane in Japan. He spent three years as a Post-Doc at the Geophysical Laboratory of the Carnegie Institution of Washington in D.C., where he studied the stability relations of sodic pyroxenes, amphiboles, aluminum silicates, and iron olivine and magnetite. He spent 15 years teaching at Virginia Tech, seven years teaching at Texas A & M (with three years at the U.S .Dept of Energy, Basic Energy Sciences, in Germantown, MD), and 17 years teaching at OU (eight and one-half years as Director), retiring in 2007. He is now Professor Emeritus at the ConocoPhillips School of Geology & Geophysics.

He re-ignited his interest in the Wichitas in 1977-78 when on a sabbatical from Virginia Tech to the Oklahoma Geological Survey. The OGS has published three Guidebooks on the Wichitas related to Gilbert's work: Guidebook 21 (1954); Guidebook 23 (1986); and Guidebook 39 (2014). He has concentrated his research on the Wichitas since the 1977-78 period. At OU, he has had long-term interactions with professorial and Survey colleagues: Dave London, George Stone, Barry Weaver, Ze'ev Reches, Ken Johnson, Jock Campbell, Randy Keller, Lynn Soreghan, Neil Suneson, and the late Dave Stearns.



Dr. R. Paul Philp

Biographical Sketch

Dr. R. Paul Philp, Emeritus Professor of the University of Oklahoma, recently retired from OU's School of Geology and Geophysics, where he served as Professor of Petroleum and Environmental Geochemistry from 1987 to the end of 2015. Dr. Philp obtained a D. Sc. from the University of Sydney, Australia, in 1998, having obtained a Ph.D. from University of Sydney, Australia in 1972 and his B.Sc. from the University of Aberdeen, Scotland in 1968. He is a pioneer in the use of biomarkers in exploration and production, using geochemical techniques to characterize and correlate hydrocarbon-containing deposits. Recently he has developed the use of biomarkers to characterize detailed sequence stratigraphy in shales, a correlation especially important in drilling horizontal wells. He has published over 400 papers and presented numerous papers at national and international meetings.

Brian Cardott

Biographical Sketch

Brian Cardott has been an organic petrologist and coal geologist with the Oklahoma Geological Survey since 1981. His primary research involves gas shales and tight oil plays (primarily the Late Devonian–Early Mississippian Woodford Shale), coalbed methane, and the petrologic characterization of coals, hydrocarbon source rocks, and solid hydrocarbons (e.g., asphaltites and asphaltic pyrobitumens) of Oklahoma.

Brian has written more than 60 articles and books on coal, coalbed methane, gas shales, unconventional energy resources, hydrocarbon source rocks, solid hydrocarbons, organic weathering, vitrinite reflectance, and graptolite reflectance (http://wichita.ogs.ou.edu/staff/brian/).

Brian is a member of The Society for Organic Petrology (serving as President, 1995-1996), International Committee for Coal and Organic Petrology, American Association of Petroleum Geologists (serving as President of the Energy Minerals Division, 2004-2005), Geological Society of America, Oklahoma City Geological Society, and Tulsa Geological Society.