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Letter to Secretary of Energy O’Leary and Enclosure A

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March 6, 1993

Honorable Hazel Rollins O'Leary
Secretary of Energy
Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Madame Secretary:

A peer-reviewed paper published at the end of last year has extremely important policy implications. It reflects studies by Dr. Leigh Price, a creative USGS geologist/geochemist with a good track record of beating conventional wisdom, and Julie LeFever, a more conservative North Dakota state geologist. They identify a vast potential in-place crude oil resource base here in America which is currently omitted from all resource estimates. If that resource could be proven up, North Dakota alone might double our country's crude oil reserves.

Needless to say, this kind of potential is by no means a certainty and it requires attention, evaluation and development to translate into real jobs, production and proven resources that could profoundly affect our lives, assuming the idea is right on track. And some will insist that government simply can not stimulate exploration or production progress that the private sector has thus far missed.

The potential scale is so great, however, that I feel confident you will want to assure intense and urgent examination of Price and LeFever's extraordinary ideas, at your personal direction. As a first step, I enclose three documents: (a) my four-page summary of the studies and some implications for DoE; (b) the Price-LeFever article: "Does Bakken Horizontal Drilling Imply a Huge Oil-Resource Base in Fractured Shales?" in GEOLOGICAL STUDIES RELEVANT TO HORIZONTAL DRILLING: EXAMPLES FROM WESTERN NORTH AMERICA (Rocky Mtn. Assoc. of Geologists, Denver: 1992) 199-214; and (c) Price's current c.v.

I trust the Department would find interest in an unsolicited proposal to advance concepts for enhanced recovery of the Price-LeFever in-place oil resource base.

Best personal wishes.

Faithfully,

David J. Bardin

Enclosures

HAVE WE A VAST IN-PLACE U.S.A. OIL RESOURCE? [February1993]

Summary

- New studies and a peer-reviewed article by Leigh Price, USGS, and Julie LeFever, N.D. Geol. Survey, indicate that enormous crude oil resources wait to be tapped in North Dakota:
    * at least 100-150 billion barrels in place -- perhaps 250.
    * this resource is omitted from all current resource base estimates -- just as coal-bed methane used to be omitted as a gas resource until a couple of years ago.
- North Dakota alone may <u>double</u> the U.S.A. oil reserves.
    * Applying similar analyses across the U.S.A. may add several times the reserves of Saudi Arabia to potential crude oil resources for the lower-48 contiguous states.
- DoE needs to examine whether technology currently exists or can be readily developed to enable commercial production.
    * There is enormous job-generating potential at generally low environmental costs and risks.
    * There are extraordinary international strategic stakes.
- This is a very desirable, marketable crude oil, at accessible and environmentally-acceptable locations.
    * This is a 40-45° API gravity crude.
    * It is mobile and found at depths up to 10-11,000 feet.
    * It is not waxy and thus easily producible.
- Some has been produced already from non-optimum areas (but not in great quantities) despite use of production techniques inappropriate for the resource base.
- Much of the in-place oil could be produced -- in all probability -- but the well drilling and completion and production techniques, including pressure maintenance, have to be tailored to this resource, or operators will miss most of their opportunity, making many prospects uneconomical.
    * Like coal-bed methane, the correct techniques may be quite simple, yet seem radically innovative at first.
    * Each North Dakota well will cost hundreds of thousands of dollars. Recoverable reserves may be 1-5 million barrels per well or even more. However much remains to be tested and demonstrated.
- DoE could spark private and public sector attention and debate, and sponsor testing and demonstration projects.

1. <u>**Price & LeFever studies identify possible vast in-place oil resource bases**</u>

US Geological Survey senior geologist/geochemist Leigh Price and North Dakota Geological Survey geologist Julie LeFever have just published a peer-reviewed article suggesting enormous crude oil resources waiting to be tapped. "Does Bakken Horizontal Drilling Imply a Huge Oil-Resource Base in Fractured Shales?" in GEOLOGICAL STUDIES RELEVANT TO HORIZONTAL DRILLING: EXAMPLES FROM WESTERN NORTH AMERICA (Rocky Mtn. Assoc. of Geols., Denver: 1992) 199-214.

- Price is a senior research geologist at the USGS, Denver. He is a well-known, independent, controversial and daring thinker who has no fear of challenging accepted wisdom. Two previous challenges to accepted wisdom, which are now accepted paradigms, are:
  * ability of oil to migrate from source rocks to reservoir rocks in gas-phase solution;
  * non-local generation of oil, in the deeper parts of petroleum basins ("oil kitchens"), with extensive vertical and horizontal migration, to shallower reservoir rocks.
- Price's professional recognition includes several awards by the AAPG and regional geological associations and editorship of the Journal of Petroleum Geology in 1992.
- LeFever is a more conservative thinker in her state's government who is responsible for stimulating resource utilization.
- Price and LeFever have studied this resource for years.

2. <u>**Estimated size of North Dakota's Bakken shale resource**</u>

Focusing solely on North Dakota Williston Basin's Bakken shales, Price & LeFever estimate at least 100-150 billion barrels in place -- perhaps as much as 250 billion barrels.

- This in-place resource is omitted from all current resource base estimates -- just as coal-bed methane used to be omitted as a gas resource until a couple of years ago.
- If this North Dakota oil resource could be proven with a 20% recovery factor, we would add 20-30 billion barrels or more to -- and so double -- DoE/EIA's current estimate of 25 billion barrels of proven, remaining, recoverable crude oil for all of the United States combined (including Alaska)!
- DOE/EIA estimated that North Dakota's year-end 1991 proven, remaining recoverable crude oil was 232 <u>million</u> barrels -- perhaps 0.1% of the Price-LeFever in-place resource base.

3. Nature of North Dakota's Bakken shale crude oil resource

This in-place resource is a desirable commodity, readily marketable as soon as it can be commercially produced. It will displace oil imports, and thus could favorably and significantly impact the U.S.A. balance of payments.

- This 40-45° API gravity crude oil is an extremely desirable refinery feedstock.
- It will flow up the well bore. (This is not a synthetic fuel to be made by heating the shales. Past geologic heat flows have already made the oil.)
- It is found at depths up to 10-11,000 feet.
- Because it is not waxy, it is easily producible. It is mobile, and some has been produced already (but not in great quantities, only about 5 million barrels) despite the operators' use of technologies that reflect serious misunderstanding of and are inapproriate for the resource.
- The resource base exists in regionally interconnected fractured networks which should be highly amenable to sustained recovery using appropriate secondary oil recovery techniques -- which the DoE is already examining in a program seeking to exploit a part of some 76 billion barrels of the in-place conventional oil resource base.
- A significant portion of Bakken oil possibly could be produced -- but well drilling, completion, stimulation and production techniques, including pressure maintenance, have to be tailored to the non-conventional characteristics of the resource.
- Industry has spent roughly half a billion dollars on a horizontal drilling program in the Bakken shales without finding an effective, economical approach. These efforts concentrated on non-optimum portions of the Williston Basin and used drilling, completion, stimulation and production techniques quite inapplicable to the characteristics of this resource base.

4. What DoE should do

The issue which DoE needs to resolve is whether technology is already available -- or can be readily developed -- to enable commercial recovery of such in-place oil resources.

- Like coal-bed methane, the correct techniques may turn out to be quite simple, yet seem radically innovative at first.
- These North Dakota wells will only cost hundreds of thousands of dollars each. Recoverable reserves may be 1-5 million barrels per well or more. However much remains to be tested and demonstrated.
- There is an enormous job-generating potential associated with this resource base at generally-low environmental costs or

risks.

- There are extraordinary strategic stakes.

- Profound and responsible curiosity should impel DoE now.

- Affirmative findings might reverse the U.S.A.'s decline as a crude oil producer within a very few years.

- Even before significant production is achieved, just proving up a significant new petroleum province will be strategically important (as was North Sea, for example).

5. Implications beyond North Dakota

The potentials go well beyond North Dakota. Turning to what is known of the organic-rich source rocks and petroleum geochemistry of other basins, Price & LeFever speculate that in-place oil resources on the order of tens to hundreds of trillions of barrels may exist in the lower 48 contiguous states.

- If you assume ultimately proving up 10 trillion barrels in place with a 10% recovery factor, you would be considering one trillion barrels of recoverable oil.

- Current crude oil reserve estimates are 260 billion barrels for Saudi Arabia and close to one trillion barrels for the world as a whole.

6. Why this resource has been overlooked

The Bakken shale of North Dakota is, conveniently, one of the best known and most studied organic-rich source rocks in the world. Price and LeFever's extraordinary estimates reflect the following principal factors:

- Contrary to industry beliefs through the 1980s (formerly shared by Price), almost none of the oil in place in the North Dakota Bakken shales ever migrated from the shale ("primary migration") and none of the shallower conventional production in North Dakota has come from the Bakken shales.

- The Bakken shales contain much more oil than previously estimated. Past analyses of Bakken rock samples were misleading because most of the oil escaped into the drilling fluids as rock chips moved up the well bore and pressures dropped.

Petroleum geology deals in issues of great uncertainty and is still a developing field. Petroleum geochemistry is an even less exact science at this time. It often takes a long time for new ideas to get real attention and to take hold.

7. Conclusion

DoE can go far to accelerate evaluation and development of this resource by judicious, timely, efficient and persistent interest and a relatively modest level of effort.

Does Bakken Horizontal Drilling Imply a Huge Oil-Resource Base in Fractured Shales?

Leigh C. Price[1] and Julie A. LeFever[2]

[1]U.S. Geological Survey, Denver, Colorado
[2]North Dakota Geological Survey, Grand Forks, North Dakota

ABSTRACT

Previous assumptions regarding high efficiencies of primary petroleum migration from mature organic-rich source rocks appear invalid. These assumptions were based on large declines in Rock Eval hydrogen indices of source rocks with progressive burial, without equivalent increases in either Rock Eval S_1 peaks or Soxhlet-extractable hydrocarbons. Thus, it followed that the generated hydrocarbons must have escaped the source rocks by efficient primary migration. However, horizontal drilling in fractured, self-sourced shales shows that this is an erroneous hypothesis, because these shales contain high hydrocarbon concentrations. A better explanation for these missing hydrocarbons is that they were lost during recovery of rock samples from the bottom of the hole.

Basin richness for basins worldwide increases with intensity of faulting over and adjacent to basin deeps. Thus, faulting and fracturing of mature source rocks may be necessary for efficient expulsion of generated hydrocarbons from such rocks. Without such faulting, generated hydrocarbons may largely remain in cracks, fractures, parting laminae, and matrix porosity in both source rocks and in the rocks immediately adjacent to them. It follows that a huge oil-resource base may be present in and adjacent to fractured, mature, self-sourced shales.

The shales of the Upper Devonian and Lower Mississippian Bakken Formation provide insight into this proposed resource base. Both historic production data from vertical Bakken wells and Rock Eval analyses of close-spaced core and cuttings from mature basinal Bakken shales demonstrate significant movement of hydrocarbons from Bakken shales for at least 50 ft (15 m) into adjacent units. Migration probably occurred through vertical fractures created by fluid overpressuring during intense hydrocarbon generation.

It is widely believed that the Bakken shales are the source of most of the conventional oil in the Williston Basin. However, newer geochemical analyses suggest that this is not the case. The Bakken shales are calculated to have generated over 100 billion BO (15.9 x 10^9 m^3). If this oil did not charge the conventional oil reservoirs, we can only conclude that it remains in the shales and in the rocks adjacent to them.

Numerous other self-sourced, fractured shale reservoirs produce oil commercially. If the thin Bakken shales have generated 100 billion BO, then it is possible that the lower 48 states of the U.S. contain an unrecognized oil-resource base in the trillions of barrels. However, economic recovery of this possible resource base would depend on development of new exploration, drilling, completion, and production techniques appropriate to the non-classical reservoir characteristics of this oil resource base.

INTRODUCTION

There are many occurrences of oil production from fractured, self-sourced shales worldwide. However, the possible magnitude of this resource base has previously gone undefined. Here we attempt to define the size of this resource base, delineate its geological and geochemical characteristics and origins, and suggest exploration, drilling, completion, and maintenance techniques appropriate to the apparent non-classical nature of this resource base.

PRIMARY MIGRATION — A PROBABLE NON-EVENT

Meissner (1978) first documented large increases in electrical resistivity with increasing depth in the shales of the Lower Mississippian-Upper Devonian Bakken Formation (Fig. 1) in the Williston Basin. He attributed these increases to mainstage hydrocarbon generation and the replacement of conductive pore water with resistive hydrocarbons. However, Soxhlet extraction of Bakken shales by two different laboratories failed to document increases in extractable bitumen with increasing depth (Fig. 1). These contradictions were previously explained (Price et al., 1984) as due to very efficient primary petroleum migration, with the high resistivities at depth due to a free-hydrocarbon gas phase present in the shales. However, horizontal drilling of the Bakken shales shows that this was an erroneous explanation, because large oil concentrations are clearly present in these shales.

Recently many other investigators (Cooles et al., 1986; Leythaeuser et al., 1987, 1988; Mackenzie et al., 1987; Talukdar et al., 1987; Ungerer et al., 1987; Espitalié et al., 1988) also concluded that primary migration is very efficient from organic-rich source rocks, such as the Bakken shales, and have provided calculations which suggest that between 75-90% of the hydrocarbons generated in organic-rich shales migrate from the shales. Furthermore, the volumes of oil which are calculated to have been generated by and moved from such source rocks are quite large and always are many times larger than the discovered oil reserves in basins. For example, Hubbard et al. (1987) calculated that the Brookian megasequence of the Alaskan Colville Basin (North Slope) alone generated 10 trillion barrels of oil. Espitalié et al. (1988) calculated that in the Paris Basin, Hettangian and Sinemurian age shales alone generated 14.7 billion BO (2.33 x 10^9 m^3), with only 10% of that as discovered, in-place oil. Calculations by other workers, including Hunt (1979), usually show that discovered oil reserves typically represent only 1-5% or less of the oil generated by all source rocks in any given basin. All such calculations are based on large decreases in Rock Eval hydrogen indices in source rocks as such rocks increase in thermal maturity. Because these decreases in hydrogen indices are not matched by numerically-equivalent increases in either Soxhlet-extracted hydrocarbons or the Rock Eval S_1 peak, most petroleum geochemists (including the senior author) have previously assumed that these generated hydrocarbons must have moved from the rock by efficient primary migration. However, recent work strongly suggests that this interpretation may be wrong.

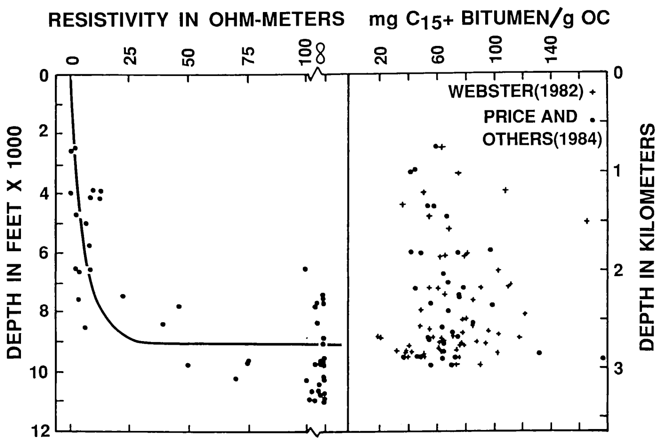

Figure 1. Plots of electrical wire-line log resistivity values in ohm-meters (after Meissner, 1978) and milligrams of C_{15+} bitumen per gram of organic carbon (mg C_{15+} bitumen/g OC, after Webster, 1982, and Price et al., 1984) both versus depth, for Bakken shales, Williston Basin.

Production data from recent Bakken shale horizontal wells show that gas:oil ratios usually range between 800 and 2,000 SCF/BO (142 to 356 m^3G/m^3O). Thus, significant amounts of gas are cogenerated and coexist with C_{15+} hydrocarbons in these source rocks. Furthermore, a large suite of aqueous-pyrolysis experiments we have carried out at the U.S. Geological Survey on six different rocks, including the Bakken shale, demonstrate that: 1.) significant amounts of hydrocarbon gas are cogenerated with C_{15+} hydrocarbons for all organic matter types over all maturation ranks, and 2.) large amounts of carbon dioxide, and lesser amounts of hydrocarbon gases, also are generated by these rocks even before mainstage hydrocarbon generation commences (Price, 1989a).

Recent work by Price and Clayton (1992) demonstrates that bitumen is not homogeneously distributed in organic-rich shales. Instead different types of voids in such rocks contain compositionally different bitumen. Price and Clayton (1992) extracted whole (unground) core of different source rocks (including six different Bakken shale cores of varying maturities) for up to ten successive extractions, by removing solvent (and the extracted solute) after each extraction, adding fresh solvent, and repeating the procedure. The resulting solutes were compositionally different from one another. The first solutes resembled crude oils, and progressive solutes became less and less like crude oil and more immature in appearance. An example from the most immature (pre-hydrocarbon generation) Bakken core extracted, for the first and sixth extractions, is given in Figure 2. Although the first and sixth extracts are from the same rock, they are quite different from, and cannot be correlated with, one another by any organic-geochemical technique, including biomarkers. Price et al. (1983) showed that methane gas preferentially entrains C_{15-} hydrocarbons, saturated hydrocarbons, and especially n-paraffins, over resins, asphaltenes, and high molecular weight aromatic hydrocarbons. As such, Price and Clayton (1992) hypothesized that a partitioning of bitumen in the rock they studied resulted from methane being dissolved in the bitumen and imparting its solution preferences onto the bitumen. Thus, an oil-like bitumen was fractionated from the entire bitumen in the rock and was concentrated in cracks, fractures, and parting laminae, poised and ready for expulsion from the rock. As such, this oil-like bitumen was most accessible to the first extractions of the unground (whole) rock. However, because of its position in the rock, this bitumen is most likely to be lost during the trip up the wellbore.

As conventional core and cuttings chips ascend the

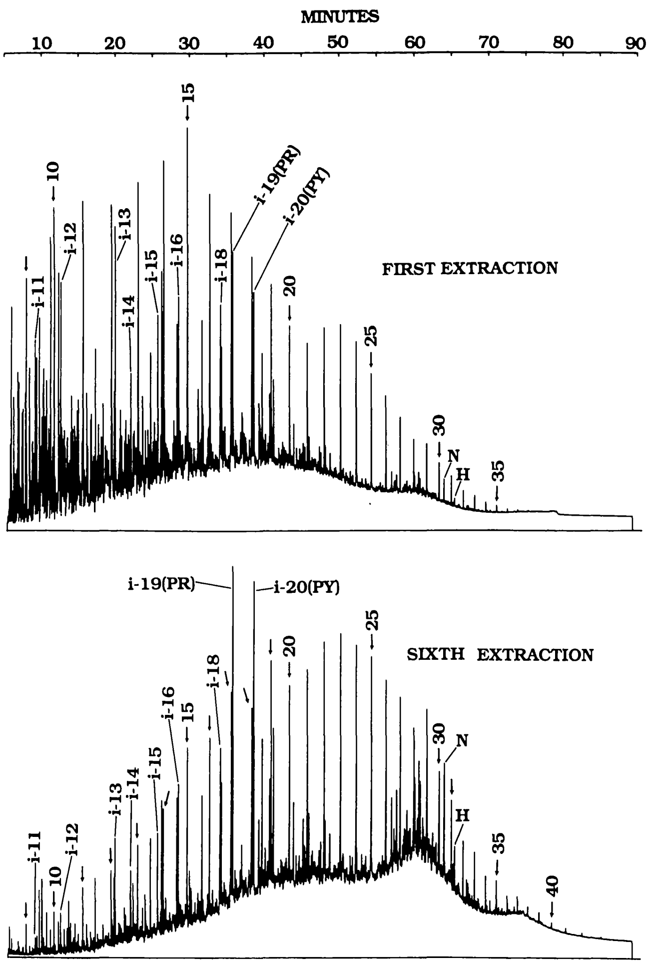

Figure 2. Gas chromatograms of C_{8+} saturated hydrocarbons from the first and sixth extractions of whole Bakken shale core (unpowdered) from NDGS 105, Ward County, North Dakota. The n-paraffins are marked by arrows with every fifth peak labeled, the isoprenoid hydrocarbons are marked by "i-" followed by their respective carbon number, PR is pristane, PY is phytane, N is norhopane, and H is hopane.

wellbore during drilling operations, the rocks undergo large fluid pressure decreases, from high formation pressures at depth to atmospheric pressure at the wellhead. Mature Bakken shales, for example, routinely decrease from 5,000 to 7,000 psi (34.4 to 48.3 MPa) at depth, to less than 15 psi (103 kPa) at the wellhead. Gases present both in the rocks and in the bitumen in the rocks greatly expand in volume as pressure deceases, and almost totally exit from the rocks to the drilling muds. Gases moving from interior rock volumes would blow out oil-like bitumen concentrated in parting laminae and fractures into the drilling mud. Sokolov et al. (1971) provided insight into the magnitude of this hydrocarbon gas loss (Table 1). They took rock samples at depth and at formation pressure in what they termed the "KC lifter" (a pressure core barrel sampler), and brought the samples to the surface, sealed and at formation pressure, with no gas loss. Sokolov et al. (1971) compared the amount of gas recovered in this manner to that recovered during an open-hole rock trip up the wellbore, where only 0.11-2.13% of the gas originally in the rock was recovered.

Table 1. Hydrocarbon-gas concentration and relative loss from equivalent core samples using the "KC core lifter" and the normal "open" method. After Sokolov et al. (1971).

			Gas	
Rock Type	Sample Depth (ft)	Sample Mode	Concentration $10^{-4}cm^3$/ kg ROCK	Relative Loss KC/OPEN
Sand	1263	KC	106,243	893
		OPEN	119	
Shale	1887	KC	2,431	47
		OPEN	52	
Shale	2034	KC	36,473	529
		OPEN	69	

Observations by well-site geologists and drilling personnel corroborate the results of Sokolov et al. (1971). Cuttings chips of organically-mature, fine-grained rocks usually violently spin and fizz at the wellhead from outgassing. This is the result of only the gas remaining in the rocks at the wellhead, which is a small fraction of the gas originally present in the rock, before the trip up the wellbore. During mud gas-logging operations, when drilling through mature organically-rich rocks, gas-logging values always dramatically increase from the outgassing of these rocks into the drilling mud. Occasionally the logging results from such shales are deleted, as the shale values can be so large as to overshadow values from gas-bearing, coarse-grained rocks. While drilling through organically-rich, mature, fine-grained rocks, mud-fluorescence values also always dramatically increase due to the effusion of oil-like bitumen from these rocks into the mud. When mature Bakken shales are penetrated with a water-based drilling mud, an oil film covers the mud pit. Source-rock cores crackle in the core barrel from gas loss at the wellhead, or bleed oil while being held at the wellhead or even in the laboratory, long after drilling.

This loss is hypothesized to be greatly enhanced by two features. First, generated hydrocarbons appear to be concentrated in fracture and parting-laminae voids (Price and Clayton, 1992), which are created or enhanced from the organic matter volume increase during hydrocarbon generation. This oil is readily mobile and easily lost to drilling muds. Second, during drilling operations, cores and especially cuttings are greatly disrupted by the drill bit. Such disruption substantially aids escape of this pre-fractionated mobile oil, poised for migration. This large loss of generated hydrocarbons during the trip up the wellbore has been well known to well-site geologists for over 40 years (C.W. Spencer, pers. comm., 1991). However, if necessary, the magnitude of this loss can be quantified by carefully designed and executed pressure-core barrel tests wherein hydrocarbon concentrations of mature, organic-rich shales brought up in sealed pressure core barrels are directly compared to hydrocarbon concentrations in shales from the same unit, but brought up-hole in the open wellbore.

Important implications follow from this loss of generated hydrocarbons to drilling muds during drilling operations: 1.) the hypothesis of high primary migration efficiencies would be erroneous, and instead would be due to very high loss of generated hydrocarbons to drilling muds, and 2.) except under conditions of intense faulting, and accompanying fracturing, almost all generated hydrocarbons might remain in, or adjacent to, the source rocks to extreme maturation ranks. This second implication carries two more. First, very large in-place oil-resource bases would exist in, and adjacent to, mature organic-rich source rocks. Furthermore, significant parts of these resource bases appear to be mobile and could thus possibly be recovered. Second, although all rocks are fractured to varying degrees, without intense structuring these fractures do not form continuous hydraulic networks able to effectively transmit fluids and thus drain source rocks. If faulting is required to effectively expel hydrocarbons from source rocks to form commercial oil deposits, then there should be a strong correlation of increased basin productivity with increased faulting over and adjacent to the hydrocarbon kitchens in basin deeps.

Basin productivity does indeed demonstrate a strong correlation with increasing deep-basin structural intensity (Table 2) for over 85% of the world's discovered petroleum. This correlation supports the hypothesis that intense faulting, with accompanying fracturing, is needed to allow significant primary migration of hydrocarbons. Without such structural disruption, we believe that the generated hydrocarbons largely remain in source systems and may constitute large, previously unrecognized oil-resource bases.

THE BAKKEN SOURCE SYSTEM

Data from the Bakken shales of the Williston Basin help delineate this oil-resource base (Webster, 1982; Price et al., 1984). The "Bakken source system," as defined here, comprises, in descending order, the lower part of the Mississippian Lodgepole Limestone, the upper shale member of the lower Mississippian-Upper Devonian Bakken Formation, the middle siltstone member of the Bakken Formation, the lower shale member of the Bakken Formation, and the uppermost shales of the Upper Devonian Three Forks Formation.

Short Distance Migration of Bakken Oil

Producing vertical "Bakken" wells in the Williston Basin are completed in the middle Bakken siltstone, either of the Bakken shales, the uppermost Three Forks, the lowermost Lodgepole, or in combinations thereof (Table 3), a fact also noted by Cramer (1991). Such production data strongly suggest migration of Bakken-generated oil into

Table 2. Average basin productivity in millions of barrels of producible oil and oil-equivalent gas per thousand square miles (10^6 Bbls/1,000 mi^2) and total estimated ultimate recovery (EUR) in billions of barrels (BBbls) for the different major basinal structural classes discussed by Price in a manuscript in preparation. Examples of each class are given in parentheses. Structural intensity over and adjacent to the basin deep increases from Class I through Class VIII. EUR and productivity data in Table 2 are for data compiled from 62 of the world's major basins, based on work by D. Klemme.

Class	Basin Type	EUR B Bbls	Productivity 10^6Bbls/ 1000 mi^2
I	Shallow cratonic (Williston, Paris)	12.48	17.4
II	Moderately deep to deep cratonic basins with slight to moderate mobile rims (Uinta, Fort Worth)	22.67	88.4
III	Pull aparts (Gabon, NW Shelf Australia)	7.58	74.9
IV	Block fault - Aborted rift (North Sea, West Texas Permian)	317.6	265
V	Mobile Foredeeps (Anadarko, Persian Gulf)	930.5	299
VI	Downwarps (Greater Gulf Coast, Tampico-Reforma)	269	472.5
VII	Deltas (Niger, Mississippi Fan)	85	555
VIII	Wrench (Los Angeles, Eastern Venezuela)	132.6	969.3

Table 3. Perforated intervals and cumulative water and oil production (with last cumulative date) for some of the more productive vertical Bakken wells in the Williston Basin. LP refers to lowermost Lodgepole Limestone, US to upper Bakken shale, SS to middle Bakken siltstone, LS to lower Bakken shale, and TF to uppermost Three Forks shale. All data are from North Dakota Geological Survey records. Cum. Production is cumulative production. Bbls. is barrels.

Well	Field	Perforations	Cum. Production Oil Bbls	Cum. Production Water Bbls	To
Shell USA 42-24A	Bicentennial	LP, US, SS	190,190	2,092	1/6/90
Apache Federal 2-4	Buckhorn	LP, US, SS	303,905	11,902	1/6/90
Federal 11-1	Buckhorn	LP, US, SS, LS	298,554	13,897	1/1/90
Supron Federal 10-1	Buckhorn	LP, US, SS	301,102	3,497	1/6/90
Tenneco Graham USA 1-15	Buckhorn	LP, US, SS, LS	131,577	1,663	1/1/90
Axem Graham 1-12	Devils Pass	LP, US, SS	136,051	3,256	1/6/90
Supron Federal 6-4	Devils Pass	LP, US, SS	108,152	1,467	6/1/89
Chambers Blacktail Federal 1-20	Elkhorn Ranch	LP, US, SS	243,756	2,592	1/6/90
Chambers Blacktail Federal 1-19	Elkhorn Ranch	LP, US, SS	204,481	1,973	1/6/90
Federal 19-1	Elkhorn Ranch	LP, US	306,109	1,647	1/1/90
Cities Service Federal DL-1	Roosevelt	SS	123,435	422	1/1/90
Beartooth Federal 1-29	Rough Rider	LP, US, SS	347,479	2,165	1/6/90
Shell USA 43-27A	Squaw Gap	LP, US, SS, TF	242,494	3,203	1/6/90

adjacent rock units, a movement supported by Rock Eval analyses of both close-spaced (3-12 in., or 7.6 to 30.5 cm) core samples from the units adjacent to the two Bakken shales and from cleaned and microscopically-picked cuttings chips from the adjacent units (Table 4). These analyses demonstrate that organically immature samples from the three organic-poor units adjacent to the Bakken shales (Group 1) have only minute capacities for hydrocarbon generation. Thus, the S_1 peak (by rock weight) ranges between 0 and 120 ppm, and averages 23 ppm, and when normalized to total organic carbon (TOC), the hydrocarbon index ranges between 0 and 53, and averages 10. The S_2 peak for these samples ranges between 0 and 270 ppm, and averages 97 ppm, with carbon-normalized values (hydrogen indices) ranging between 0 and 80 and averaging 28. In contrast, Rock Eval values of these same units from organically-mature areas of the Williston Basin (Groups II and III) yield ranges and averages 10 to 50 times the values of immature samples. Thus, the three units adjacent to the Bakken shales in mature basinal areas contain 10 to 50 times more hydrocarbons than they possibly could have generated.

Two explanations are possible: 1.) the hydrocarbons in mature samples of these rocks are nonindigenous and have migrated into the rocks, or 2.) facies changes occur within the three units adjacent to the Bakken shales, such that these units become organically richer towards the deeper basin. The second possibility is improbable because microscopic examination reveals no lithologic change laterally in these units and TOC values do not measurably change laterally. Furthermore, Rock Eval data for the North Dakota Geological Survey (NDGS)-607 wellbore (Fig. 3) testify that the hydrocarbons are non-indigenous. In NDGS 607, the Bakken shales are well into hydrocarbon generation and the S_1 and S_2 pyrolysis peak values in the three units adjacent to the Bakken shales are much higher than values from immature examples of these units (Table 4). The Rock Eval transformation ratio exhibits high values in the three units adjacent to the two Bakken shales, compared to the transformation ratio values in the Bakken shales themselves (Fig. 3). Such elevated transformation ratio values are usually attributed to migrated, non-indigenous hydrocarbons. Also, T_{max} declines from values of 435 to 441 C in the two Bakken shales to values of 350 to 420 C in the three adjacent units (not shown in Fig. 3), which is a strong indication of migrated, non-indigenous hydrocarbons.

The Rock Eval results from NDGS-607 with regard to the three units adjacent to the Bakken shales are repeated in the nine organically-mature wells which we have thus far examined. Both these Rock Eval results and historic oil-production data lead to the conclusion that an effusion of hydrocarbons has occurred from the two Bakken shales to the three adjacent units. Furthermore, from the Rock Eval data thus far in hand, this effusion of hydrocarbons appears to extend continuously through the middle siltstone member and at least 50 ft (15 m) into the lowermost Lodgepole Limestone and uppermost Three Forks shale in mature basinal areas. This hydrocarbon emplacement no doubt occurred along vertical fractures extending from the Bakken shales into these units; fractures caused by fluid overpressuring from organic matter volume expansion during mainstage hydrocarbon generation.

Table 4. Rock-Eval analyses for cuttings chips and core samples from the Lodgepole Limestone, Bakken siltstone, and Three Forks shale where values from the three stratigraphic units are averaged together for nine wells from organically immature ("Group I", hydrocarbon generation not yet begun in the Bakken shales) areas of the Williston Basin; for one well (NDGS 607) from a moderately-mature area ("Group II") of the basin; and for four wells (NDGS 1405, 527, 12162, and 4340) from organically-mature areas ("Group III") of the basin. For each entry, the upper line is the range of values and the lower line is the average value. NDGS NUM. is the North Dakota Geological Survey well number. The Rock-Eval S_1 and S_2 pyrolysis peak values are normalized to rock-weight (ppm); and to organic carbon (mg/g OC); HCI (hydrocarbon index) for the S_1 pyrolysis peak, and HI (hydrogen index) for the S_2 pyrolysis peak.

NDGS NUM.*	Unit	S_1 ppm	S_2 ppm	mg/g OC S_1 (HCI)	mg/g OC S_2 (HI)
		Immature			
	Siltstone Lodgepole Three Forks	0-120 23	0-270 97	0-53 10	0-80 28
		Moderately Mature			
607	Lodgepole	260-6,460 903	110-6,740 1,207	96-264 151	58-297 168
607	Siltstone	90-1,480 797	0-1,490 791	28-282 179	0-276 138
607	Three Forks	300-1,540 1,003	240-1,170 813	78-232 136	38-211 143
		Very Mature			
1405	Siltstone	260-1,210 987	110-1,250 786	45-149 122	23-157 117
527	Siltstone	310-1,820 1,233	70-840 633	151-364 224	39-168 119
527	Three Forks	140-1,140 507	160-980 614	20-178 83	22-153 107
12162	Lodgepole	320-2,210 1,251	400-1,150 747	169-539 257	0-205 138
12162	Siltstone	2,060-3,600 2,650	290-660 530	286-947 557	73-174 121
4340	Siltstone	40-1,930 321	0-550 121	29-625 187	0-128 47

*NDGS 527 is the California Oil Co. Rough Creek-1, S13 T148N R98W; 1405 is the Gofor Oil Inc., Catherine E. Peck-2 S27 T150N R95W; 12162 is the Meridian MOI 13-21 S21 T43 R101; and 607 is the Socony-Vacuum Angus Kennedy F-32-24-D S24 T149N R93W; 4340 is the Pan Am. Petrol. Corp. Clifford Marmon-1 S2 T154N R95W.

Bakken Shales as the Madison Oil Source

Dow (1974), using then extant petroleum-geochemical correlation tools concluded that the oil in mid-Madison reservoirs in the Williston Basin had been sourced from Bakken shales. However, Osadetz et al. (1990, 1992a, 1992b), using more sophisticated present-day correlation tools, concluded that most mid-Madison oils were not sourced from the Bakken shales but were sourced from Mississippian Madison Group rocks. Osadetz and Snowdon (1992) also provided a large body of geochemical data that delineates possible Paleozoic source rocks in the Williston Basin. Separate studies carried out by two major oil company research centers have also concluded that the Bakken shales did not source the mid-Madison oils, either in Canada or in the U.S. (pers. comm. from personnel at those research centers, 1990).

Gas chromatograms of C_{15+} saturated hydrocarbons from mid-Madison oils are quite different from those of bitumen from Bakken shales (Fig. 4). Bakken samples are depleted in n-paraffins, have generally larger naphthene envelopes, and have n-paraffin profiles different from the mid-Madison oils. Sidney B. Anderson, the past North Dakota State Geologist, has long maintained that the Bakken shales are not the source of the mid-Madison oils on the basis of geology, variations in oil composition, and petroleum geochemistry (various personal communications, 1980-1991). Price et al. (1984) could not correlate Bakken shale bitumen to mid-Madison oils using isoprenoid hydrocarbon profiles, although this technique has been successfully used to relate other oil families (Price, 1990). Also, Price et al. (1984) noted that saturated and aromatic hydrocarbon gas chromatograms from the mid-Madison oils were identical to each other but always significantly different from those from Bakken shale extracts.

There are no avenues of vertical transport to move Bakken-sourced oils upward through the 1,000 to 1,500 ft (305 to 457 m) of low permeability Mississippian limestone separating the Bakken shales from the mid-Madison oil reservoirs. The near absence of faulting in the Williston Basin compelled Meissner (1978) to call on hydrocarbon generation in the Bakken shales to induce hydraulically continuous fractures from the Bakken shales through the Mississippian carbonates to the mid-Madison oil reservoirs. This is an untenable hypothesis. Although non-indigenous hydrocarbons have migrated into adjacent units from mature Bakken shales (Fig. 3), Rock Eval analyses show that the vertical extent of this migration is limited.

Leenher (1984) claimed correlation of Bakken shale bitumen to mid-Madison oils in the Williston Basin. However, her correlation examples were for shallow Bakken shales (about 6,500 ft, or 1,980 m). Price et al. (1984) found that shallow Bakken shales near the depositional edge of the Bakken Formation could undergo a facies change from type II organic matter to type III organic matter. Although TOC contents remained high, hydrogen indices strongly decreased, and the C_{15+} saturated hydrocarbon gas chromatograms became more mature in appearance with strong increases in n-paraffins (from the influence of the terrestrial type III organic matter). Leenher's (1984) C_{15+} saturated hydrocarbon gas chromatograms from Bakken shales are overlays of those presented by Price et al. (1984) from samples at depositional-edge sites, and are not representative of the type II organic matter present in the Bakken shales in the deep Williston Basin.

Geochemical comparison of 15 oils produced from the Bakken shales with 19 oils produced from mid-Madison Group reservoirs is being carried out at the U.S. Geological Survey. Even by superficial examination, the two groups of oils are quite different. The mid-Madison oils for the most part are black oils, opaque to transmitted light in an 8-dram vial, solid or slightly liquid at 6 C (43 F), with API gravities of 28-41 . The Bakken-produced oils are shades of reddish-brown to orange-brown, moderately translucent to transparent to transmitted light, very liquid at 6 C, with API gravities of 40-46 . Distinct differences are present in whole-oil gas chro-

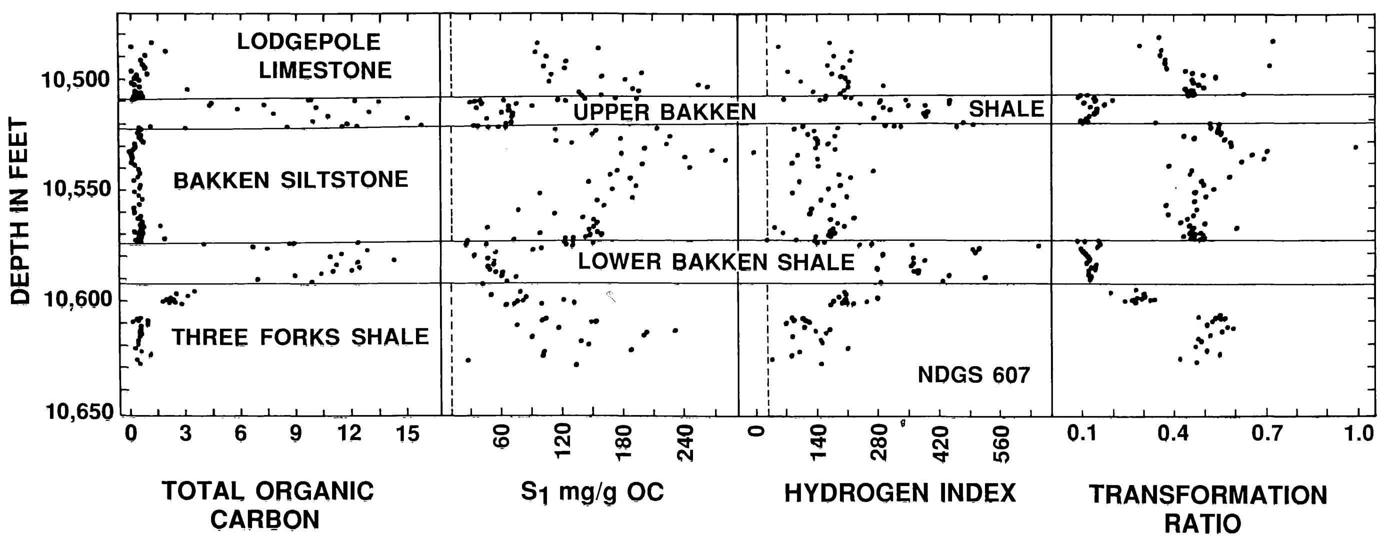

Figure 3. Total organic carbon (in weight percent); and Rock Eval S_1 pyrolysis peak normalized to organic carbon (mg/g OC), hydrogen index, and transformation ratio (S_1/S_1+S_2) for cores from the Socony-Vacuum Angus Kennedy F32-24-D (NDGS-607), Sec. 24, T149N, R93W, Williston Basin, North Dakota. The sample density for NDGS-607 is typical of the different wells of Table 4.

matograms (Fig. 5): 1.) the pristane to phytane ratios are different, 2.) the Madison oils are distinctly more paraffinic, having higher n-paraffin peaks in the n-C20 to n-C30 elution range, and having smaller peaks between the n-C10 to n-C17 n-paraffins than the Bakken oils, and 3.) the Bakken-produced oils have larger naphtheno-aromatic (unresolved) envelopes.

Whole-oil gas chromatograms for the same six oils for the n-C9 to n-C20 elution range (to show that elution range in expanded detail) are given in Figure 6, and some of the principal peaks are labled in Figure 7, which serves as a guide for the other chromatograms in Figure 6. The peaks labeled 00 through 10 and A through M were used to construct "generic-hydrocarbon" ratio plots (Fig. 8, discussed below). Again, differences exist between the two groups of chromatograms: 1.) the naphtheno-aromatic (unresolved) envelope is higher in the Bakken oils, 2.) the compounds between the n-paraffins have greater peak heights in the Bakken oils, and 3.) the mid-Madison oils are distinctly more paraffinic. Furthermore, clusters

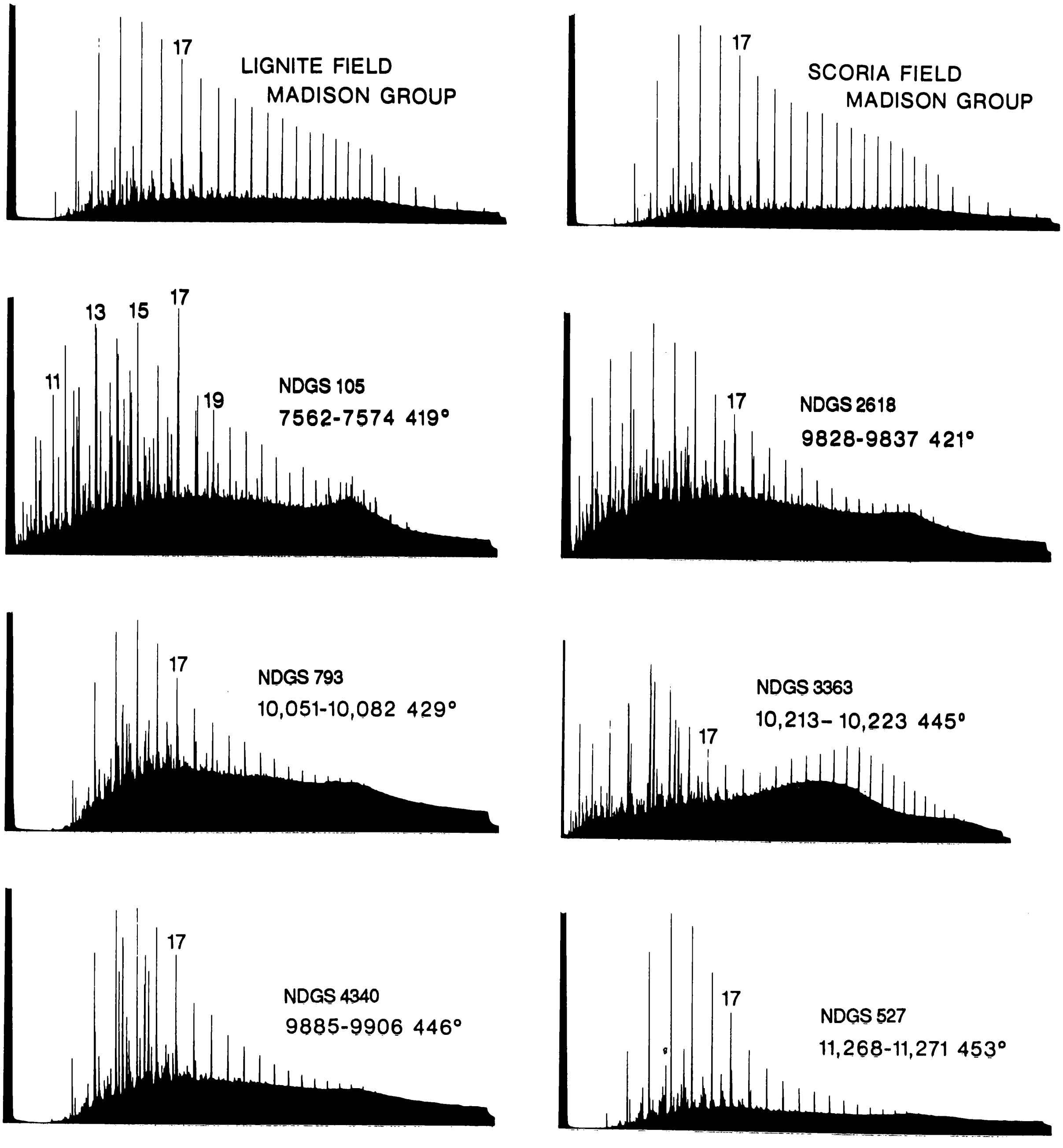

Figure 4. Gas chromatograms of C_{15+} saturated hydrocarbons from two mid-Madison crude oils and from six Bakken shale core composites (identified by NDGS numbers) from Price et al. (1984). The NDGS well number, sample depth (ft), and Rock Eval T_{max} values (C) for the samples are given above each chromatogram. Crude oil and well information are in Price et al. (1984).

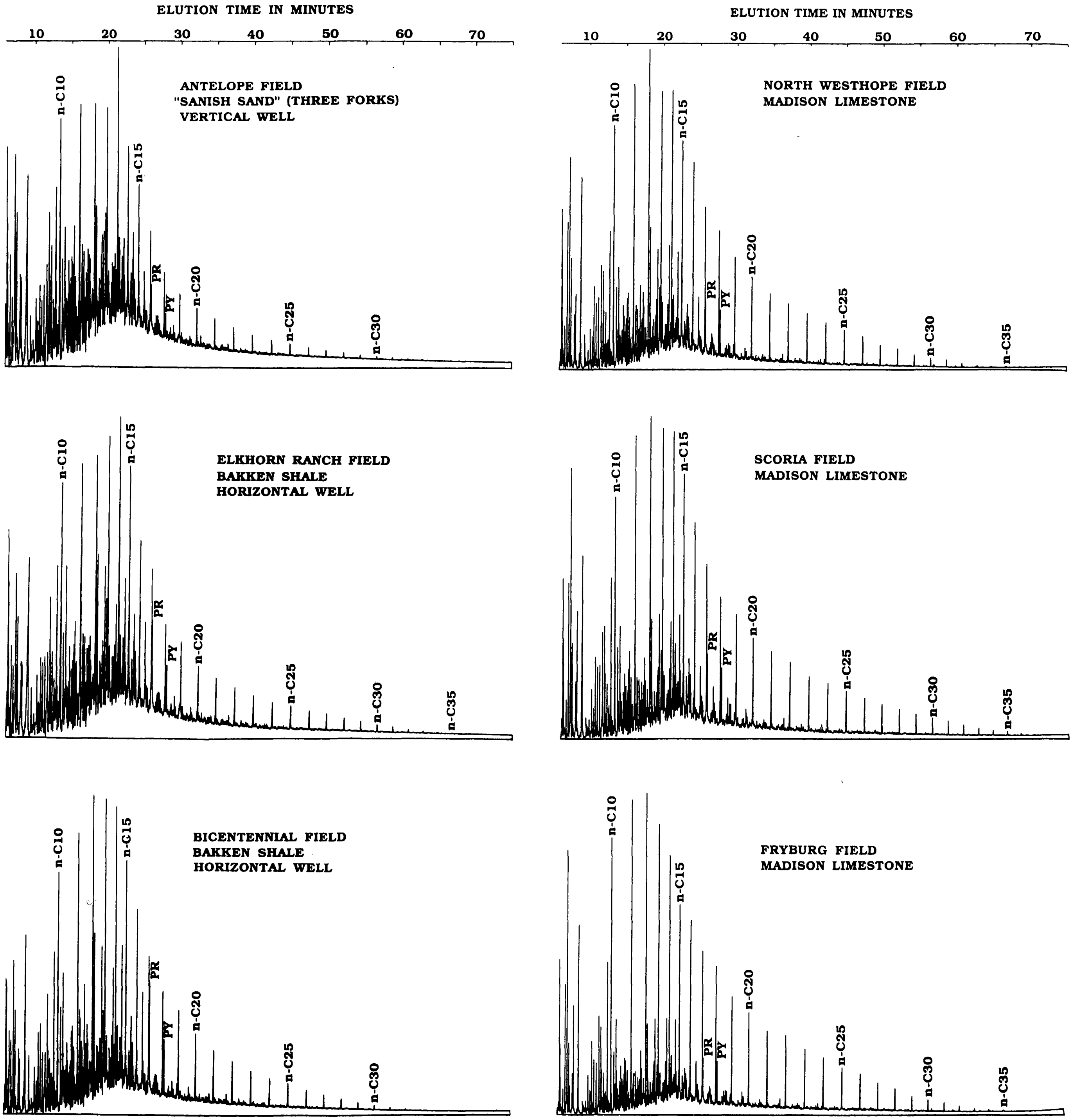

Figure 5. Whole-oil (resins and asphaltenes removed) gas chromatograms for three oils produced from mid-Madison reservoirs (North Westhope, unknown well Bottineau County, North Dakota, 37.0 API; Scoria, #1 Scoria Unit, Sec. 10, T139N, R101W, Billings County, North Dakota, 41.7 API; Fryburg, #1-23 State, Sec. 23, T141N, R101W, Billings County, North Dakota) and three Bakken-produced oils (Antelope, Brenna-Lacey-1, Sec. 1, T152N, R95W, McKenzie County, North Dakota, 45.4 API; Elkhorn Ranch, MOI 44-25H Sec. 25, T143N, R102W, Billings County, North Dakota, 40.0 API; Bicentennial, MOI 33-19 Sec. 19, T145N, R103W, McKenzie County, North Dakota. The Rock Eval hydrogen indices of the Bakken shales at the Antelope well are 130, at the Elkhorn Ranch well are 150, and at the Bicentennial well are 490. Every fifth n-paraffin is numbered (n-C followed by the respective carbon number), PR is pristane, PY is phytane.

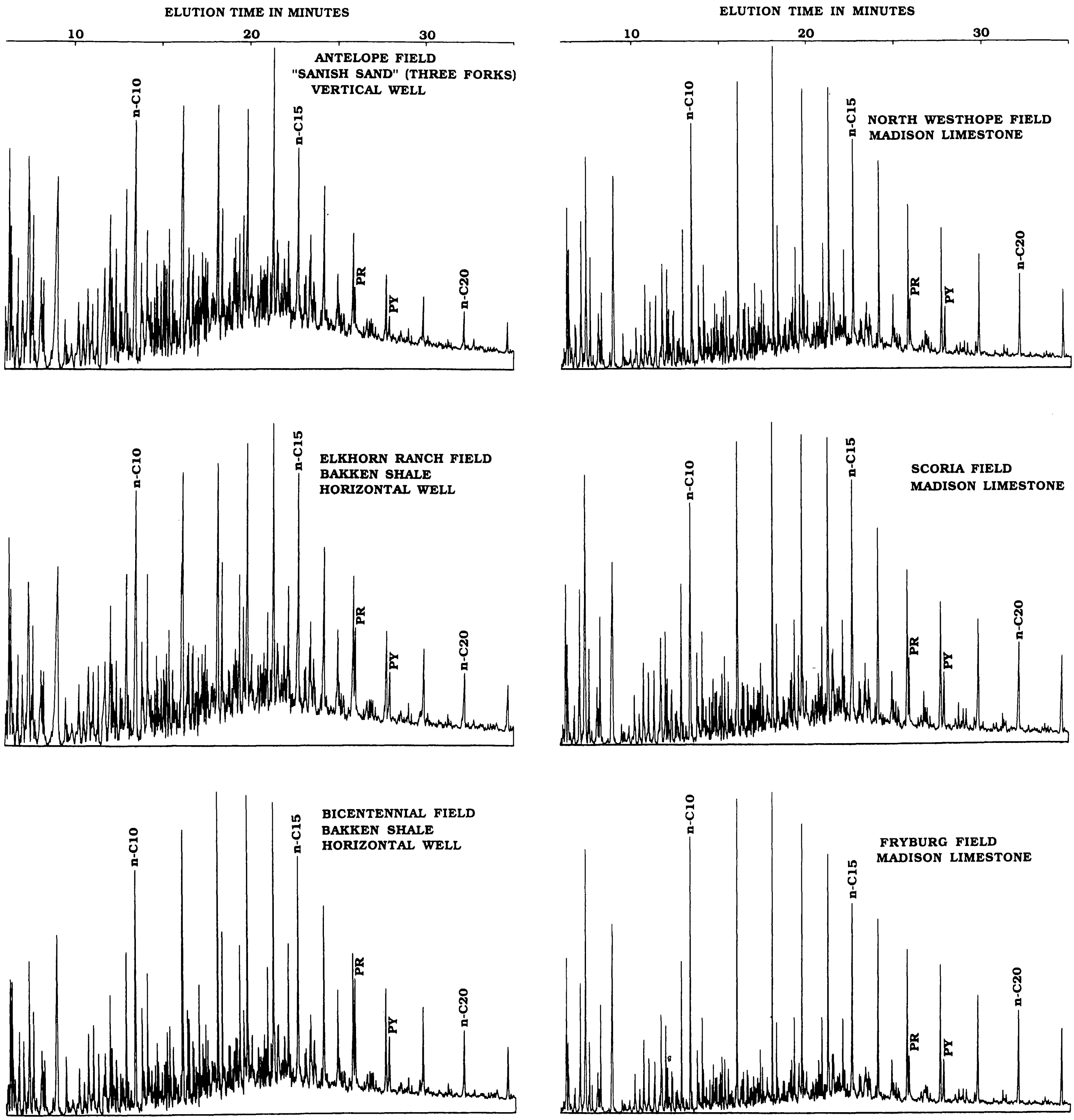

Figure 6. Whole-oil gas chromatograms of the six oils in Figure 5 over the n-C_9 to n-C_{21} elution interval. Compound labeling and oil origins as in Figure 5 caption. See Figure 7 for detailed index of compounds.

of peaks are similar within each oil group but different between the two oil groups. Thus, the two small clusters of peaks betwen the n-C17 and n-C18 and the n-C18 and n-C19 n-paraffins are similar for the Bakken oils but different for the mid-Madison oils, which are similar to each other. The trimethylnaphthalenes have been proposed as useful indices for both maturity and source-facies, much like biomarkers. The trimethylnaphthalene distributions between the two oil groups are distinctly different; the middle group of peaks containing peak "D" (Fig. 7) is much higher than the other two groups of peaks in the Bakken oils, compared to the mid-Madison oils.

Biomarkers are widely used to type oils into oil families. However, in moderately-mature to mature oils, these compounds rarely make up more than several hundred ppm (and often much less) of the whole oil by weight, and are found in only a restricted boiling range of the oil. A superior method of oil correlation was presented by Kaufman et al. (1990) and Price (1990), using ratios or percentages of "generic" hydrocarbons found over all boiling ranges and in much higher concentrations in oils than biomarkers. Kaufman et al. (1990) were even able to demonstrate whether oils from the same family were in the same hydraulically connected reservoir. This technique was applied to the different oils of Figure 5. A number of ratios were calculated (based on the peaks labeled 00 to 10, A through M, and on some n-paraffins) and the ratios plotted in three different figures, one of which is Figure 8. The three Bakken oils plot in a tight cluster far from data for three mid-Madison oils. The three Bakken oils are clearly a different oil family than the three mid-Madison oils.

The tight distribution of the plots for the three Bakken oils in Figure 8 is unexpected and surprising considering the wide maturity range (Rock Eval hydrogen indices = 130 to 490) and geographic separation (23 to 69 mi or 37 to 111 km) of the oils examined. The variance in the plots of the three mid-Madison oils is also unexpected considering that the mid-Madison oils are thought to be a single oil family. The other two compound ratio plots constructed for the six oils of Figure 5 lead to the same conclusions as Figure 8.

These preliminary results corroborate the findings of Osadetz and his coworkers and support the conclusion that the Bakken shales have not sourced much of the mid-Madison oil in the Williston Basin.

The Bakken Source System Resource Base

Webster (1982), Artindale (1990), and Schmoker and Hester (1983) estimated that the Bakken has generated 92 to 150 billion BO (14.6 to 23.8 x 10^9 m^3). However, a large Rock Eval data base for the Bakken shales we have compiled suggests these calculations may be conservative. Both the original TOC and hydrogen index values for basin-center shales, before commencement of hydrocarbon generation, appear to have been higher than the values used by the above investigators. The large amount of oil generated by the Bakken shales could not have been expelled from the shales and leaked out of the basin over geologic time without charging the conventional mid-Madison reservoirs. Thus it appears that an in-place resource base of 100 to 150 billion BO (15.9 to 23.8 x 10^9 m^3), a portion of which is mobile and possibly could be recovered, exists over a large part of the Williston Basin in fractures, cracks, parting laminae, and matrix porosity within the Bakken source system.

Such a large oil-resource base is reasonable from both

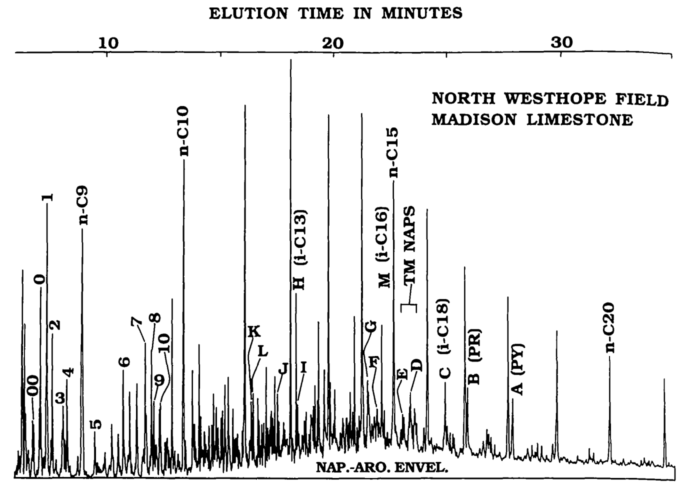

Figure 7. N-C_9 to n-C_{21} whole-oil gas chromatogram with those peaks labeled which were used in the calculation and construction of the generic-hydrocarbon compound-ratio plot of Figure 8 (peaks 00 through 10). Peaks A through M were used in other compound ratio plots (not shown). Compound labeling as in Figure 5 caption. i-C_{13}, i-C_{16}, and i-C_{18} are all isoprenoid hydrocarbons of the respective indicated carbon numbers, TM NAPS refer to trimethylnaphthalenes, NAP.-ARO. ENVEL. refers to the unresolved naphtheno-aromatic envelope.

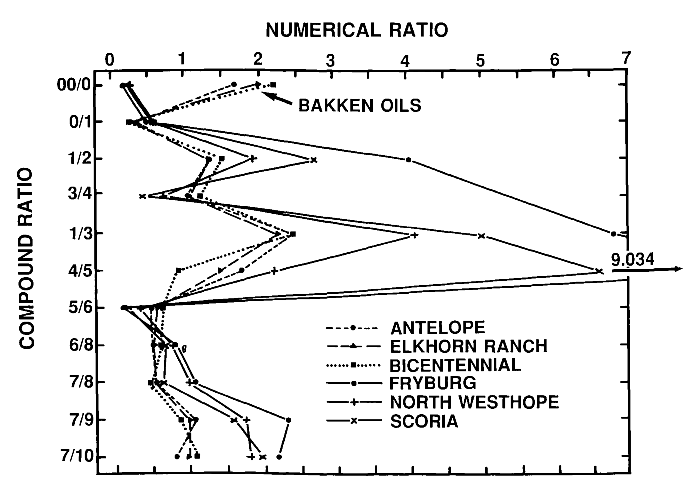

Figure 8. Compound ratio plot for the six oils of Figure 5. Bakken oils are shown by dotted and dashed lines and mid-Madison oils by solid lines. Also see Figure 7 caption.

rock-storage capacity and geologic standpoints. To estimate rock storage capacity, the following assumptions were made: 150 billion BO (8.42×10^{11} ft^3) are stored in the rocks; the upper Bakken shale is mature over an area of 22,345 mi^2 (57,873 km^2) (J.W. Schmoker, pers. comm., 1991); the average thickness of the Bakken Formation (both shales and the middle siltstone) over the mature area is 75 ft (22.9 m); the oil has penetrated 150 ft (45.7 m) into the lowermost Lodgepole and uppermost Three Forks; the total thickness of rock where the oil is stored is thus 375 ft (114 m). Therefore, the volume of rock where the oil is stored is 1.472×10^{11} $ft^3/mi^3 \times 22{,}345$ $mi^2 \times 0.071$ mi (= 375 ft/5,280 ft/mi) = 2.336×10^{14} ft^3 (2.174×10^{13} m^3). The volume of stored oil is 150×10^9 BO x 5.615 ft^3/BO = 8.422×10^{11} ft^3, and the stored oil thus equals 0.361% ($8.42 \times 10^{11}/2.34 \times 10^{14}$) of the volume of the rock in which it resides.

From a geologic standpoint, the Williston Basin is a "pancake" cratonic basin (Table 2), which, as a class, is the least oil-rich of petroleum-basin types. The Williston Basin is also characterized by flat-lying sediments with almost no faulting. This lack of structuring makes reasonable the hypothesis that most hydrocarbons generated in the sealed and undeformed source rocks have remained in place over geologic time.

MIXED RESULTS OF HORIZONTAL BAKKEN DRILLING

In spite of the huge volume of in-place oil proposed above, horizontal drilling and production results in the Bakken shales thus far have been mixed, and do not support the existence of such large in-place reserves. These mixed results have largely been attributed to lack of fractures. However, a key hypothesis of this paper is that the lack of success may be due in part to use of drilling, completion, maintenance, and production practices which may be inappropriate to the non-classical Bakken source system.

Organically-mature Bakken shales are oil-wet (Meissner, 1978; Webster, 1982; Cramer, 1991). Marginally to moderately mature Bakken shales may contain small amounts of immobile and discontinuous water (Fig. 9). However, mature shales apparently contain no water in the small remaining rock porosity (Schmoker and Hester, 1990). The three organic-poor units adjacent to the two Bakken shales have had substantial amounts of oil emplaced into their porosity (Fig. 9). However, these units, because they cannot generate meaningful amounts of hydrocarbons, probably still retain significant water saturations, even at very mature ranks. The fracture porosity in the two Bakken shales, and the three adjacent units should also be oil-wet, as this fracture porosity was created by abnormal pressuring due to organic matter volume expansion during hydrocarbon generation and charged by an oil-only phase. However, fractures that existed in the three units adjacent to the two Bakken shales before mainstage hydrocarbon generation would have been water wet, and thus would still retain mobile water. Production records of vertical "Bakken" wells testify to the largely oil-wet nature of the Bakken source system (Table 3); because production of such small percentages of water is unusual, given the volumes of produced oil. The water that has been produced likely originated from the partially water-saturated indigenous fracture and matrix porosity in the three units adjacent to the Bakken shales.

Fully oil-wet systems are very rare compared to conventional water-and-oil-wet oil reservoirs. Consequently, the industry is unaccustomed to dealing with oil-wet systems, which cannot be treated like conventional reservoirs. During drilling, completion, or maintenance operations, if water is introduced into these systems, the principles of two-phase fluid flow (Fig. 10) and the Jamin effect (Hedberg, 1980) come into effect.

The principles of two-phase fluid flow state that where two immiscible fluid phases (here water and oil) coexist in matrix porosity, both fluids have critical fluid saturation levels that must be exceeded before either fluid can flow. If the concentrations of both fluids under consideration exceed their respective critical fluid saturation levels, then both fluids can move through the solid. However, their relative permeabilities will be greatly reduced with

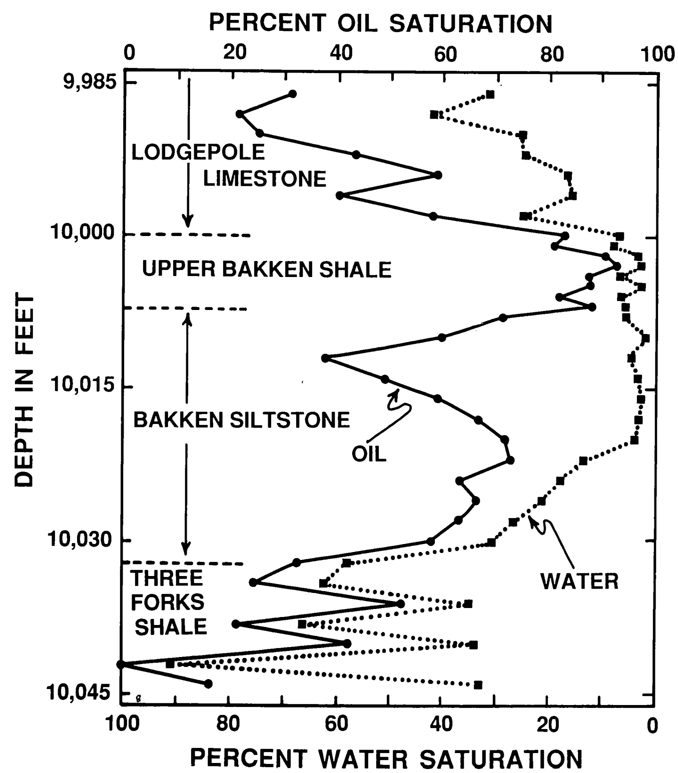

Figure 9. Residual oil and water saturations for core samples from the Vaira 44-24 wellbore, Richland County, Montana (Sec. 24, T24N, R54E). At this location the Bakken shales are extrapolated to be marginally to moderately organically mature.

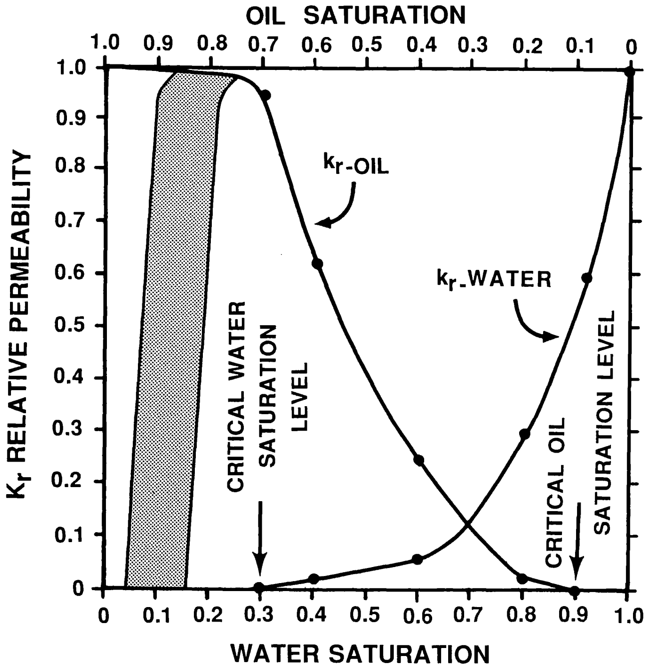

Figure 10. Plot of relative oil (k_r-OIL) and water (k_r-WATER) permeabilities versus oil and water concentrations. The shaded field represents reduced or zero permeability with respect to oil from the Jamin effect at water saturations below the critical water saturation level. Water saturation value of 1.0 represents 100% water saturation.

respect to what their permeabilities would be if one fluid were in the solid alone.

The Jamin effect states that where two separate and immiscible fluid phases coexist in a rock, and one phase (water) is below its critical fluid saturation level, a portion of that water may be in the form of immobile spherical globules that cannot be distorted, and that occupy a percentage of connecting pore throats. These globules decrease, or reduce to zero, the permeability of the rock with respect to the other fluid phase. In natural systems, water below its critical fluid saturation is largely in the form of continuous or discontinuous films. However, in drilling, completion, and maintenance operations, significant percentages of the water introduced into the Bakken source system from the wellbore will have the form of discontinuous, pore-throat-plugging, spherical globules.

We hypothesize that introduction of water into the largely oil-wet Bakken source system creates a skin effect around the wellbore. This results in reduced, or zero, permeability with respect to oil, which greatly reduces or takes to zero the potential oil-productivity of the well. Introduction of such water occurs from drilling with a salt-water-based mud, acidizing the wellbore, or fracturing with water. Drilling with an oil-based mud reduces such damage, but does not eliminate it, as an oil-based drilling mud is an emulsion (small globules) of water in a greater volume of oil.

As Cramer (1991) noted, the Bakken shales have little or no carbonate minerals, and thus there is no reason to acidize these shales. Some productive Bakken source-system wells have been treated with acid during maintenance operations on the premise that scaling around the perforations had impaired fluid flow to the wellbore. Scaling occurs by precipitation of minerals from a water phase during production. However, the low water production from "Bakken" wells (Table 3) strongly suggests that scaling should be minor. Furthermore, NDGS records reveal that acidization of previously oil-productive vertical "Bakken" wells often greatly diminishes, or ruins, the oil-productive capability of the well.

Cramer (1991) noted that low-productivity vertical "Bakken" wells can have productivity increases after a fracture treatment. Examination of NDGS production histories reveals that many such previously nonproductive wells had water introduced into them. The subsequent fracture treatments penetrated water-induced skin damage surrounding the wellbore. NDGS records also suggest that fracture treatments using lease oil are much more effective than water-based or gelled-water fracture treatments. Cramer (1991) also noted that gelled-oil fracture treatments on low productivity "Bakken" wells are more effective than gelled-water treatments, because in the latter case, the wells have trouble unloading their water after treatment. Cramer (1991) further noted that post-fracture treatment of the wellbore with a liquid gel breaker, after fracturing with a gelled-oil system, greatly improves a well's productivity, as incompletely degraded gelled oil can impair the productivity of "Bakken" wells. Skin damage around vertical "Bakken" wellbores from inappropriate drilling, completion, or maintenance operations can almost always be rectified by a lease-oil fracture treatment. Apparently this is not always possible with horizontal wells drilled within the Bakken shales, because much of the fracture treatment appears to be directed into a limited number of pre-existing fractures.

The introduction of water to the largely oil-wet Bakken source system is not the only possible detriment to "Bakken" productivity. With horizontal Bakken wells, two other possible controlling parameters are: 1.) the time the drill bit and string spend in the horizontal portion of the hole, and 2.) overbalanced drilling muds. With horizontal drilling, the drill bit and string spend a large amount of time in the beginning and middle portions of the horizontal segment of Bakken wells, ample time to inflict significant damage to the relatively plastic Bakken shales. Evidence of such damage arises from visual examination of Bakken shale cuttings chips. A significant percentage of these chips has been highly deformed and smeared out by the drill bit.

Because of the sloughing characteristics of horizontal Bakken holes during drilling, mud weights must be kept relatively high to prevent hole collapse. The intrusion of mud into, and caking of mud onto, Bakken shale fracture walls during drilling operations would greatly reduce Bakken oil productivity.

Because of the greater competence of the middle Bakken siltstone member and the Lodgepole Limestone and Three Forks Formation, horizontal drilling in these rocks would be possible with reduced mud weights. Attempting to produce oil from these rocks while drilling might also help to reduce formation skin damage.

Lastly, productivities of individual Bakken horizontal wells have significantly decreased due to apparent regional decline in Bakken source-system reservoir pressures in the "fairway" area of the Bakken play. Schmoker (1992) hypothesized, and we agree, that this regional pressure decline was enhanced by an interconnected fracture network in the Bakken source system. This regional decline in "reservoir" pressure is a consequence of overproduction of individual Bakken wells in attempts to drain as much oil as possible from adjacent sections. The pressure decline also results from the nature of the organic matter in the Bakken shales; the type II and II/I organic matter of the Bakken shales is a poor generator of hydrocarbon gases (per unit of oil) compared to type III and III/II organic matter (Price, 1989b). Because the principal drive mechanism of the Bakken source system is gas expansion, this limited capability for gas generation will greatly detract from ultimate production of this resource base. It is likely that only a small fraction of the in-place resource base in the Bakken source system will be recovered unless reservoir pressure maintenance by gas injection is instituted.

Given the excellent sweep capabilities demonstrated by carbon dioxide in tertiary oil-recovery programs, carbon dioxide would be a natural candidate for such a gas injection program. If the Bakken source system is well interconnected by a regional fracture system, given the diffusive capabilities of carbon dioxide, a gas-injection program could be expected to be effective.

OTHER SOURCE SYSTEMS

The Bakken source system is not unique. Other examples of self-sourced, fractured-shale oil deposits include the prolific Upper Cretaceous Austin Chalk in South Texas and the Upper Cretaceous Niobrara Formation in the Silo Field, Laramie County, Wyoming (Johnson and Bartshe, 1991a, b). Lucas and Drexler (1976) discussed the Altamont-Bluebell trend of the Uinta Basin, Utah, where oil is produced from highly fractured, low-porosity, thin sandstones and organic-rich shales, marls, and silts of the Eocene Wasatch and Green River and Paleocene Flagstaff Formations. Abnormal fluid pressures were originally present throughout the field; some pressure gradients exceeded 0.8 psi/ft (18 kPa/m). Gas-oil ratios averaged 1,000 SCF/BO (178 m^3G/m^3O). During initial production, the wells produced only oil with little or no water. Thus, this Tertiary source system in the Uinta Basin has many points in common with the Bakken source system.

McGuire et al. (1983) discussed oil production from fractured mid-Miocene Antelope and McDonald Shale Members of the Monterey Formation at the crest of the southeastern end of the Lost Hills anticline, San Joaquin Basin, California. Where oil productive, these organic-rich shales are overpressured and exhibit increased resistivities and decreased water contents. Maturity indices suggest that these shales have just begun mainstage hydrocarbon generation. Tensional fractures at the anticline crest have aided migration of oil fractionated from shale bitumen, possibly by the hydrocarbon-gas-driven mechanism outlined by Price and Clayton (1992).

The fractured shale oil pool at Lost Hills demonstrates two favorable characteristics relevant to fractured-shale oil resources in general: 1.) a moderate degree of structuring, with the creation of tensional fractures, creates voids necessary for the trapping and storage of this oil at much lower maturation ranks than if creation of fractures is dependent solely on organic matter expansion, fluid overpressuring, and subsequent fracturing from intense hydrocarbon generation, and 2.) fracturing even marginally mature, organic-rich shales by structuring, allows the formation of seemingly mature, high-quality oil deposits at unexpectedly low maturation ranks (Price and Clayton, 1992). Moderate structural intensity will enhance both in-place reserves and recovery of this resource, as such structuring aids the mobilization and concentration of oil into producible voids, and greatly augments any fracturing created by hydrocarbon generation. However, limits exist to such structural enhancement. A point will be reached where intense structuring allows many of the generated hydrocarbons to escape the source system entirely, perhaps to form conventional oil deposits.

Truex (1972) discussed oil production from fractured, organic-rich, black shales in the East Wilmington Field, Long Beach, California. These shales, possibly equivalent to the mid-Miocene Altamira Shale Member of the Monterey Formation, are highly organic-rich (Price, 1983, his Figs. 3 and 4) and are at burial temperatures of 105 C or higher. Yet by conventional maturity indices, these shales appear not to have begun hydrocabon generation. Rock Eval transformation ratios range between 0.016-0.046 and R_O ranges between 0.23 and 0.40%. Rock Eval T_{max} values of 431-444 C reflect the elevated burial temperatures of these rocks. Given the established oil production from these shales and their elevated burial temperatures, it appears that hydrocarbons generated in these shales were lost to the drilling mud during the trip up the wellbore, and thus were not measured by Rock Eval or Soxhlet extraction.

Production from the shales in the East Wilmington Field is from vertical tensional fractures in organic-rich black shales, silts, cherty shales, marls, and phosphatic shales on the crest of the Wilmington anticline. As of November, 1971, five productive wells (of ten attempts) in the fractured shale had produced 2,100,000 BO (334,000 m^3). Truex (1972) noted that the five nonproductive wells had good oil and gas shows, produced only hydrocarbons and no water during completion attempts, but were abandoned due to restricted fluid entry into the wells. The oil-bearing zones appeared to have been damaged during drilling. All ten wells were drilled with water-based mud. Truex (1972) noted that the fracture systems are highly sensitive to damage from emulsion blockage by drilling and kill fluids.

As of 1971, fractured, self-sourced, shale reservoirs had produced over 100,000,000 BO (15.9 x 10^6 m^3) from fields in California (Truex, 1972). Organic-rich, fractured shales have been penetrated many times in California basins, and always have had abundant oil and gas shows. Yet few formation tests of completions have been attempted away from established production (Truex, 1972). Truex (1972, p. 1938), discussing self-sourced, fractured shales noted, and we concur, "It is time for all petroleum geologists to enlarge their thinking to include this neglected reservoir."

DISCUSSION

Assume that most of the 100-150 billion barrels (15.9 to 23.8 x 10^9 m^3) of oil generated by Bakken shales has remained in place. Then it is not difficult to estimate an in-place oil resource base in the lower 48 United States in the tens to hundreds of trillions of barrels, given the facts that the Bakken shales are thin and that thick sections of mature, organic-rich shales of many different geologic ages exist in many other onshore U.S. basins. Examples include the up to 9,000 ft (2,700 m) thick Eocene and Paleocene shales in the deep Uinta Basin; the different units in the several thousand foot thick Upper and Lower Cretaceous black shale section present in Rocky Mountain basins; the rich Permian Phosphoria and Minnelusa shales and equivalents in Rocky Mountain basins; the Pennsylvanian black shales of the Paradox, Anadarko, and other basins; the organic-rich Tertiary shales of the California petroleum basins; Mississippian-Devonian black shales equivalent to the Bakken shales and present in the mid-continent and eastern basins, such as the Woodford Shale in the Anadarko basin; and possibly the Austin Chalk.

This resource base has largely been unrecognized in the past because we have simply not looked for it and because most onshore U.S. wells are drilled with water-based drilling muds. However, drilling, logging, and production records contain evidence of this resource base. The delineation, exploitation, and possible recovery of this resource base, if it does exist, will depend on: 1.) improved interaction between the many different disciplines of the petroleum industry, 2.) development of new exploration techniques centered around the poorly known geological-geochemical controlling parameters of the resource base, and 3.) development of appropriate drilling, completion, stimulation, and maintenance techniques which take into account the peculiar, non-classical characteristics of the resource base.

Some geologic and geochemical controls come to mind. Moderate local structuring, especially faulting, fracturing, or tensional fractures from structural drape, enhance both in-place and producible reserves. Plumbing would play a key role, as source rocks sandwiched between tight rocks (such as the case with the Bakken source system) will retain generated oil more efficiently than source rocks with good drainage conduits. Organic matter type and true maturation rank are also pivotal, as the different organic matter types require different maturation ranks to achieve the same degree of hydrocabon generation. In particular, ranks greater than $R_O = 0.6\%$ (as read in type III organic matter) are required for commencement of intense hydrocarbon generation in hydrogen-rich organic matter; and the required ranks increase as the original hydrogen content of the organic matter increases (Price, 1991). Recent dry holes in the Denver Basin in drilling attempts of the Niobrara Chalk away from the Silo Field serve as examples of this point.

If the in-place oil resource base that we hypothesize does exist in the lower 48 U.S., it would fulfill the most important requirements for frontier exploration: the possible reserves are huge and are in a politically and economically stable country. Furthermore, established markets are near possible production, and an infrastructure already exists which includes pipelines, refineries, and distribution centers.

CONCLUSIONS AND SUMMARY

1.) In all petroleum basins examined, strong decreases in source-rock hydrogen indices toward the organically-mature basin deeps are not matched by numerically-equivalent increases in either Soxhlet-extractable hydrocarbons or the Rock Eval S_1 pyrolysis peak. Furthermore, the amount of oil in conventional deposits in basins is typically much smaller (1-5%, or less) than the hydrocarbons calculated to have been generated by the mature source rocks in the basin. Thus, based on recent petroleum-geochemical literature, primary migration was thought to be very efficient, whereas secondary migration and accumulation were very inefficient. Petroleum basins were thus inferred to be very leaky systems, and most generated hydrocarbons were thought to be lost through leakage over geologic time.

3.) Increasing basin richness (as measured by recoverable oil normalized to basin area) strongly correlates with increase in faulting over and adjacent to basin deeps. We hypothesize that faulting and fracturing are necessary to disrupt mature source rock systems and to free generated hydrocarbons for migration. Without such faulting, generated hydrocarbons would remain in the source rocks, or in the rocks adjacent to the source rocks, to extreme maturation ranks.

4.) In the Bakken source system of the Williston Basin, evidence suggests an exodus of oil from mature Bakken shales to adjacent rocks for vertical distances of at least 50 ft (15 m) in mature basinal locations.

5.) Bakken-shale bitumen and Bakken-produced oils do not resemble or correlate to Williston Basin mid-Madison oils. Furthermore, lack of viable migration paths would seem to preclude possible vertical migration of Bakken-generated oil to the mid-Madison reservoirs. The 100 to 150 billion barrels (15.9 to 23.8 x 10^9 m^3) of Bakken-generated oil certainly did not leak out of the basin without charging the conventional basinal reservoirs. We thus conclude that almost all of this generated oil remains in the Bakken source system in cracks, fractures, parting laminae, and matrix porosity.

6.) The mixed economic success of the Bakken play is probably due less to geologic reasons than to drilling, completion, and maintenance procedures inappropriate to the largely oil-wet Bakken source system.

7.) There are other examples of self-sourced, fractured-shale oil deposits that have been commercially produced and that have characteristics in common with the Bakken source system. Given the huge amount of oil generated from relatively thin Bakken source shales, the very thick and areally extensive source rocks in many different basins in the lower 48 United States may hold in-place oil resources on the order of tens of hundreds of trillions of barrels, a portion of which is clearly mobile and thus possibly recoverable.

8.) If such a large in-place oil resource base indeed exists, we believe that its recovery will depend on the development of new, non-classical exploration, drilling, completion, production, and maintenance techniques. Furthermore, a much closer working relationship, than has previously been the case, between research scientists and engineers of these varied disciplines will be ncessary.

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U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY - GEOLOGIC DIVISION

PROFESSIONAL/TECHNICAL PERSONNEL RECORD

1. NAME (last) (first) (initial)	2. Birth Date	3. Date prepared
Price Leigh C.	2/27/1944	1/26/93

4. Duty Station	5. Classification title	Series	Grade
Denver, Colorado	Geologist		14

6. List first and second scientific or technical specialties

a. Petroleum geology and geochemistry | b. General geochemistry

7. Other scientific, technical, or special skills (regardless of relation to present position)

Igneous studies, metamorphism, hydrothermal ore deposits, mineralogy

8. Education (including secondary schools)

School	Major and minor specialization	Dates Attended	Degree, year or anticipated year
Milliken High School		1960-1962	
Colo. School Mines	Chemistry	1962-1964	
Univ. California Riverside	Chemistry	1964-1966	BS, Chemistry 1966
"	Geology	1964-1973	BS, Geology 1968
"	Geology	1964-1973	MS, Geology 1970
"	Minor: Geochemistry	1964-1973	Ph.D, Geology 1973

9. Civil Service grades and dates **Career employee** yes

Grade	GS-12	GS-13	GS-14							
Date	1/7/74	7/30/78	6/82							

***Use asterisk for any grade obtained in a management or other nonresearch capacity above GS-12**

10. Specialized training (including post-graduate and government courses)
Esso Prod. Research Co., - Structural School
AAPG Clastic Diagenesis School 6/5-6/9 1978 Boulder, CO

11. Memberships in professional societies. List, give dates, and include significant offices held

American Association of Petroleum Geologists 1974-present
Association of Petroleum Geochemical Explorationists 1988-present
Rocky Mountain Association Petroleum Geologists 1991-present

12. SCIENTIFIC AND PUBLIC SERVICE

12a. Lectureships, symposia, invited conference participation. Give dates, nature of entry (were you sought out or did you apply to participate?) and level of participation.

1974 Gordon Research Conference on Organic Geochemistry - Invited to attend conference and give paper.
1974 AAPG Conference on Hydrology of Deep Sedimentary Basins - Invited to give paper.
1978 AAPG Short Course on Primary Petroleum Migration - Invited to give paper.
1981 AAPG Research Conference - Temperature environment of oil and gas - Invited to give paper.
1981 Fifth Conference on Geopressured - Geothermal Energy - Invited to give paper.
1982 AAPG Research Symposium at Annual Mtg. - Invited to give paper.
1985 SEPM Research Symposium: Determining the thermal history of sedimentary basins: Methods and case histories, AAPG Annual Meeting - Invited to give paper.
1985 Fourth Conference on Unconventional Methods in Exploration - Invited to give paper at SMU, May 3,4.
1988 - Ninth Annual Research Conference Gulf Coast Section SEPM - Invited to give paper, December 4-7. Gave two papers orally and two papers were published in the Symposium Volume.
1990 - Invited to and gave paper at Gordon Research Conference on Organic Geochemistry (1990) with all expenses paid by Conference. This is a prestigious meeting with only limited invitations offered, much less all expenses paid.
1991 - Invited to lecture at all principal universities and research centers in New Zealand in the fall of 1991, all expenses paid, by the New Zealanders. Approximately 30 lectures on seven topics given.
1991 - Invited to give talk at GSA/ACS cosponsored symposium on high temperature behavior of C_{15}+ HC's at Oct. 1991 National GSA Meeting, San Diego.
1991 - Invited to submit paper and abstract for talk ("On the Origin of Gulf Coast Neogene Oils) for 41st Annual Meeting of Gulf Coast Association of Geologic Societies, Houston, Oct. 16-18, 1991.

1991 - February. Invited to give, and gave, talk to University of California at Berkley Geology Department and gave 2-day short course to the organic-geochemistry group there.

1991 - July. Invited to give talk at Rocky Mt. Regional AAPG meeting Billings, Montana on Bakken fractured shale oil resource base for a Symposium on Horizontal Drilling.

From 6/1990 to 2/1991 I was invited to speak at five major oil companies on different topics.

1992 Invited to give talk at AAPG Hedberg Research Conference on Surface Geochemical Exploration to be held in 1994 (accepted invitation).

1992 Invited to give talk at ACS meeting on natural gas, to be held 8/93, Chicago (accepted invitation).

I routinely decline 3-6 invitations per year to give papers at symposia or meetings.

Univited:

1974 AAPG Annual Meeting - Applied to give paper at meeting.

1977 Third Conference on geopressured-geothermal energy - Applied to give paper at conference.

1978 AAPG Annual Meeting- Applied to give two papers at meeting.

1979 29th Annual Meeting GCAGS - Applied to give paper at meeting.

1992 8th Annual McKelvey Forum - Applied to give paper.

12b. Committees to render scientific judgment. Include scientific review panels, editorial boards, editorships, with dates. Include the capacity in which you served

1980 AAPG Annual Meeting - Poster committee judge and member of abstract review committee.

1992 Editor Journal of Petroleum Geology.

12c. List inventions, patents held, techniques or methods developed or improved. Include dates.

NA

12d. Other committees, special assignments, and administrative duties. Name organization, group, dates, and nature of contributions

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I am asked to, and do review, about 5 proposals per year for various organizations (DOE, NSF, etc.)

I am asked to, and do review 15-20 papers per year for outside journals, and/or symposia and conference volumes.

13. Honors, awards, recognition, elected membership. List and give dates.

NDEA Fellowship 1968-1972
Matson Award (Best Paper at National AAPG Mtg.) May 1973. At the time, youngest person ever to receive award.
AAPG Distinguished Lecturer Jan. 1974
AAPG Distinguished Lecturer Oct 1974 - April 1975
Matson Award (AAPG) May 1975. At the time, first person to ever receive award twice.
Best paper 29th Annual Meeting Gulf Coast Association of Geological Societies
Best Paper Branch of Oil and Gas - 1983
Third best talk, 1985 RMAG Luncheon Series
1990 - Branch Promotion Panel
1992 - Committee member on Ray Thomasson's/AAPG's oil resource assessment group for the U.S.

14. CAREER EXPERIENCE

Dates	Brief description of work and position (if USGS, give name of supervisor and organization
From To	

December, 1972-December 1973

Esso Production Research Co., P. H. Monaghan. Carried out independent research on the origin and migration of oil and gas.

January, 1974 - Present

USGS, Branch of Oil and Gas, P. R. Rose, R. F. Mast, P. A. Scholle, D. D. Rice, D. Gautier, T. Ahlbrandt. Responsible for designing and carrying out self-directed, unsupervised, original research related to the origin, migration, accumulation and post-accumulation processes of oil and gas to: 1) delineate processes of hydrocarbon (HC) origin and migration which result in conventional HC deposits and develop exploration strategies based on these processes; 2) define the thermal (depth) limits for conventional oil and gas deposits; 3) study unconventional exploration techniques (surface geochemical exploration) for conventional HC deposits based on accumulation/post-accumulation processes; and 4) study the possibility of unconventional HC-based energy resources, among which are: 1) geopressured-geothermal gas, 2) basin-centered gas, 3) deep-basin (high-rank) gas, 4) possible deep-basin conventional oil resources, 5) oil resource bases in self-sourced, fractured shales. Unless otherwise noted, I designed and was/am the sole and/or principal investigator of the projects below.

1974-1978

1. With no guidelines or supervision, I designed and supervised (up to 3 other people on the project) oil- and HC gas-aqueous experimental solubility studies carried out up to temperatures of 400°C, pressures of 30,000 psi, and in the case of oil, with and without methane or carbon dioxide in the system. These are fundamental experimental data which are pivotal to understanding the unanswered question of primary petroleum migration and which should have been available decades ago to the petroleum industry but were never gathered because of the pronounced experimental difficulties involved. The studies were carried to at the F. W. Dickson high pressure laboratory at Stanford University, a lab which I obtained the loan of (uncompensated use), for over two years. The data from this project allowed a definitive appraisal of the conditions in nature under which aqueous molecular solution could or could not act as an agent for primary oil migration. Products (Bib: 3,4, 7, 10, 16, 20; Abs: 1 (first Matson Award), 4, 10).
2. I designed and carried out a project, with no guidelines or supervision, to test the hypothesis that oils were not generated by, and do not migrate from, fine-grained rocks spatially close to the reservoirs where they are found. Instead, oils were hypothesized to originate from source rocks in the deeper (hotter) areas of petroleum basins ("HC kitchens") and undergo significant vertical or long lateral migration to their reservoirs. In this synthesis study, I examined oil occurrence in all major petroleum basins worldwide to check if worlwide HC occurrences corresponded to my hypothetical model (which they did). From the results of this

project, I advanced three points, very controversial at the time because of a then firm belief among petroleum geologists and most geochemists of a local and low temperature origin of oil. These three points, now accepted paradigms, were: A) In most cases, oil is not generated locally to reservoirs but is from the deeper, hotter areas of basins ("HC kitchens"). B) Major faulting extending to the basin deep is absolutely necessary as a vertical migration conduit from source rocks, thus HC deposits (in certain basinal classes) and should be exclusively associated with major faults. C) In foreland-foldbelt basins, long lateral oil migration (up to 1,000 miles) is common in flat-lying rocks on stable shelves. Specific exploration strategies for different basin types were developed in the products from this project: Products (Bib: 6, 9, 13, 15 (13 and 15 impact papers); Abs: 5 (second Matson Award), 9)

<u>1974-Present</u>

1. I designed and have continuously carried out an unguided, unsupervised research project to delineate and provide evidence for possible controlling parameters of organic metamorphism in nature from: A) petroleum-geochemical analyses of rocks from nature, B) laboratory experiments, and C) literature data where available. Early data I had strongly conflicted with the then current models of organicmetamorphism centered around only geologic time and burial temperature controlling first-order reaction kinetics. Five controls (besides burial temperature) have since been identified and are being studied:
    1. Geologic Time: In a 1983 impact paper (Bib: 21), I took the (unpopular) position and provided substantial evidence that the effect of geologic time (first-order reaction kinetics) had been significantly overestimated in organic metamorphism. This position has currently (1993) been supported by other investigators and the effect of time in computerized models has been scaled back from 1970-1985 estimates. Products: (Bib: 21, 25; Abs: 13, 14).
    II. Organic Matter (OM) Type: A large body of my unpublished data demonstrates that: A) OM type is a profound and unappreciated controlling parameter of the maturation ranks over which HC generation occurs. B) The widely-quoted maturation ranks estimated for HC generation from the different OM types are in substantial error. C) In sulfur-poor OM, as the original hydrogen content of the OM increases so do the burial temperatures required for HC generation because of increasing kerogen bond strength. Two major papers are in preparation. Products (Bib: 26, 40; Abs: 16, 25).
    III. Pressure: Laboratory aqueous-pyrolysis experiments conclusively demonstrate that increasing fluid pressures strongly retard all aspects of organic metamorphism including HC destruction. Products (Bib: 42; Abs: 20, 21).
    IV. Water: Retards HC destruction and enriches kerogen in hydrogen. Laboratory experiments are in progress.
    V. System Openness: Product escape promotes organic metamorphic reactions, product retention retards it. Laboratory experiments are in progress.

2. I have designed and carried out an unsupervised and unguided project on the detailed petroleum-geochemistry of ultra-deep (to 31,000') high-rank (to R_o = 7.0-8.0) well bores to define and provide evidence for the: A) true limits of C_{15}+ HC

thermal stability, and B) the ranks over which the different OM types go through (and end) mainstage HC generation. The large data base from this research project provides strong evidence that C_{15}+ HC's are thermally stable for beyond the hypothesized end of the oil window at R_o = 1.35. Although this stand previously was highly controversial, other investigators have recently published evidence supporting the proposition of extended C_{15}+ HC thermal stability, and many petroleum geochemists now orally acknowledge that the HC deadline at R_o = 1.35 is erroneous. The results of this study: A) suggest that in certain basins conventional oil deposits may exist at greater ranks than R_o = 1.35, and thus resource-base estimates of conventional oil reserves may be too low; and 2) suggest that source rocks could "hold" their generated HC's long after generation and finally release them at high ranks when migration routes (faulting) becomes available. An extended thermal stability of HC's to higher maturities also obviously has other strong implications for numerous different petroleum geochemical topics. Products (Bib: 11, 18, 19, 30, 36, 44; Abs: 3, 11, 19, 26.)

Two "sub-projects" are associated with this study:

2A. Research to demonstrate that the very strong and large bodies of evidence supporting the hypothesized end of the oil window at Ro = 1.35 are due to other processes operating in petroleum basins. Products (Bib: 14, 32, 45; Abs: 2, 27).

2B. Research delineating the compositional changes which take place in saturated and aromatic HC's as the true HC thermal destruction is approached and gone through by studying bitumens: A) generated by increasingly high-temperature, aqueous-pyrolysis experiments; B) from rocks at the bottom of high-rank wellbores, and C) from metamorphic rocks or rocks from hydrothermal mineral deposits. Products (Bib: 44; Abs: 26).

3. I have carried out an unguided and unsupervised research project to evaluate: A) the presence of a probable deep, geopressured-geothermal energy base in the Gulf Coast; B) the controlling parameters of this energy base; and C) the factors controlling the feasible economic recovery of this energy base. This research strongly suggests that an essentially infinite gas-resource base exists (in some petroleum basins) and is rooted in the presence of a dispersed, free-gas phase at low concentration levels (1-5 volume percent) in the porosity of deeply buried sands and shales in addition to the high levels of gas dissolved in the pore waters of these rocks (determined from my pevious solubility studies of gas in water). Wells tapping this resource should flow gas only, at high rates (100-200 MMCF per day) with none of the water production problems associated with the Department of Energy's current geopressured production technique (surface extraction of methane dissolved in brines) in the Gulf Coast. Evidence for the existence of this energy resource base has recently also been provided by the work Roger Anderson at Lamont-Doherty. Anderson has also proposed the same production technique which I previously proposed. Products (Bib: 5, 8; Abs: 6, 7, 8).

1977-1990

I designed unsupervised, unguided research projects to carry out three solubility studies at Idaho State University; approached the reserachers there to obtain use of their facilities; and wrote a proposal to DOE to obtain funding for the projects, which were funded by DOE for four years for a little over $400,000. Furthermore, I was the chief investigator in all these projects. Two of the studies were:

A) Aqueous methane solubility as a function of variable NaCl content, variable high pressures, variable high temperatures, and the presence of other gases (1977-1981).

B) The solubility and solution kinetics of methane in waters of variable NaCl concentrations at low and variable temperatures and pressures (1977-1981).

Both of these studies provided fundamental petroleum-geochemical data which are pivotal for a number of different petroleum geochemical topics and were extensions of previous work (1974-1978) I did at Stanford University. I designed the sampling and analytical methods for both studies and helped design the experimental (pressure vessel) approach. These methods and approaches allowed the acquisition of very difficult sets of experimental data which are necessary for valid modeling of different petroleum geological and geochemical topics. Products (Bib: 12, 17; Abs: 12).

C) The third study involved experimental determination of the solubility of oil in methane gas with water present at variable and elevated temperatures (50°-250°C) and pressures (1,000-15,000 psi). The data from this study demonstrated that primary oil migration by gaseous solution was possible in nature. I designed the experimental approach and sampling and analytical methods for this project which allowed acquisition of another pivotal set of petroleum-geochemical data, which had previously been impossible to take. The data were taken during (1977-1981), however, this aspect of the DOE project was part of a longer term research project of my own which was to delineate the controlling parameters, limitations, characteristics, and applications to nature of primary oil migration by gaseous solution. Products (Bib: 22, 31 (both impact papers), 32; Abs: 15).

1980-Present

1. I have carried out an unsupervised and unguided research project to define the controlling parameters of the generation and accumulation of both conventional and non-conventional (deep-basin, high-rank, and basin-centered) gas deposits and gas resource bases and their respective characteristics. Some important points have resulted form this study: A) Basin-centered gas deposits originate from a specific set of basinal processes and which basins should have these deposits can be specifically predicted. B) Methane in "dry-gas" deposits appears to originate mainly as gas co-generated with $C_{15}+$ HC's and not from $C_{15}+$ HC thermal destruction. True high-rank methane deposits from $C_{15}+$ HC destruction do exist but are rare. C) Many deep portions of most sedimentary basins appear to be closed systems regarding fluid flow such that only limited, or no-, deep-basinal fluid flow occurs when no faulting is present. Thus the size of deep-basin-basin gas resource bases may be

significantly larger than previously thought, and their grade (richness or concentration) also may be much higher than previously thought. By comparing gas data from two unique sources with gas data from nature, unique insights into the natural system are possible, which would not otherwise be the case. These two sources are: A) Gases have been generated and analyzed from six different rocks (of variable OM types) over wide temperature ranges (150°-550°C) in aqueous-pyrolysis experiments I've carried out (see below). B) In a project with Martin Schoell at Chevron, gases are being collected directly from one source rock (Bakken shale) of variable (and known) maturities by taking gas samples co-produced with Bakken oil. This is the first time such a unique set of gases (directly from a source rock) have ever been available. The gas compositional data from both the Bakken oils and aqueous-pyrolysis experiments agree with each other and are much wetter than predicted by existing models. Products (Bib: 34, 45; Abs: 27).

2. I have designed and carried out an unguided, unsupervised research project centered on aqueous-pyrolysis experiments using different organic-rich "source rocks (six as of 1/1993) in small pressure vessels to delineate possible controlling parameters of organic metamorphism in Nature. These experiments are being carried out with widely variable conditions - e.g.: temperature (150°-550°C in 25°C intervals: pressure (100-30,000 psi), time (4 hours to 1 year); water content; and system openness (product escape). Because of the wide scope of both experimental conditions and rock types and because all products (from methane to the asphaltenes) are being collected and analyzed, along with the reacted rocks, this study provides unique data sets which are simply unavailable from other sources. I cannot over emphasize the pivotal applications the different data sets from this study have had, and will continue to have, to different areas of study in petroleum geology and geochemistry. The unique experimental techniques and sampling and analytical methods which I designed allows all reaction products to be trapped and analyzed unlike many other similar studies, which capture only part of the total products. Also, my reaction vessels are smaller and much cheaper than other experimental techniques and thus allow more versatility than many of these other techniques. This study is being jointly carried out with Lloyd Wenger of Exxon Production Research CO. (EPR), and EPR has supplied both funds (about $17,000 as of 1/93) and manpower (other than Wenger) towards the project. Products (Bib: 40, 42, 45; plus parts of 31, 34, 44; Abs: 20, 21, 25, 27; plus papers in preparation).

3. I have carried out a long-term, unguided, and unsupervised extensive petroleum geochemical study of the Williston Basin, centering on the Bakken shale, but extending to all rocks from the Tertiary to Devonian. This study will, when complete, provide a huge data base with application to: A) resource assessment; B) organic-geochemical modeling; C) basin-wide thermal maturation maps at all depths for the basin; D) testing established organic geochemical precepts and hypothesizing alternate concepts, when necessary; E) evolution of the Williston basin; and F) highlight the Bakken shale as a "type section" for oil resource bases in self-sourced fractured shales. Products (Bib: 23, 28, 29).
   A number of realted research projects have spun off this study:

1990-Present

3A. Previous hypotheses appear erroneous that HC expulsion from organic-rich rocks is very efficient and accumulation is very inefficient such that most generated HC's are lost along secondary migration paths or as leakage to the surface. Instead, data I've gathered from the Williston basin, centered on the Bakken shale, strongly suggest that most generated HC's are retained in, or directly adjacent to, the source rocks that generate them when such source rocks are not faulted. Of the 100-250 billion barrels of oil that the Bakken shales are known to have generated, none has yet been identified in any of the conventional mid-Madison reservoirs of the Williston Basin (see 3B below). This suggests that a huge in-place oil resource base exists in the Williston Basin, a resource base which can be extrapolated to the order of tens to hundreds of trillions of barrels of generated oil for all source rocks in all lower 48 oil basins. As of 1/91, my goals in this project are to provide solid evidence to the scientific community of the existence and magnitude of this in-place oil-resource base such that it will be better appreciated and taken seriously. Long-term goals are to delineate the characteristics and controlling parameters of this resource base such that non-classical drilling, completion, stimulation, and maintenance techniques, which are appropriate to the unique characteristics of this resource base, can be applied to affect possible economic recovery of a significant part of the resource base. This is because it has become quite clear that application of conventional recovery techniques will take only a minute percentage (far less than 1%) of the resource base. On the other hand, only a 10-25% economic recovery of this in-place oil resource base would profoundly affect long-term U.S. energy policies and needs. Products (Bib: 43; Abs: 23, 24).

1991-Present

3B. A detailed petroleum-geochemical cross comparison between 15 Bakken-produced oils and 18 mid-Madison produced oils (all from the Williston basin) is being completed. These two groups of oils are different oil families, a conclusion (and the documentation of which) have strong application to: A) the self-sourced, fractured-shale oil resource base (3A, above) in the Bakken shales (and in other source rocks of the of the lower 48); B) a much better understanding of expulsion and accumulation processes, and the controlling parameters thereof, for conventional oil deposits; and C) a better delineation and understanding of "petroleum systems" (source-rock/reservoir plumbing pairs), because the Bakken shale-mid Madison petroleum system, one of our best examples of a "petroleum system", doesn't exist. The importance of the facts to petroleum geochemistry that: 1) the Bakken shales have not sourced the mid-Madison oils in the Williston Basin, and 2) no Bakken oil has yet been found in a mid-Madison reservoir, cannot be overemphasized. (A paper is almost completed).

3C. Bakken rock samples from 16 wells (or wells very close, ± 1 section) to the wells which produced the Bakken oils of "3B" (above) have been analyzed by ROCK EVAL for maturity and will be compared with numerous maturity indices of the produced oils. Other Bakken-produced oils and accompanying rock samples are also being collected for this study. Martin Schoell at Chevron is also running specific carbon isotope analysis on some of these oils. This will be the first time that the maturities of a suite of oils can be directly compared to the maturities of the rocks which are unequivocally known to have sourced the oils. (The rocks have a wide maturity range e.g. - beginning HC generation to post mature.) This study will provide much better insight into both the validity of oil maturity indices currently in use and into the origin of single oil families as observed in the cases of long lateral oil migration on the stable shelves in different basins.

3D. The 18 mid-Madison oils of "3B" (above) have been augmented by mid-Madison oils from Manitoba and Saskatchewan (supplied by the Canadian Geological Survey) and also by other oils on the American side of the Williston Basin. These oils represent a full suite of an oil family of a wide maturity range which has undergone known long lateral oil migration and oil geochemical characteristics will be cross compared versus both distance of migration and oil maturity. This study will provide more insight into changes in oil parameters versus both increasing migration distance from the generation site and maturity for a single oil family.

3E. A study has been initiated to examine organic facies changes in the Bakken shales for a traverse of immature shales from the 15-20% TOC/800-900 hydrogen index shales in North Dakota, east-northeast to the 5-10% TOC/100-300 hydrogen index shales of Saskatchewan and Manitoba. Also vertical organic facies changes will be examined in immature Bakken shales from single wells as formation contacts are approached (15-20% TOC/800-900 hydrogen index shales go to 1-2 TOC/100-300 hydrogen index shales.) This study will provide well documented insight into the control that organic-matter facies variations have on many different petroleum geochemical parameters of source-rock bitumen and kerogen.

<u>1981-Present</u>

1. I initiated an unsupervised, unguided large petroleum-geochemical source rock study for the California petroleum basins. This study centers around a very large sample base of fine-grained rocks from the California basins which I have assembled, and when complete this study should contribute to: A) the application of organic geochemistry to possible HC exploration of the onshore and highly prospective offshore southern California petroleum basins; B) help delineate the controls that OM type has on organic metamorphism; C) general studies of the California Miocene rocks; and D) a detailed petroleum geochemical data base for three of the richest basins (normalized to sediment amount) in the world (Los Angeles, Ventura, and Southern San Joaquin).

<u>1983-Present</u>

1. I initiated and have overseen an unguided, unsupervised, very large cooperative study of HC microseepage (surface geochemical exploration-SGE). It is recognized that even in mature American Basins, much more oil exists in subtle structural and stratigraphic traps on the stable shelves of certain basins than has yet been found.

Although this oil may represent a possible significant resource base, this oil has gone undiscovered because no good exploration tool exists to look for it. Indeed SGE presently represents the only possible tool. However, SGE is a field which has minimal background scientific research and minimal credibility with explorationists and has previously proven to be impossible to apply as a consistently useful exploration tool.

This study of HC microseepage and SGE has been designed designed to: A) ascertain if it is possible to unambiguously detect HC mciroseepage and/or its effects on the rocks through which it vertically passes; B) distinguish HC microseepage from other forms of vertical HC migration; and C) determine if anomalies based on measurement of present-day HC microseepage (direct detection), or based on measurement of altered rock properties (indirect detection), have any geometrical coincidence to the surface outline of petroleum deposits, and thus can be used as exploration tools. Three different techniques have been studied in detail: one was an outright failure; another, also a failure, demonstrated why many previous (and present-day) SGE techniques have failed. The third technique, microbial soil surveying appears to be a possible powerful exploration tool. Even a partially successful completion of this project could have a profound impact on: A) oil exploration for stratigraphic, and other subtle, traps in the U.S.; B) specifically delineating areas of by-passed oil (due to reservoir heterogeneity) for enhanced oil-recovery techniques in mature large to giant fields; C) significantly decreasing new field development costs by outlining surface traces of newly discovered fields before development drilling, which would eliminate or greatly decrease the number of expensive and wasteful dry stepout wells around the field; D) a tool to confirm or condemn wildcat drilling sites generated by conventional geologic techniques; E) a research tool to study reservoir heterogeneity, field shapes, and secondary migration paths. Products (Bib: 27 (impact paper in field), 24; Abs: 17; two papers are in preparation).

<u>1989-Present</u>

1. I began an unsupervised, unguided study to delineate compositional changes of aromatic HC's versus maturation rank. This study involves detailed identification of many of the aromatic HC's found in complex distributions in different well-controlled suites of oils, powdered-rock extracts, whole-rock extracts (see below), and bitumens from laboratory (aqueous-pyrolysis) experiments. Compositional changes in these compounds are being examined versus maturation rank. (Maturity index trends within the saturated and gasoline-range HC's are also being run for some of these suites). This study, when complete, should provide much better insight into changes in maturity trends in oils and bitumens.

<u>1990-Present</u>

1. A joint research project with Lloyd Wenger at Exxon Production Reserach to firmly define changes in biomarkers versus maturity from: A) the aqueous-pyrolysis runs, B) oil suites of variable maturity, and C) different rock sample suites of variable maturity. Work by different investigators has shown that the utility of many

biomakrer ratios as maturity indices has been overstated, because both facies (organic matter type) and primary migration effects (and probably other unidentified effects) can strongly change biomarker ratios. This work will contribute to clearing up some of the questions about biomarker utility.

<u>1991-Present</u>

1. I initiated an unguided, unsupervised research project to document and provide evidence of the prefractionation that occurs in source-rock bitumen into an oil-like phase and moves (or is moved) to cracks and parting laminae in source rocks to be poised and ready for migration from the rocks. This fractionation occurs in rocks at all stages of HC generation (including rocks that have not yet begun HC generation) and is probably caused by HC gases. The fractionated oil-like phase is not seen by conventional Soxhlet extraction of powdered rocks, only by Soxhlet extraction of whole (unground rocks). This fractionation has not been observed before because we petroleum geochemists have always extracted powdered rocks, such that the rock matrix (and evidence of bitumen fractionation) was destroyed. It is thus a strong possibility that many of our previous petroleum geochemical analyses could be based on an erroneous analytical technique. This work has profound implications regarding: A) proper laboratory techniques which must be used to achieve valid oil-source rock correlations; B) insights into primary migration mechanisms; C) validity of maturity and source facies indices; and D) origin of small oil deposits at immature ranks. Two study approaches are being used: A) Five Bakken oil-source rock pairs (where oil has been actually produced from the rock samples) are being correlated using rock bitumen from Soxhlet extraction of both powdered rocks and whole rock samples; B) whole rock (core) of varying maturities of Bakken shale (6 each) and coal (5 each) are being successively extracted (8-10 extractions). Powdered samples of the same rock are also being extracted. The extracts are being subjected to full petroleum-geochemical workup to show the significant differences between sequential whole-rock extractions from oil-like in the first extracts to tar-like in the latter extracts and the significant differences between whole rock versus powdered
rock extracts. Products (Bib: 41).

2. I initiated a research project to test the hypothesis that source rocks must be physically disrupted by faulting for significant oil expulsion to occur. A study has been completed which documented that increasing basin richness (EUR oil/basin sediment volume or area) strongly correlates with increasing intensity of normal or extensional faulting in the basin deep containing mature HC kitchens. This study covered 85-90% of world's known reserves, and thus supports the above hypothesis. For example, wrench basins, are by far the most structurally-intense basinal class and are also by far the richest basinal class and have the greatest number of oil-productive basins of all basinal classes. Cratonic ("pancake") basins are the least structured basinal class, have the fewest number of producing basins, and by far are the poorest basinal class. This work has strong application to resource assessment as a function of basinal class, frontier exploration evaluation, HC expulsion, and

provides further evidence for the existence of large in-place oil-resource bases in mature (self-sourced) fractured source rocks. Products (Paper in TRU review).

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27. Dyman, T. S., Schmoker, J. W., Spencer, C. W., Perry, W. J., Jr., Price, L. C., Palacas, J. G., Dolton, G. L., Burruss, R. C., Keighin, W. C., Hester, T. C., Wandrey, C. J., Vaughan, D. K., Nielsen, D. T., Obuch, R. C., Baird, J. K., and Westcott, P. A., [accepted], Geologic controls and resource potential of natural gas in deep sedimentary basins in the U.S. [abs.]: American Association of Petroleum Geologists National Meeting, New Orleans, La., April 25-28, 1993.
(Branch Chief approval 17-Sept-1992, and CTR log-in 18-Sept-1992.)

16. SIGNIFICANT CONTRIBUTIONS

Price, L. C., and LeFever, J. A., 1992, Does Bakken horizontal drilling imply huge oil-resource bases in fractured shales? *in* Geological Studies Relevant to Horizontal Drilling, Western North America (Schmoker, J., ed.): Rocky Mountain Association Geologists, p. 199-214.

Based on my work on oil expulsion, expulsion appears very inefficient and most HC's generated in source rock may never leave the system, unless the rocks are physically disrupted by faulting and fracturing. The inefficien of expulsion, combined with detailed petroleum geochemistry carried out in the Williston Basin and on the Bakken Shale, has led to the proposal of a previously unrecognized monstrous in-place oil- resource base (tens t hundreds of trillions of barrels) in brittle, fractured, mature, self-sourced shales in the lower 48. Research is bei carried out on the topic using the Bakken shales as a "type section". A part of this resource base is mobile and may be recoverable; however, recovery will depend on the development of new exploration, drilling, completio and production techniques applicable to the unique characteristics of this resource base.

Price, L. C., and Clayton, J. L., 1992, Extraction of whole vs. ground source rocks: Fundamental petroleum geochemical implications including oil-source rock correlation: Geochimica et Cosmochimica Acta, v. 56, 1213-1222.

Oil expulsion is the least understood aspect of petroleum geochemistry and oil-source rock correlation is the mo difficult operative aspect in this field. This paper demonstrates that an oil-like phase is fractionated from bitumen (probably by HC gases) during, and even before, intense HC generation. Thus, good oil-source rock correlations are best achieved by whole (unground) rock Soxhlet extractions, where only a small part of the HC in source rocks (residing in fractures and parting laminae) are taken in the first extractions, in a series of successive extractions. Bitumens from extractions of powdered rock, the time-honored method, do not correlat as well to oils because the whole extracted bitumen is unlike the oil which has been fractionated from the bitumen and which has migrated from the rock. This paper demonstrates both why oil-source rock correlation has previously been so difficult and how such correlations may be better achieved. The paper also: 1) explains t origin of small oil deposits from immature source rocks; 2) provides significant insights into expulsion mechanisms; and 3) discusses severe modification of maturity and source-facies indices (including biomarkers) this pre-migration source-rock fractionation.

Non-Publication Contribution

As stated in my Position Description (PD), my charge of duties for the Branch is to research, understand, and evaluate: 1) possible unrecognized significant conventional HC resource bases, 2) possible new, unconventional exploration methods for conventional HC resource bases, and 3) possible significant unconventional HC resour bases. Also as stated in my PD, "Incumbent's research requires an extreme degree of originality in pursuing no traditional solutions to important problems." I have provided large data bases and detailed discussions of both 1) very large in-place, mobile, oil-resource bases in self-sourced fractured shales (Bib: 43, Abs: 23,24); 2) much larger and higher grade deep-basin unconventional gas resource bases than previously thought to be the case (Bib: 34, 45; Abs: 27); and 3) evidence and discussion of a deep geopressured-geothermal resource base in the G Coast (Bib: 45, 8,; Abs: 6, 7, 8). Furthermore, I am currently preparing a major paper on the use of microbial soil surveying to explore for conventional HC deposits in the flat-lying sediments on the stable shelves of basins where no good exploration currently exists to explore for such deposits. This will be the first in a series of pape on the general use of surface geochemical exploration culminating eight years of laboratory research. This worl will be a major contribution in the field which follows a previous impact paper (Bib: 27; Abs: 17).

By fully meeting my charge as outlined in my PD, I am helping the Branch meet its charges. Lastly, in pursuing research on unconventional topics, often by unconventional research methods, a high degree of individualized effort is required, such effort should not be mistaken as lack of "team playing".

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