PS Production of Migrated Oil from Horizontal Wells Landed in the Eagle Ford on the San Marcos Arch*

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Abstract

Migrated oil produced from the Austin Chalk and the Buda Formation in south Texas was generated by – and expelled from – deeper Eagle Ford source-rock beds. The origin of oil samples produced from Austin Chalk, Eagle Ford, and Buda reservoirs on the San Marcos Arch was determined by comparing their composition to the composition of extracts obtained from conventional core plugs selected in the Austin Chalk and Eagle Ford Formation at two nearby wells. Lower Eagle Ford (LEF) marl core plugs are very good source rocks that contain oil-prone kerogen at VRE ≈0.70. Upper Eagle Ford (UEF) and LEF clay shale core plugs are good source rocks that contain oil + gas-prone kerogen, while leaner Austin Chalk core plugs contain only gas-prone or inert kerogen. HRGC data were used to calculate oil source and maturity parameters, classify the oil samples, and allocate commingled samples. The API gravity of the produced oil samples is controlled by the temperature at which they were generated. Oil extracted from core plugs selected in a deeper well was generated at a slightly higher temperature than oil extracted from the same stratigraphic intervals in a shallower well. Two geochemical source parameters that utilize only saturate compounds indicate that the extracts obtained from the shallower well and the produced oil samples were generated by the same kind of oil-prone kerogen that is different than the oil-prone kerogen that generated the extracts obtained from the deeper well. But extracts obtained from LEF marl core plugs selected in the shallower well are assigned to a different family than the produced oil samples using HRGC peak-height ratios that include aromatic compounds because all Eagle Ford core-plug extracts are enriched in aromatic compounds compared to the produced oil samples. Allocation results using the produced oil samples indicate a 30°API oil obtained from the Austin Chalk is a migration mixture of medium-gravity oil generated locally by the LEF marl, and much lighter oil that migrated laterally and updip. An oil produced from a horizontal well landed in the UEF is a commingled production mixture of end-member oil samples obtained from the Austin Chalk and from the UEF at a nearby vertical monitor well. Similarly, the oil produced from a horizontal well landed in the LEF reservoir is a commingled production mixture of end-member oil samples obtained from the LEF marl and the underlying Buda Formation. Allocation results for extracts obtained from several UEF core plugs indicate the basal portion of the UEF also contains some oil that was generated and expelled locally by LEF marl source-rock beds. UEF SR beds have not efficiently charged the overlying Austin Chalk reservoir because they have not generated a significant amount of oil at low thermal maturity. These results can be used to help de-risk the charge of light oil in the Austin Chalk that was generated and expelled by very mature Eagle Ford SR beds, migrated updip via the Buda regional carrier bed, and then migrated vertically into the Austin Chalk via faults that penetrate the Eagle Ford top seal.

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Abstract

Migrated oil produced from the **Austin Chalk** and the **Buda Formation** in south Texas was generated by – and expelled from – deeper Eagle Ford source-rock beds. The origin of oil samples produced from **Austin Chalk**, **Eagle Ford**, and **Buda** reservoirs on the San Marcos Arch was determined by comparing their composition to the composition of extracts obtained from conventional core plugs selected in the **Austin Chalk** and **Eagle Ford Formation** at two nearby wells. **Lower Eagle Ford (LEF) marl** core plugs are very good source rocks that contain oil-prone kerogen at VRE ≈0.70. **Upper Eagle Ford (UEF)** and **LEF clay shale** core plugs are good source rocks that contain oil + gas-prone kerogen, while leaner **Austin Chalk** core plugs contain only gas-prone or inert kerogen. HRGC data were used to calculate oil source and maturity parameters, classify the oil samples, and allocate commingled samples. The API gravity of the produced oil samples is controlled by the temperature at which they were generated. Oil extracted from core plugs selected in a deeper well was generated at a slightly higher temperature than oil extracted from the same stratigraphic intervals in a shallower well. Two geochemical source parameters that utilize only saturate compounds indicate that the extracts obtained from the shallower well and the produced oil samples were generated by the same kind of oil-prone kerogen (which is different than the oil-prone kerogen that generated the extracts obtained from the deeper well). But extracts obtained from **LEF marl** core plugs selected in the shallower well are assigned to a different family than the produced oil samples using HRGC peak-height ratios that include aromatic compounds because all **Eagle Ford** core-plug extracts are enriched in aromatic compounds compared to the produced oil samples. Allocation results using the produced oil samples indicate a 30°API oil obtained from the **Austin Chalk** is a migration mixture of medium-gravity oil generated locally by the **LEF marl**, and much lighter oil that migrated laterally and updip. An oil produced from a horizontal well landed in the **UEF** is a commingled production mixture of end-member oils obtained from the **Austin Chalk** and from the **UEF** at a nearby vertical monitor well. Similarly, the oil produced from a horizontal well landed in the **LEF** is a commingled production mixture of end-member oil s obtained from the **LEF marl** and the underlying **Buda** Formation. Allocation results for extracts obtained from several **UEF** core plugs indicate the basal portion of the **UEF** contains some oil that was generated and expelled by **LEF marl** source-rock beds. **UEF** SR beds have not efficiently charged the overlying **Austin Chalk** reservoir because they have not generated a significant amount of oil at low thermal maturity. These results can be used to help de-risk light oil charge in the **Austin Chalk** that was generated by downdip Eagle Ford SR beds, migrated updip via the **Buda** carrier bed, and then vertically along faults penetrating the **Eagle Ford** top seal.

1. INTRODUCTION: THE GENERATION AND MIGRATION OF EAGLE FORD OIL INTO UPPER CRETACEOUS RESERVOIRS ON THE SAN MARCOS ARCH

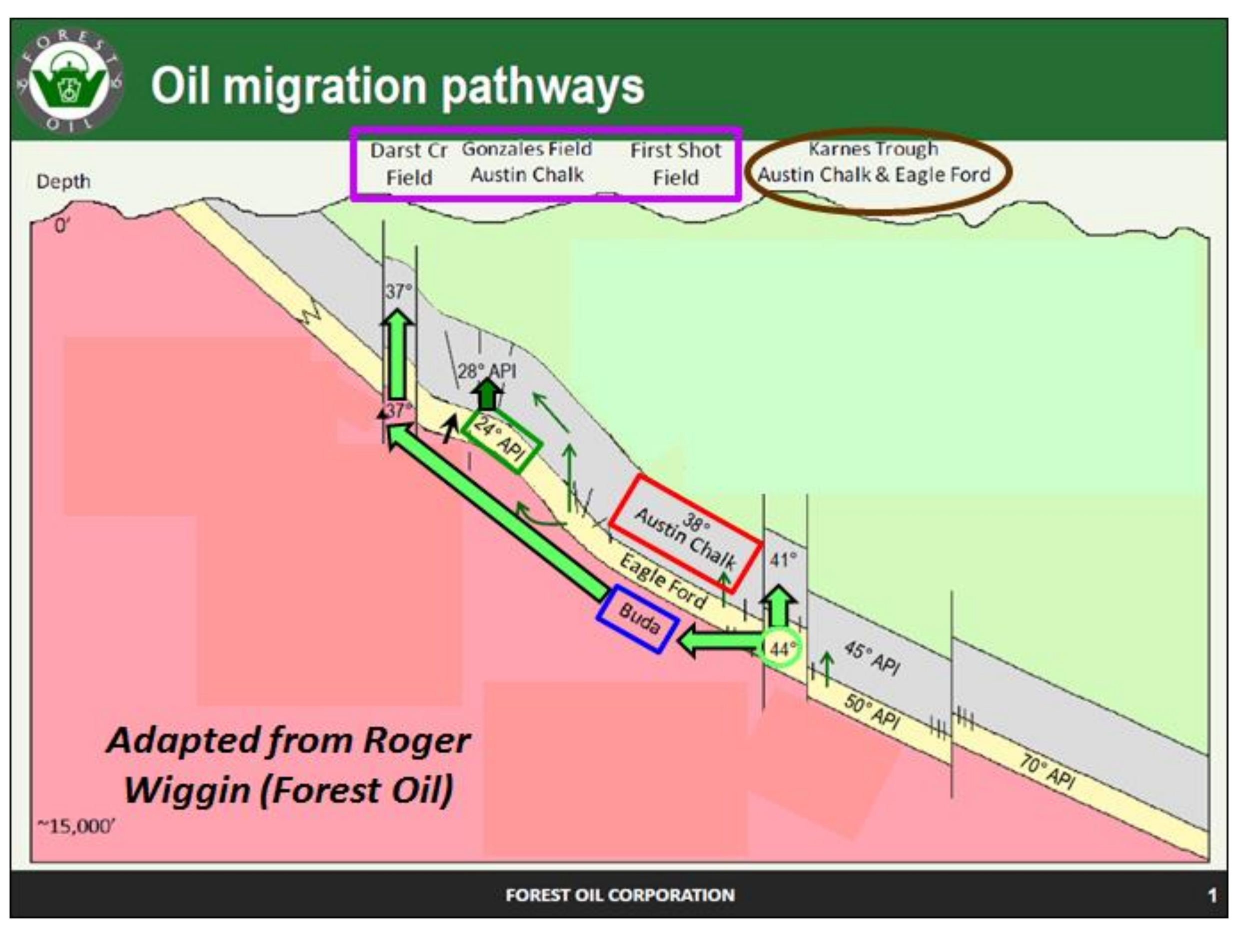


Figure 1. Model of the migration of Eagle Ford oil into the Austin Chalk and Buda reservoirs.

Oil produced from the **Austin Chalk** and the **Buda** Formation was generated by Eagle Ford source-rock (SR) beds (Zumberge et al., 2016). The light (≥30°API) oil produced from those reservoirs where Eagle Ford SRs only are in the early oil window migrated laterally and updip after it was expelled by deeply buried Eagle Ford SR beds (Figure 1).

I used high-resolution GC (HRGC) data measured on oil samples produced from **Austin Chalk**, **Eagle Ford**, and **Buda** reservoirs on the San Marcos Arch – which separates the South Texas Basin and the East Texas Basin – and oil extracted from center-cut conventional core plugs selected in the **Austin Chalk**, the **Upper Eagle Ford (UEF)**, and the **Lower Eagle Ford (LEF) marl** and **LEF clay-shale** at two nearby wells to study the migration and mixing of crude oil generated by **UEF** and **LEF** SR beds.

2. SELECTION OF PRODUCED OIL SAMPLES AND CONVENTIONAL CORE PLUGS

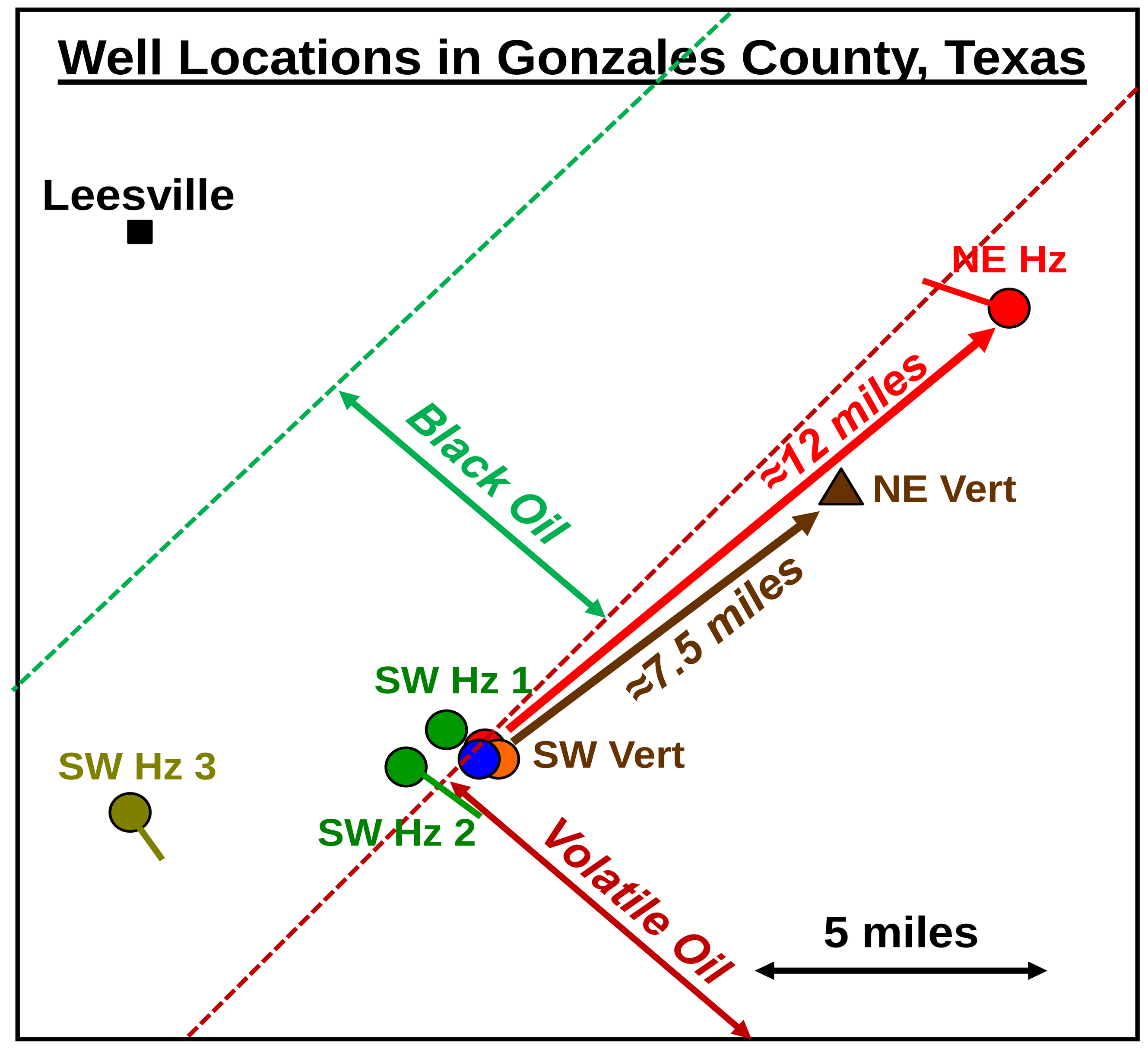


Figure 2. Map of vertical and horizontal wells where oil samples and core plugs were obtained.

Core plugs were selected from the **Austin Chalk**, the **UEF**, and the **LEF marl** and **clay-shale** at the NE Vertical Well. Core plugs also were selected from the **UEF** and from the **LEF marl** at the shallower SW Vertical Well (Figure 2). The **LEF marl** is a very good oil-prone SR. The **UEF** and **LEF clay-shale** are good SRs that contain oil + gas-prone kerogen. The **Austin Chalk** is very lean – it contains only gas-prone or inert kerogen.

Oil samples produced from the **Austin Chalk, UEF,** and **Buda** Formation were obtained at the SW Vertical Well. Oil samples also were obtained from SW Horizontal Wells #1-#3 (landed in the Eagle Ford Formation), and from the NE Horizontal Well (landed in the **Austin Chalk**).

3. UPPER AND LOWER EAGLE FORD STRATIGRAPHY AT THE VERTICAL WELLS

The Eagle Ford Formation is <100 feet thick in the study area. At this location, the basal Eagle Ford is an argillaceous mudstone (**clay-shale**) that thickens in the direction of the NE Vertical Well (towards the East Texas Basin). The **UEF** and the **LEF marl** are thinner in that direction (Figure 3).

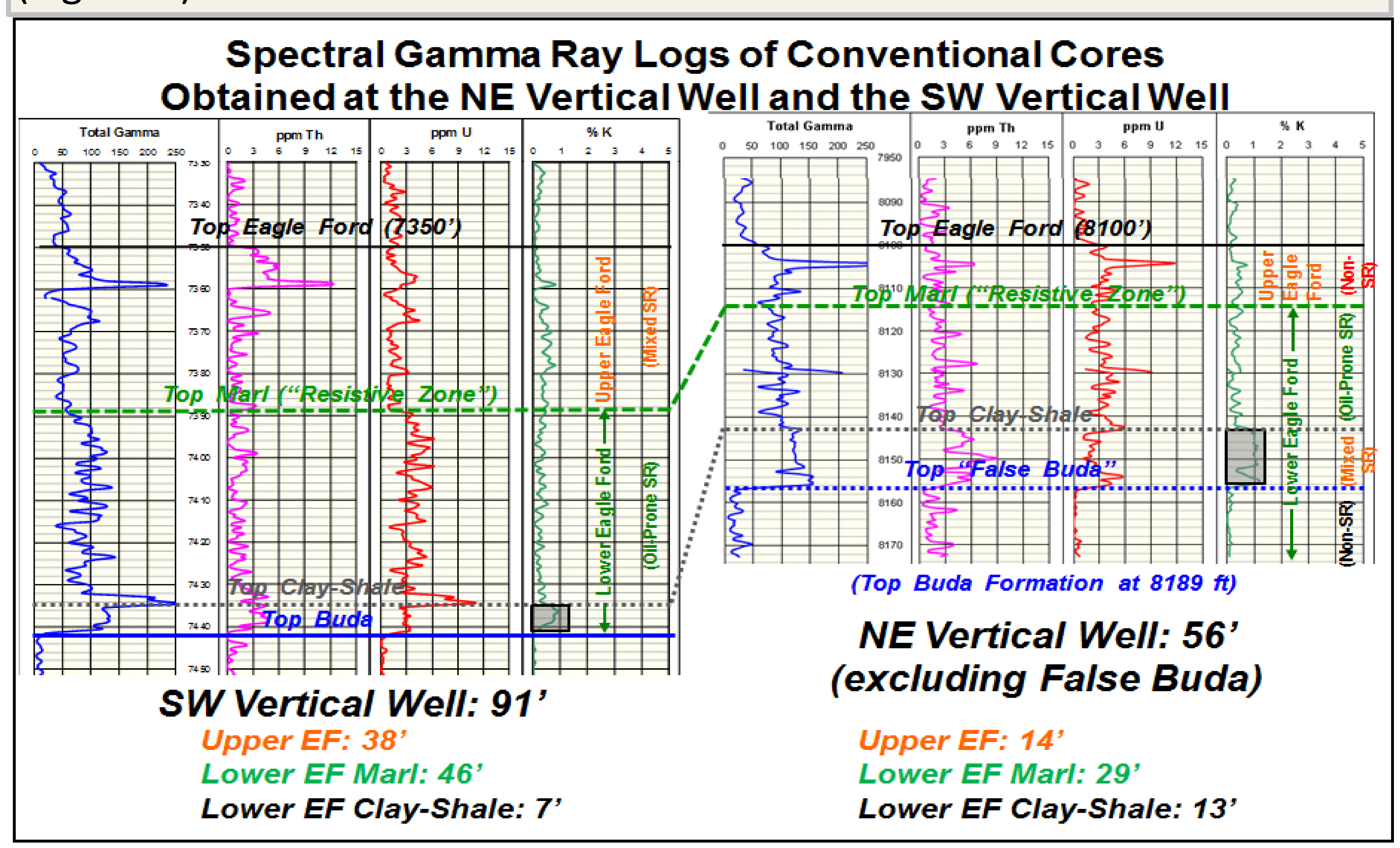
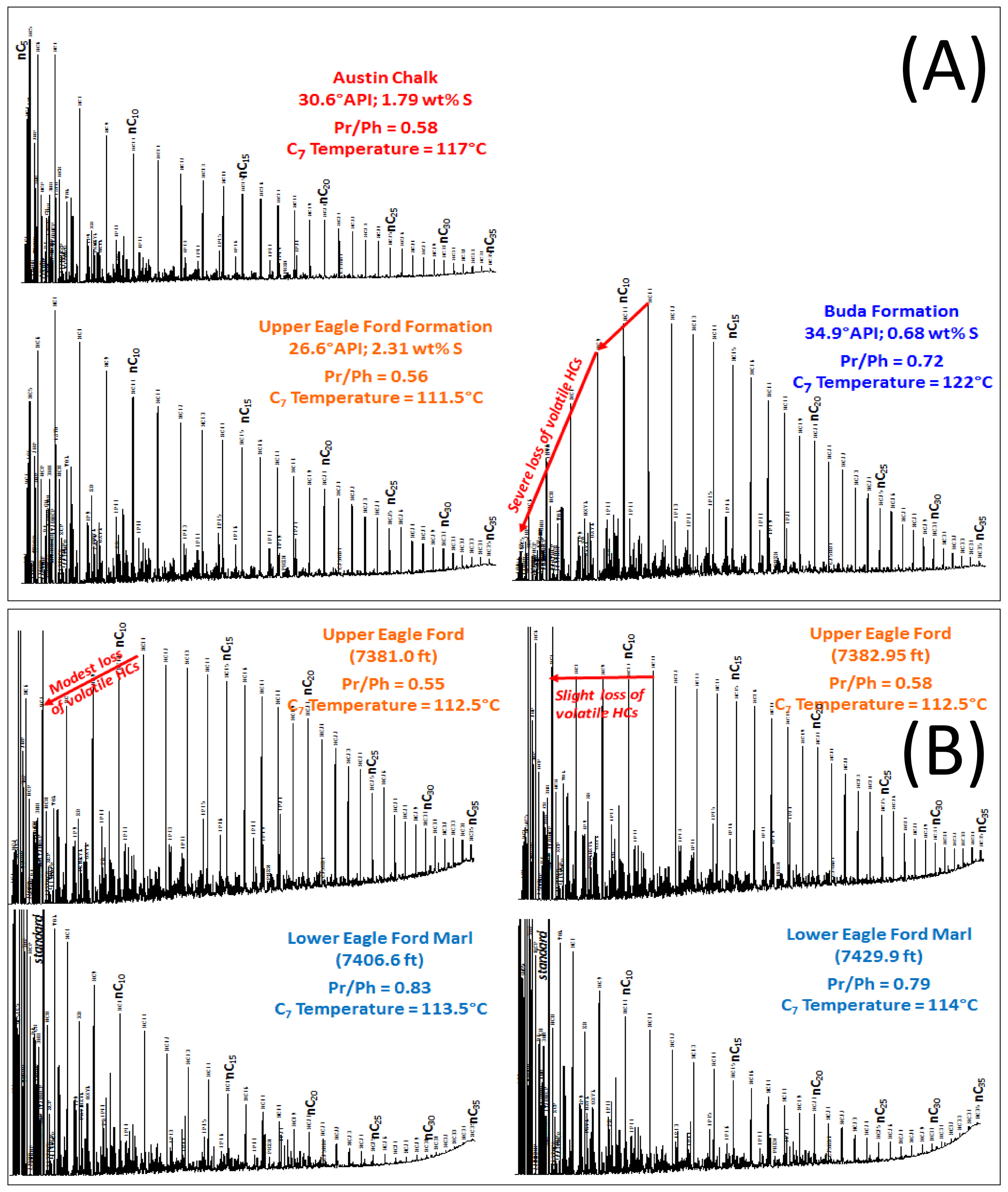


Figure 3. Stratigraphic cross section through the Eagle Ford Formation from the SW Vertical Well to the NE Vertical Well.

Production of Migrated Oil from Horizontal Wells Landed in the Eagle Ford on the San Marcos Arch

4. HRGCs MEASURED ON PRODUCED OIL SAMPLES AND CORE-PLUG EXTRACTS



Oil samples were obtained from the **Austin Chalk**, **UEF**, and **Buda** reservoirs at the SW Vertical Well. Some volatile compounds are depleted in the **Buda** oil sample (Figure 4A). Volatile compounds are not significantly depleted in any of the oil samples produced from the horizontal wells. High-quality oil also was extracted from most of the core plugs. Volatile compounds are slightly depleted in some of the **UEF**, **LEF marl**, and **LEF clay-shale** core-plug extracts (Figure 4B).

Figure 4. HRGCs measured on oil samples obtained from three reservoirs at the SW Vertical Well (A), and oil extracted from **UEF** and **LEF marl** core plugs from the same well (B).

5. THERMAL MATURITY AND API GRAVITY OF PRODUCED OILS AND EXTRACTS

The gravity of the produced oil samples is controlled by the temperature at which they were generated (Figure 5). The 35°API **Buda** oil sample was generated at a temperature higher than indicated by the C_7 maturity parameter because the loss of volatile C_7 compounds artificially decreases the C_7 temperature. The 23.4°API oil sample obtained from SW Horizontal Well #3 was generated at a lower temperature than the lighter oil samples obtained from the **Austin Chalk** and from the **UEF** reservoir at the SW Vertical Well, or the lighter oil samples obtained from SW Horizontal Well #1 and from SW Horizontal #2.

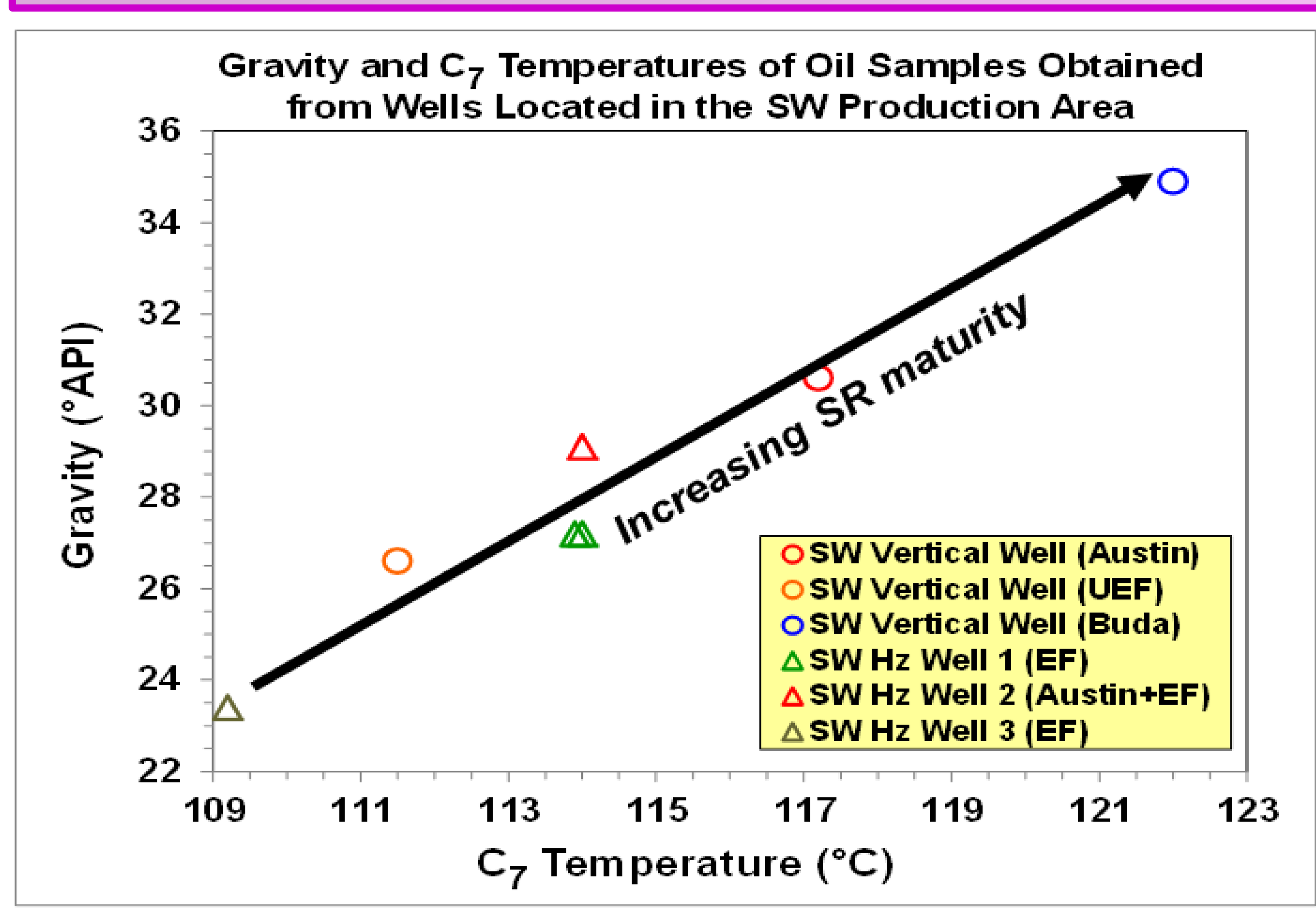


Figure 5. C_7 temperature and API gravity of oil samples produced from the vertical and horizontal wells.

As expected, extracts obtained from **UEF** and **LEF marl** core plugs selected in the NE Vertical Well were generated at slightly higher temperature (≈118°C) than the extracts obtained from the same zones in the shallower SW Vertical Well (≈113°C)

6. CORRELATION OF THE PRODUCED OIL SAMPLES AND CORE-PLUG EXTRACTS

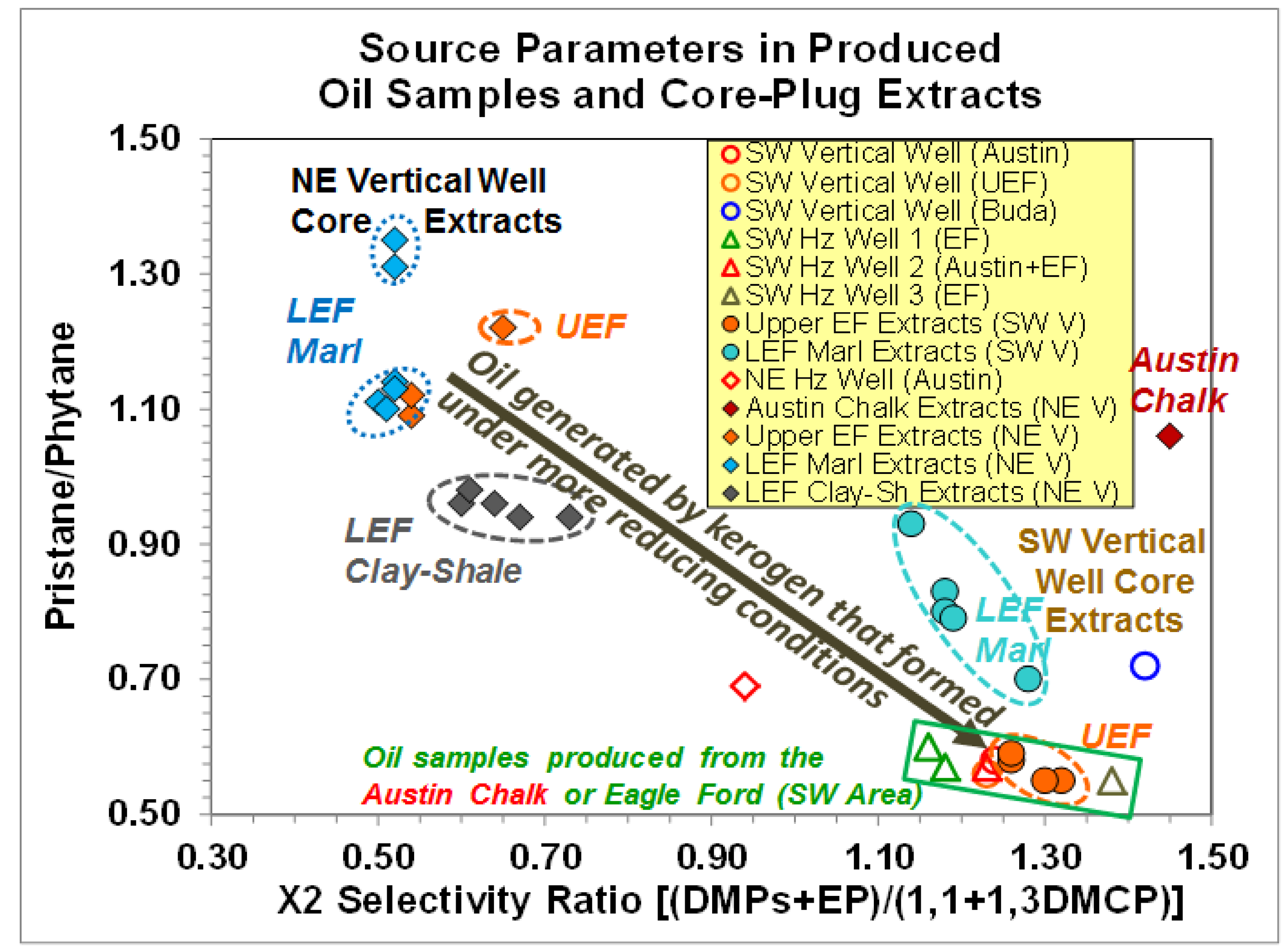


Figure 6. Light HC (C_7 selectivity ratio) and mid-range HC (pristane/phytane ratio) source parameters indicate different kinds of oil-prone kerogen generated the oil samples and core-plug extracts obtained in the SW area, and the core-plug extracts obtained in the NE area.

The values of two geochemical source parameters in oil samples produced from **Austin Chalk** and EF reservoirs in the SW area are similar to the values in extracts obtained from **UEF** and **LEF marl** core plugs in the SW Vertical Well. But they are different than the values measured in core-plug extracts that were obtained in the NE Vertical Well (Figure 6).

7. HCA CLASSIFICATION OF THE PRODUCED OIL SAMPLES AND CORE-PLUG EXTRACTS

Oil samples also can be classified using the values of HRGC **peak-height ratios**. A Hierarchical Cluster Analysis (HCA) performed using 17 peak-height ratios that vary significantly in these samples confirms that the composition of the produced oil samples is significantly different than the core-plug extracts obtained from the NE Vertical Well. Surprisingly, HCA results also demonstrate that extracts obtained from **LEF marl** core plugs at the SW Vertical Well **do not correlate** to the produced oils (Figure 7).

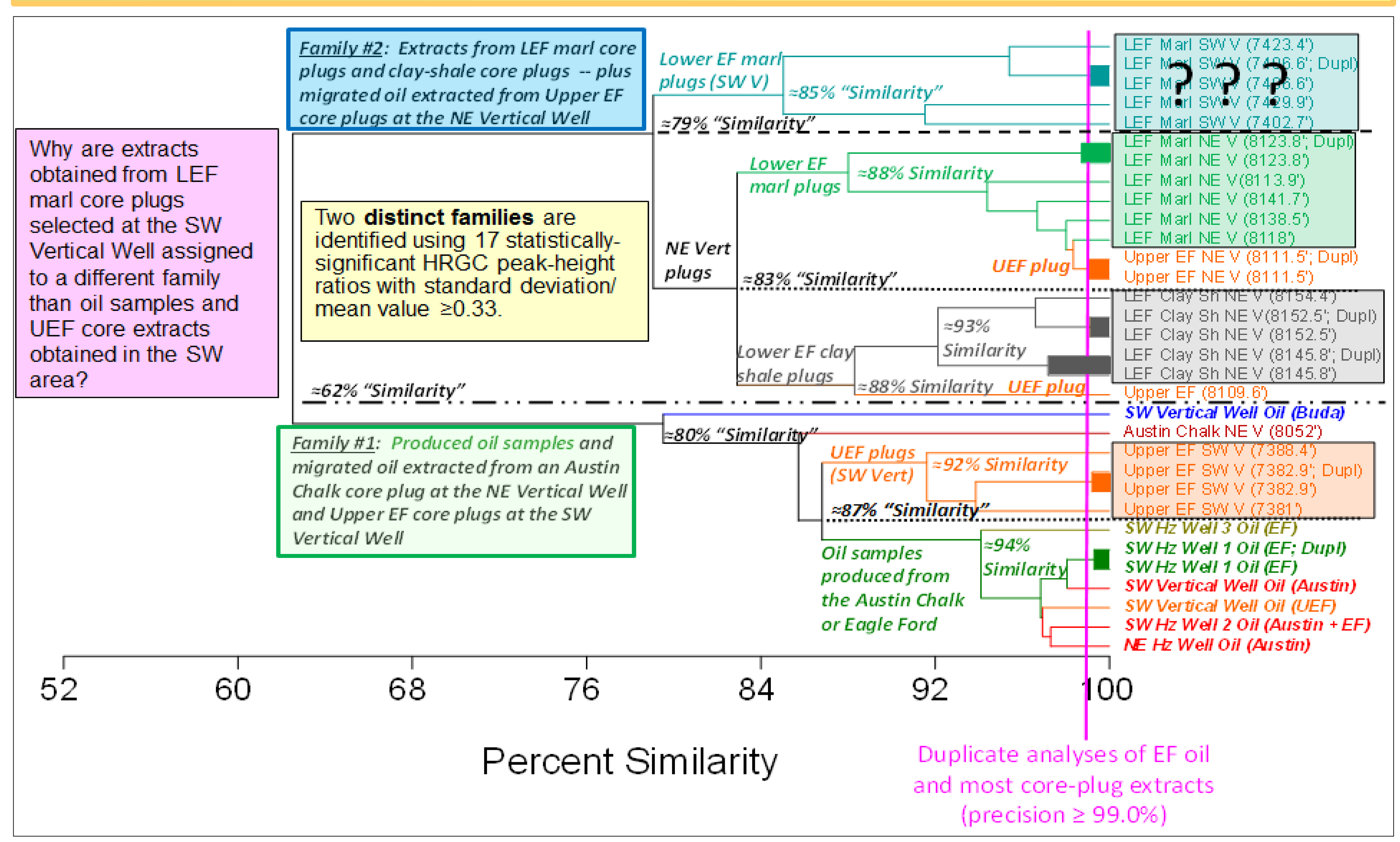


Figure 7. HCA classification of the produced oil samples and core-plug extracts.

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8. AROMATIC AND SATURATE COMPOUNDS FRACTIONATE WHEN OIL IS PRODUCED

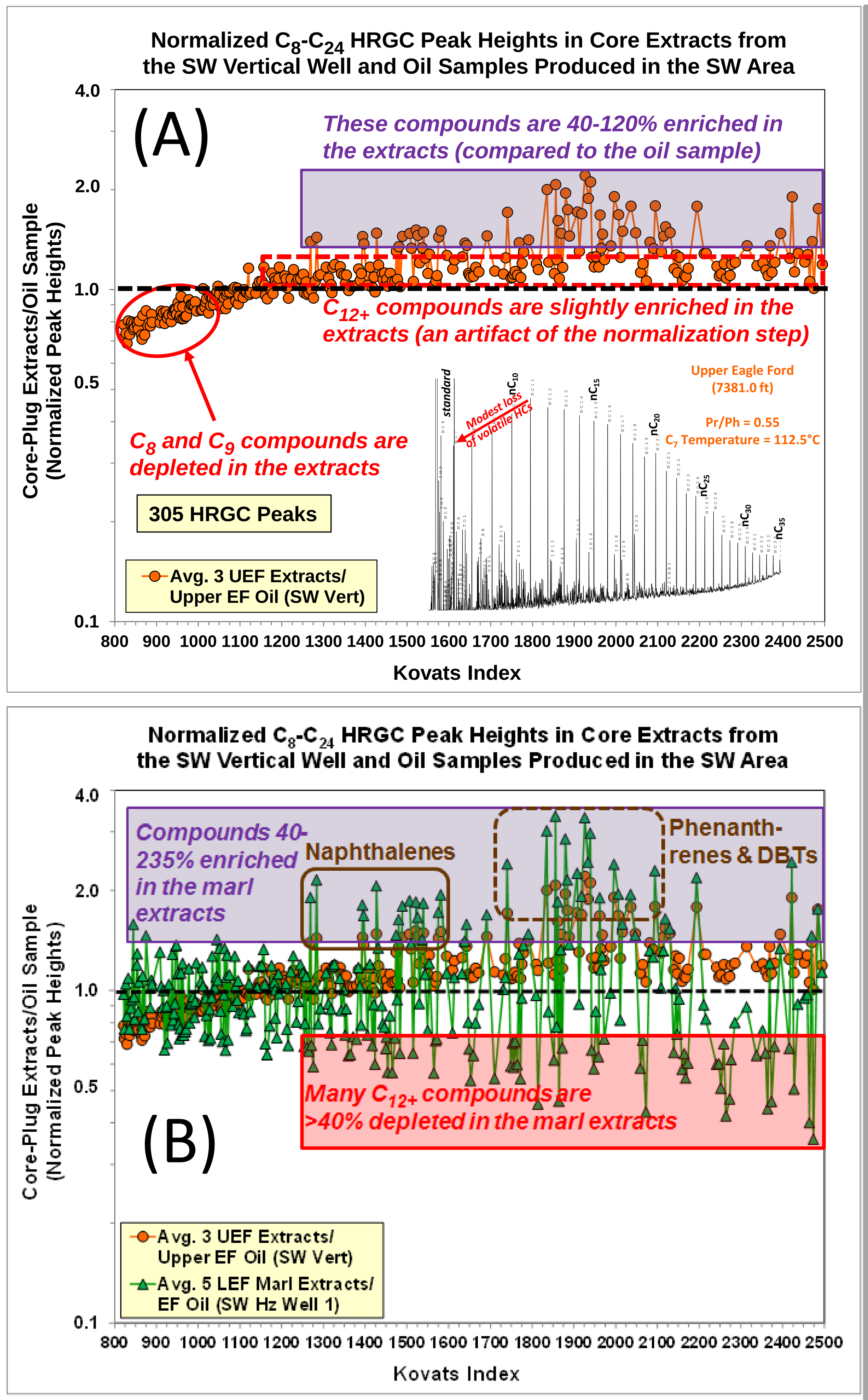


Figure 8. Aromatic compounds are more abundant in UEF core-plug extracts (A) and LEF marl core-plug extracts (B) than in oil samples produced from those reservoirs.

The explanation is that **aromatic compounds** (e.g., naphthalenes; DBTs; phenanthrenes) are significantly enriched in extracts obtained from core plugs selected in the **UEF**, **LEF marl**, and **LEF clay-shale** at both vertical wells compared to their abundance in oil samples produced from nearby wells. In addition, many branched alkane compounds are less abundant in extracts obtained from **LEF marl** core plugs than in an oil sample produced from a nearby horizontal well that was landed in the LEF reservoir (Figure 8).

Aromatic compounds may not flow from SR reservoirs as readily as saturate compounds because aromatic compounds have more affinity for kerogen and/or clay minerals.

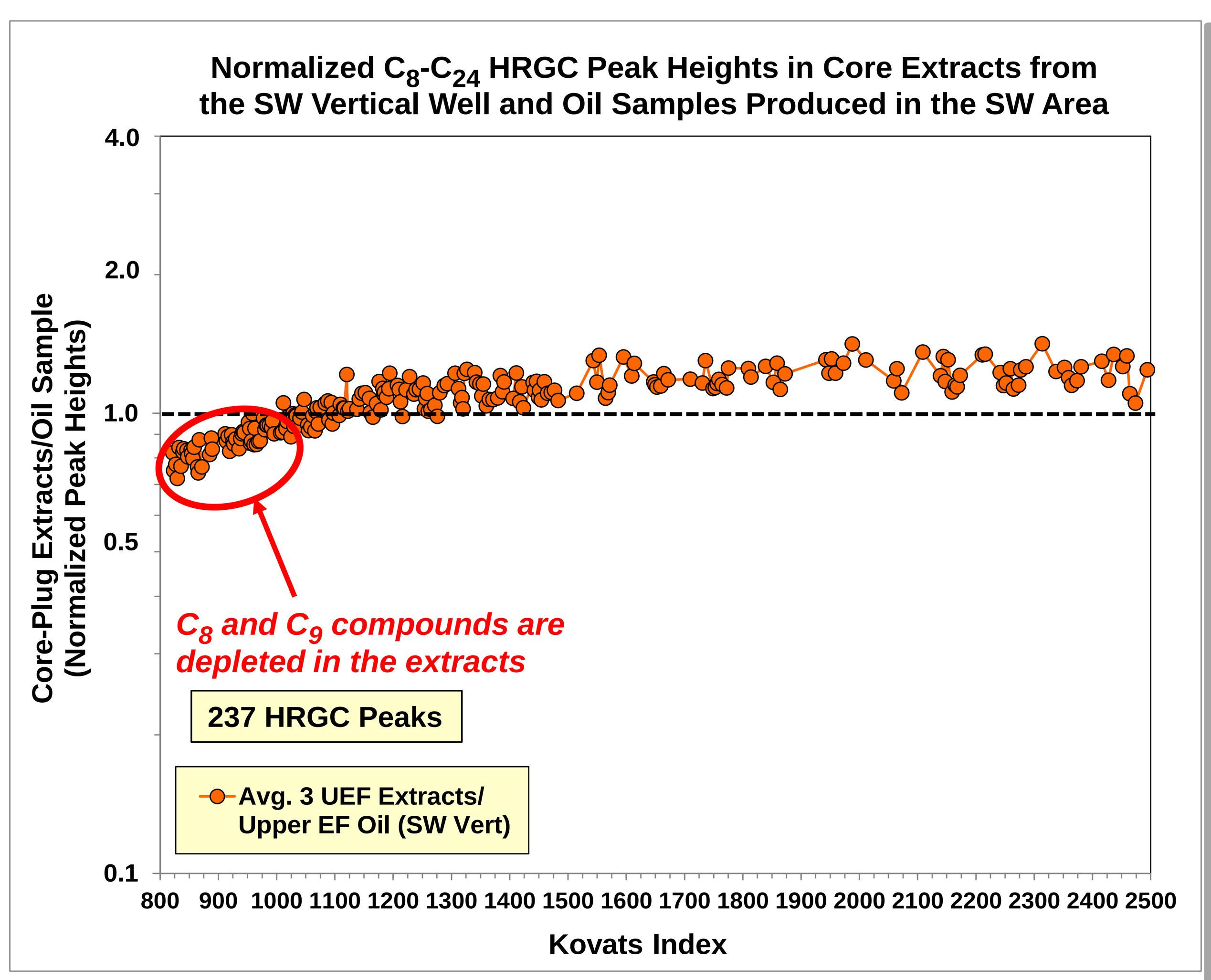


Figure 9. The abundance of most saturate compounds are very similar in UEF core-plug extracts and an oil sample produced from that reservoir (after accounting for the loss of compounds more volatile than C_{11} from the core-plug extracts).

After removing 68 HRGC peaks due to aromatic compounds, all HRGC peak heights are **very similar** in the **UEF** core-plug extract and in an oil sample produced from that reservoir (Figure 9). But the similarity of peak heights in **LEF marl** core-plug extracts and oil samples does not significantly improve after removing the same aromatic peaks.

Sonnenfeld and Canter (2016) showed that C_{15+} saturate and aromatic compounds (as well as resins and asphaltenes) are fractionated between extracts obtained from core plugs selected in Upper and Lower Bakken SR beds, in the lean Middle Bakken carrier bed, and in an oil sample produced from the Bakken Formation. That is a **geochromatography effect** that apparently occurs on a geological time scale when oil was expelled from Bakken SRs, and on a production time scale when oil flowed from the Middle Bakken reservoir after it was stimulated.

9. IDENTIFICATION AND ALLOCATION OF COMMINGLED PRODUCED OIL SAMPLES

Commingled oil samples are allocated using HRGC **peak heights** (not peak-height ratios). HRGC data measured on oil samples obtained from wells located in the SW area were used to try to allocate them using as end members the oil samples obtained from the **Austin Chalk**, the **UEF**, and the **Buda** at the SW Vertical Well – plus the 23.4°API oil sample obtained from SW Horizontal Well #3 (= the **LEF marl** end-member oil).

Table 1. Allocation Results for Several Oil Samples Produced in the SW Area.

Good allocation solutions using end-member oils obtained from the SW Vertical Well and SW Horizontal Well #3 that also are consistent with source and maturity parameters are:

Produced Oil	Wt% Austin Oil	Wt% UEF Oil	Wt% LEF Oil	Wt% Buda Oil
SW Vert Well (Austin)			74 ± 1.0	26 ± 1.0
SW Hz Well #2 (UEF)	53 ± 3.5	47 ± 3.6		
(Stimulated Austin,	33 ± 6.9	40 ± 4.7	27 ± 8.7	
UEF, LEF, and Buda)		39 ± 6.6	61 ± 6.5	
		40 ± 4.8	52 ± 5.3	8 ± 1.9
			93 ± 3.6	7 ± 3.5
SW Hz Well #1 (LEF)			84 ± 1.6	16 ± 1.5
(Stimulated Austin,		13 ± 2.7	71 ± 2.9	16 ± 1.9
UEF, LEF, and Buda)		11 ± 6.5	89 ± 6.4	
	61 ± 4.2	13 ± 2.4	26 ± 5.3	

The **Austin Chalk** oil sample is an ≈75:25 **migration mixture** of medium-gravity oil that was generated locally by the **LEF marl** (which migrated vertically into the **Austin Chalk**), and the kind of much lighter **Buda** oil that migrated laterally and updip. The 29°API oil sample obtained from SW Horizontal Well #2 – which was landed in the **UEF** reservoir – probably is a commingled **production mixture** of the kind of oil obtained from the **Austin Chalk** and from the **UEF** at the SW Vertical Well. Similarly, the 27°API oil sample obtained from SW Horizontal Well #1 – which was landed in the **LEF** reservoir – is a commingled **production mixture** of the type of medium-gravity oil generated locally by the **LEF marl,** and lighter **Buda** oil (possibly with some **UEF** oil) (Table 1). Other allocation results for oil samples produced from the two horizontal wells are rejected because they have higher uncertainties, or the solution is geologically unreasonable: e.g., the solution indicating that the oil sample obtained from the horizontal well landed in the **UEF** reservoir is a production mixture that principally contains oil that flowed from the deeper **LEF** and **Buda** reservoirs.

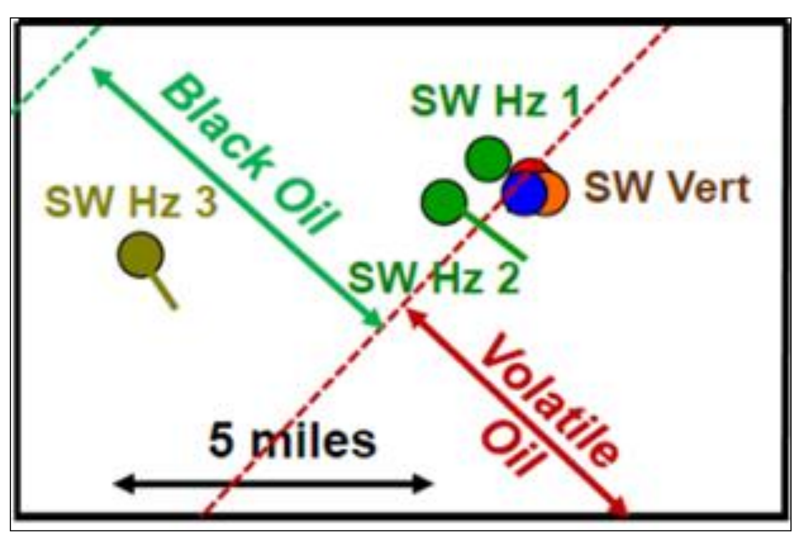
10. ALLOCATION OF UPPER EAGLE FORD CORE-PLUG EXTRACTS (SW VERTICAL WELL)

Satisfactory results were not achieved trying to use core-plug extracts selected in the vertical wells as end members to allocate any of the produced oil samples. For example, allocation results indicate the **UEF** oil sample at the SW Vertical Well is a mixture containing ≈79 wt% and ≈21 wt% of extracts obtained from two **UEF** core plugs selected in that well – but that result has relatively high uncertainties (±7.9-8.0 wt%). However, it is possible to allocate some of the core-plug extracts using produced oil samples as one of the end members. For example, a good allocation result was obtained for extracts obtained from three **UEF** core plugs selected in the SW Vertical Well using as end-members: (1) the **UEF** oil sample produced at that well; and (2) the average composition of extracts obtained from four **LEF marl** core plugs selected in that well.

The basal **UEF** reservoir apparently contains a mixture of oil generated by the oil + gas-prone kerogen present in that interval – plus variable amounts of migrated oil that was generated and expelled by **LEF marl** SR beds (Table 2). More **LEF marl** oil migrated vertically into the basal **UEF** reservoir near the top of the **LEF marl** (which occurs at a depth ≈ 7,390 feet) than into the **UEF** reservoir nine feet above that contact: i.e., the Lower **UEF** reservoir has a vertical compositional gradient at this well.

Table 2. Allocation Results for Several UEF Core-Plug Extracts Selected in the SW Vertical Well.

UEF Extract	Wt% 4 LEF Marl	Wt% UEF Oil
7381.0 ft	1.6 ± 4.1	98 ± 4.0
7382.9 ft	28 ± 4.6	72 ± 4.5
7388.4 ft	62 ± 2.7	38 ± 2.7



11. EXPULSION AND MIGRATION OF OIL GENERATED BY UEF AND LEF SOURCE ROCKS

The **LEF marl** contains better SR beds than does the **UEF**. On the San Marcos Arch, the **Austin Chalk** contains a mixture of: (1) medium-gravity oil expelled by **LEF marl** SR beds; and (2) lighter EF oil that migrated updip and laterally via the fractured **Buda** Formation (the regional carrier bed), and then vertically into the **Austin Chalk** via faults. **UEF** SR beds (which contain only ≈1.5-2.5 wt% TOC) have not efficiently charged the overlying **Austin Chalk** reservoir because they have not generated a large amount of oil at a relatively low level of thermal maturity (VRE ≈ 0.70). The basal **UEF** also contains oil expelled by the underlying **LEF marl**. (Figure 10).

Acknowledgements: I thank Joseph Westrich for his contributions during the initial phase of this project; Stephen Palmer and Jennifer Adams for identifying aromatic compounds enriched in core-plug extracts; Roger Wiggin for sharing ideas about the migration of oil on the San Marcos Arch; and Sabine Oil & Gas and Weatherford Laboratories for permission to publish these results.

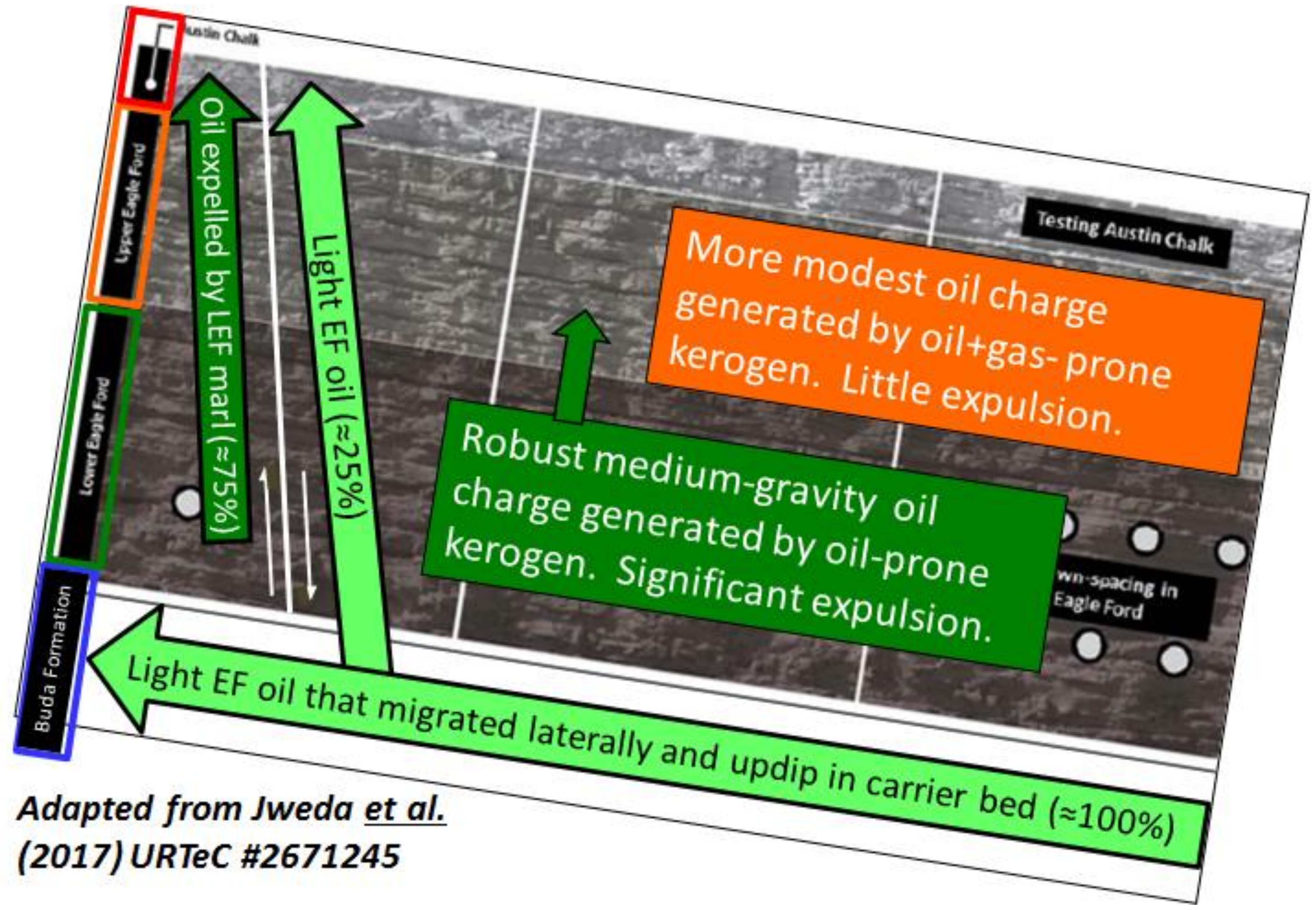


Figure 10. HC charge model for the Austin Chalk, Upper Eagle Ford, Lower Eagle Ford, and Buda Formation on the San Marcos Arch.

12. DE-RISKING MIGRATED OIL CHARGE IN THE AUSTIN CHALK

Successfully developing Austin Chalk oil reserves requires identifying areas where oil saturation in that quasi-conventional reservoir is high enough to sustain high oil production and low water cut. This can be done by identifying where: (1) **UEF** SR beds – as well as **LEF marl** SR beds – are rich enough and thermally mature enough to have generated and expelled a significant amount of oil into the **Austin Chalk**; and (2) faults penetrate the Eagle Ford Formation, allowing light oil that migrated laterally and updip via the **Buda** regional carrier bed to subsequently migrate vertically through the **Eagle Ford** top seal into the **Austin Chalk**.

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