PS Using Statistical Techniques to Identify End Members for Allocating Commingled Oil Samples Produced from Unconventional Reservoirs*

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Abstract

High-resolution GC (HRGC) data can be used to allocate oil samples that are mixtures of different types of oil produced from distinct reservoir zones if end-member samples are available from each zone. However, it often is difficult to obtain suitable end-member oils from "shale" reservoirs. If core extracts are used for that purpose, the number of potential end-member samples can be too high to easily interpret HRGC data. However, several statistical methods can be used to identify suitable end members using HRGC peak-height ratios. A Hierarchical Cluster Analysis (HCA) assigns oil samples and core extracts to different groups based on the similarity of their composition. This method provides insight about the number of distinct zones in a shale reservoir, but HCA results cannot easily be used to identify end members because a commingled oil sample generally is a mixture of different types of oil assigned to different HCA groups. HRGC peak-height ratios form distinctive patterns on star diagrams that can be used to identify different groups of oil samples and extracts, and relationships between different kinds of patterns can be used qualitatively to identify potential end members. Principal Components Analysis (PCA) of HRGC peak-height ratios is the most useful statistical method to identify end members. This method converts the values of peak-height ratios into new, independent (i.e., orthogonal) variables (principal components; PCs). The first PC (PC1) explains the largest percentage of the compositional variance, and each succeeding PC explains a smaller additional percentage of the variance. PCA case-score values are similar for produced oil samples and for core extracts with similar compositions. That relationship prevails on three-dimensional case-score figures created using PC1, PC2, and PC3 values, and on each of the three analogous two-dimensional figures: i.e., PC1 vs. PC2, PC1 vs. PC3, and PC2 vs. PC3. Furthermore, potential mixing lines between end-member samples can be readily identified using 2D PCA case-score figures. A mixing line initially identified using only one 2D case-score figure (e.g., PC1 vs. PC2) can be evaluated rapidly by determining if the same mixing line exists on other 2D figures. In addition, PCA variable loading figures can be used to determine how HRGC peak-height ratios influence the assignment of oil samples and core extracts on PCA case-score figures. We illustrate these principles using HRGC data measured on oil samples and core-plug extracts obtained from the Eagle Ford Formation, and from adjacent conventional reservoirs that contain migrated oil that was generated and expelled by Eagle Ford source-rock beds. After identifying the end members, we calculate their contribution to commingled oil samples.

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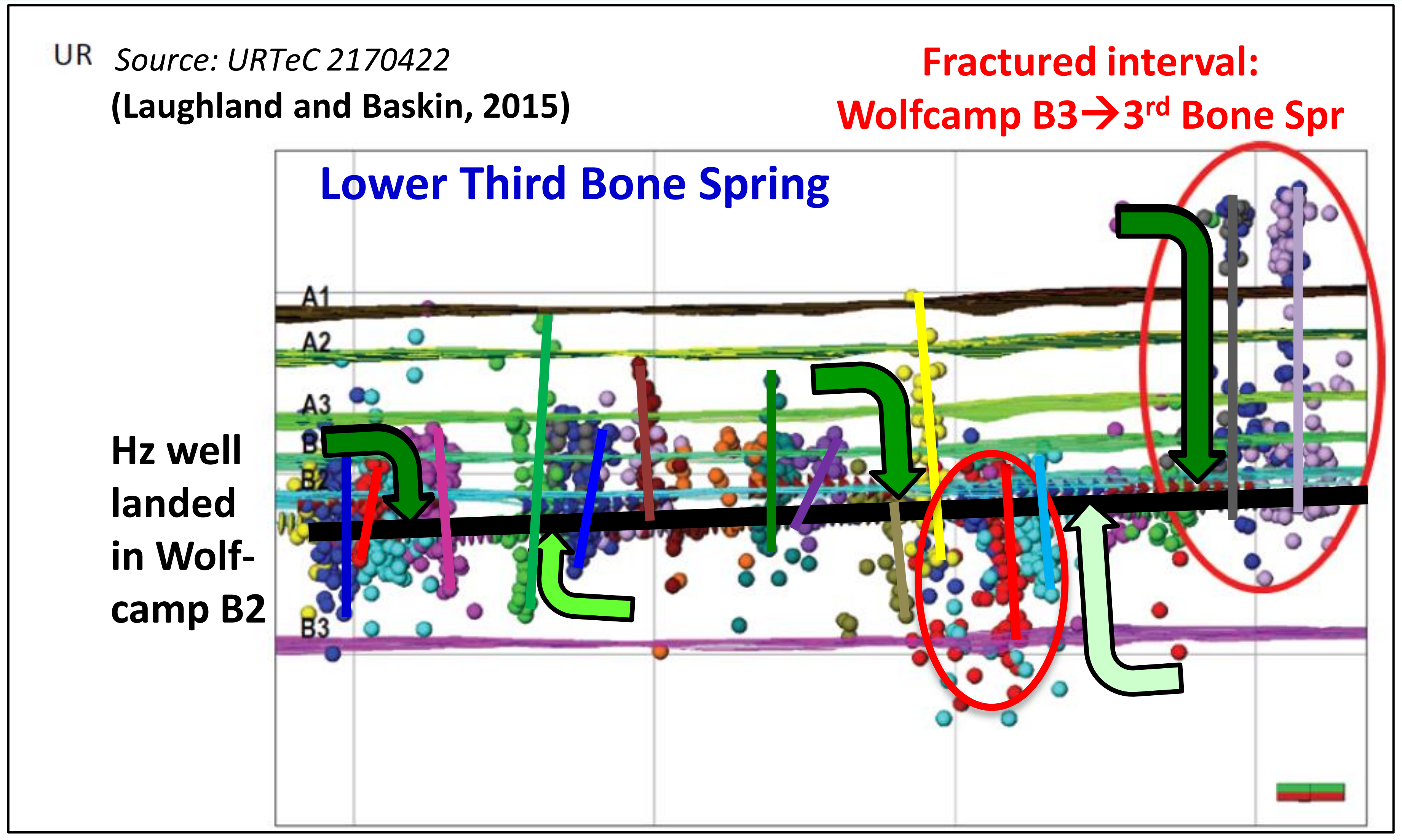
Abstract

High-resolution GC (HRGC) data can be used to allocate oil samples that are mixtures of different types of oil produced from distinct reservoir zones if end-member samples are available from each zone. However, it often is difficult to obtain suitable end-member oils from "shale" reservoirs. If core extracts are used for that purpose, the number of potential end-member samples can be too high to easily interpret HRGC data. However, several statistical methods can be used to identify suitable end members using HRGC peak-height ratios. A Hierarchical Cluster Analysis (HCA) assigns oil samples and core extracts to different groups based on the similarity of their composition. This method provides insight about the number of distinct zones in a shale reservoir, but HCA results cannot easily be used to identify end members because a commingled oil sample generally is a mixture of different types of oil assigned to different HCA groups. HRGC peak-height ratios form distinctive patterns on star diagrams that can be used to identify different groups of oil samples and extracts, and relationships between different kinds of patterns can be used qualitatively to identify potential end members. Principal Components Analysis (PCA) of HRGC peak-height ratios is the most useful statistical method to identify end members. This method converts the values of peak-height ratios into new, independent (i.e. , orthogonal) variables (principal components; PCs). The first PC (PC1) explains the largest percentage of the compositional variance, and each succeeding PC explains a smaller additional percentage of the variance. PCA case-score values are similar for produced oil samples and for core extracts with similar compositions. That relationship prevails on three-dimensional case-score figures created using PC1, PC2, and PC3 values, and on each of the three analogous two-dimensional figures: i.e., PC1 vs. PC2, PC1 vs. PC3, and PC2 vs. PC3. Furthermore, potential mixing lines between end-member samples can be readily identified using 2D PCA case-score figures. A mixing line initially identified using only one 2D case-score figure (e.g., PC1 vs. PC2) can be evaluated rapidly by determining if the same mixing line exists on other 2D figures. In addition, PCA variable loading figures can be used to determine how HRGC peak-height ratios influence the assignment of oil samples and core extracts on PCA case-score figures. We illustrate these principles using HRGC data measured on oil samples and core-plug extracts obtained from the Eagle Ford Formation, and from adjacent conventional reservoirs that contain migrated oil that was generated and expelled by Eagle Ford source-rock beds. After identifying the end members, we calculate their contribution to commingled oil samples.

1. INTRODUCTION: ALLOCATING COMMINGLED OIL SAMPLES PRODUCED FROM HORIZONTAL WELLS LANDED IN UNCONVENTIONAL RESERVOIRS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(Laughland and Baskin, 2015)

Figure 1. Microseismic data measured when hydraulic fractures were induced in a horizontal well landed in the Wolfcamp B2 reservoir.

Oil samples produced from horizontal wells landed in an unconventional reservoir generally are **commingled mixtures** of oil that flowed from several distinct pay zones (Figure 1). Because the composition of the oil in each pay zone typically is slightly different, oil fingerprinting methods can be used to allocate commingled samples if high-quality oil samples obtained from each pay zone are available (Jweda et al., 2017; Kornacki et al., 2017). But it is difficult to obtain the end-member oil samples.

2. OBTAINING END-MEMBER OIL SAMPLES FROM UNCONVENTIONAL RESERVOIRS

End-member oil samples can be obtained by purposefully completing distinct pay zones in a vertical pilot well or monitor well. Alternatively, oil can be extracted from conventional core plugs that are selected in each pay zone. Finally, a suite of oil samples produced from several horizontal wells landed in the same unconventional reservoir may include one or more samples that principally flowed from one distinct pay zone. In that case, how do you identify the end-member samples?

3. ALLOCATING OILS PRODUCED FROM HORIZONTAL WELLS LANDED IN THE EAGLE FORD FORMATION IN SOUTH TEXAS: USING PRODUCED OIL SAMPLES AS END MEMBERS

Most of the oil produced from the Buda Formation (a fractured carbonate) and the Austin Chalk migrated into those reservoirs after it was generated and expelled by Eagle Ford source-rock (SR) beds (Zumberge et al., 2016). However, the composition of oil produced from the Eagle Ford Formation and the migrated oil produced from those conventional reservoirs are different because Eagle Ford SRs retain the most recent **increment** of oil that was generated by their indigenous kerogen, while the Austin Chalk and Buda reservoirs contain a **cumulative charge** of oil expelled by Eagle Ford SR beds over geological time.

We interpreted high-resolution GC (HRGC) data measured on oil samples obtained from 10 horizontal wells landed in the Eagle Ford Formation at the Brisco Ranch field, and from four vertical wells completed in the Austin Chalk plus four wells completed in the Buda Formation in the nearby Pearsall field. HRGC data also were measured on an oil sample produced from the deeper Edwards Lime (a Lower Cretaceous reservoir) (Figure 2).

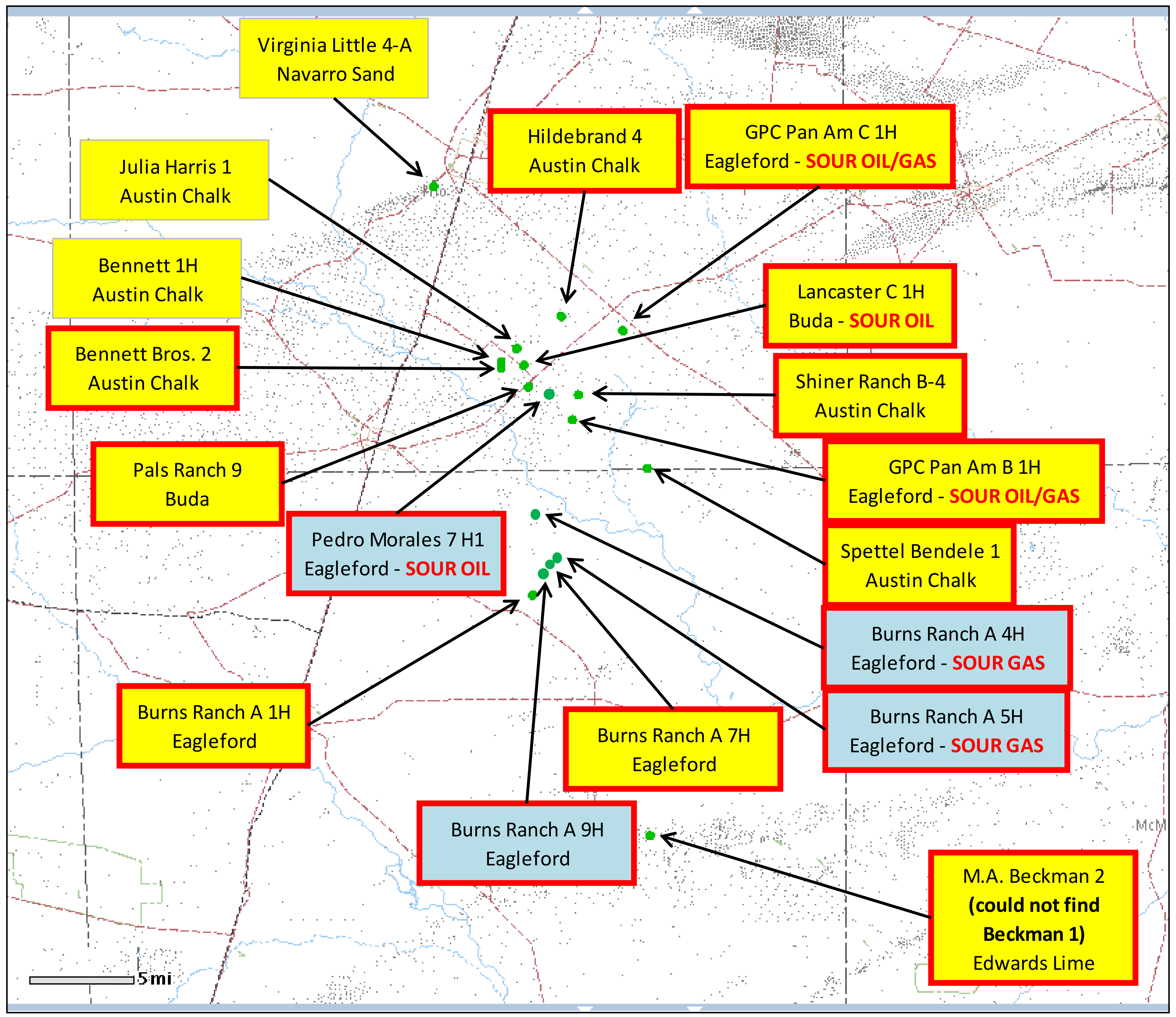


Figure 2. Map of well locations where oil samples were obtained.

Using Statistical Techniques to Identify End Members for Allocating Commingled Oil Samples Produced From Unconventional Reservoirs

4. HRGCs MEASURED ON AUSTIN CHALK, EAGLE FORD, AND BUDA OIL SAMPLES

HRGCs measured on oil samples obtained from wells completed in the Eagle Ford and Buda reservoirs are very similar. In contrast, the C_{10}-C_{20} normal-alkane envelope of the oil sample produced from the Austin Chalk has a more pronounced concave-downward profile (Figure 3).

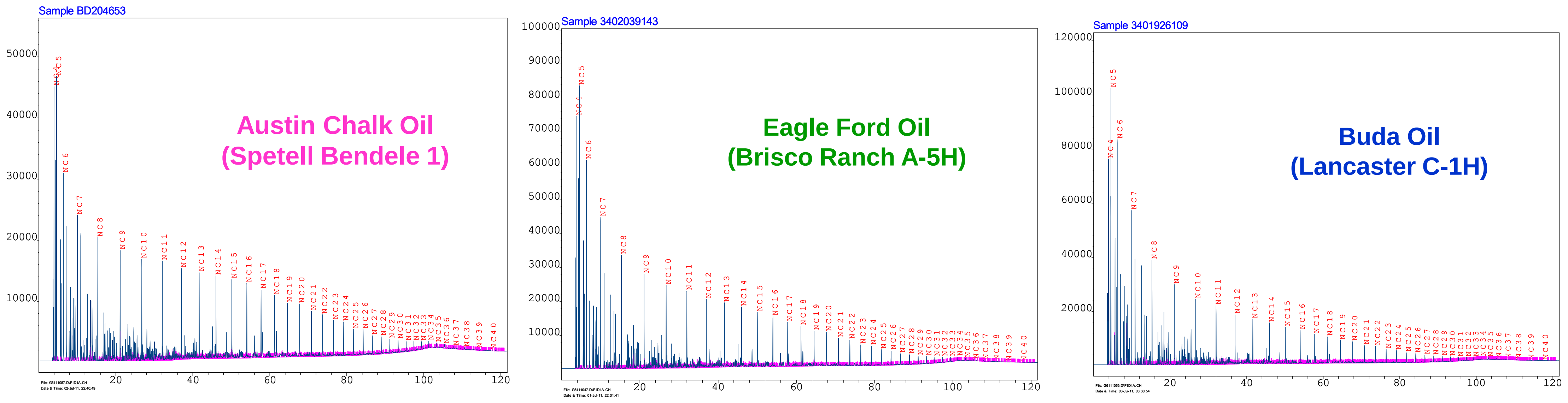


Figure 3. HRGCs measured on oil samples obtained from wells completed in the Austin Chalk, the Eagle Ford Formation, and the Buda Formation.

5. CLASSIFICATION OF THE AUSTIN CHALK, EAGLE FORD, AND BUDA OIL SAMPLES

The oil samples were classified by performing a **Hierarchical Clustering Analysis (HCA)** based on the similarity of the values of 24 HRGC peak-height ratios that vary significantly among them. These oil samples form five distinct groups (Figure 4). Buda oils (Group #2) and Austin Chalk oils (Group #4) are distinct from Eagle Ford oils. Group #1 oils from the Eagle Ford reservoir in LaSalle County are distinct from the Eagle Ford oils from Frio County (Group #3). The oil sample produced from the deeper Edwards Lime (Group #5) differs the most from the other four groups.

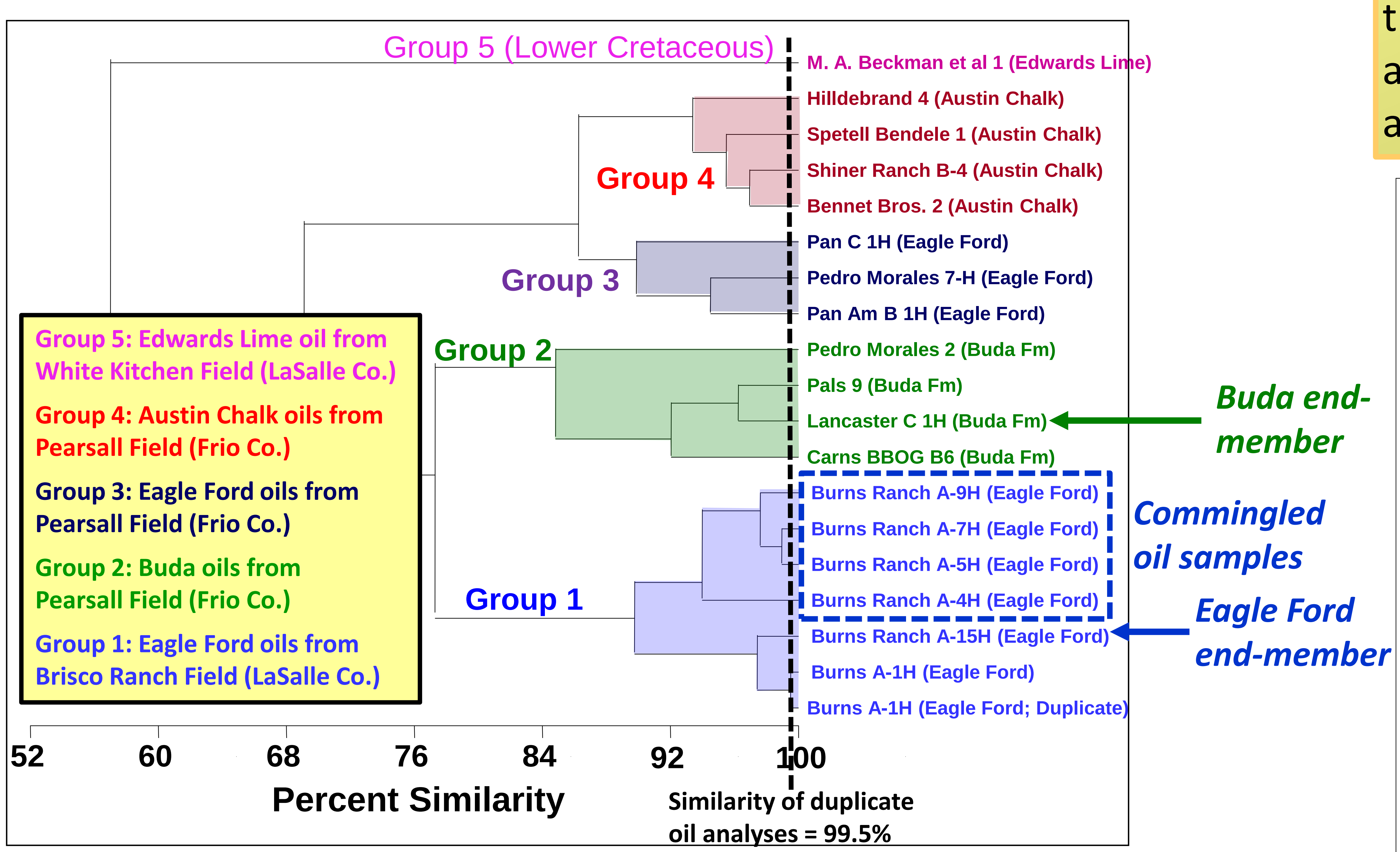


Figure 4. HCA classification of oil samples produced from the Austin Chalk, the Eagle Ford Formation, and the Buda Formation (modified from Baskin et al. , 2013). PCA results (discussed later) were used to identify the end members and commingled samples

6. AUSTIN CHALK, EAGLE FORD, AND BUDA OIL STAR DIAGRAMS

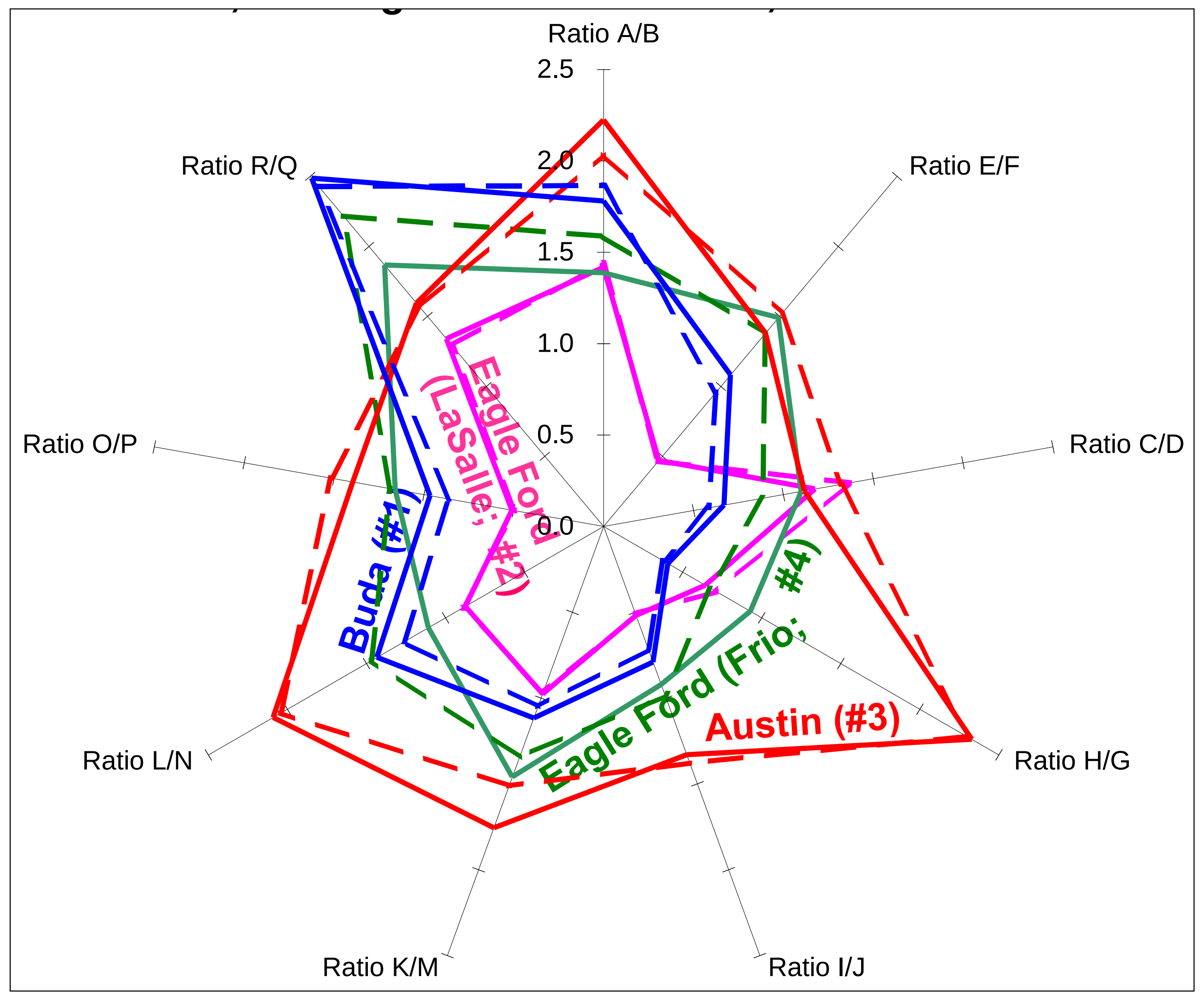


Figure 5. Star diagram for oil samples produced from the Austin Chalk, the Eagle Ford Formation, and the Buda Formation.

A **star diagram** based on the values of nine HRGC peak-height ratios in representative pairs of oil samples assigned to different HCA groups illustrates differences in the composition of oil samples produced from the Austin Chalk, the Eagle Ford reservoir, and the Buda Formation (Figure 5).

7. IDENTIFYING MIXING LINES AND END MEMBERS USING PCA CASE-SCORE FIGURES

The compositional differences among a suite of oil samples can be evaluated by performing a **Principal Components Analysis** (PCA), a multivariate calculation that reduces the dimensionality of the oil compositions by finding a smaller number of "synthetic" variables (Principal Components; PCs) that still explain most of the variance in the compositional data. A PCA can be considered a rotation of the original axes to new orthogonal positions (Figure 6). PC1 explains the greatest percentage of the variance in the data; PC2 is the orthogonal variable that explains the next greatest amount of variance. PC3 (and higher PCs) explain additional smaller amounts of variance.

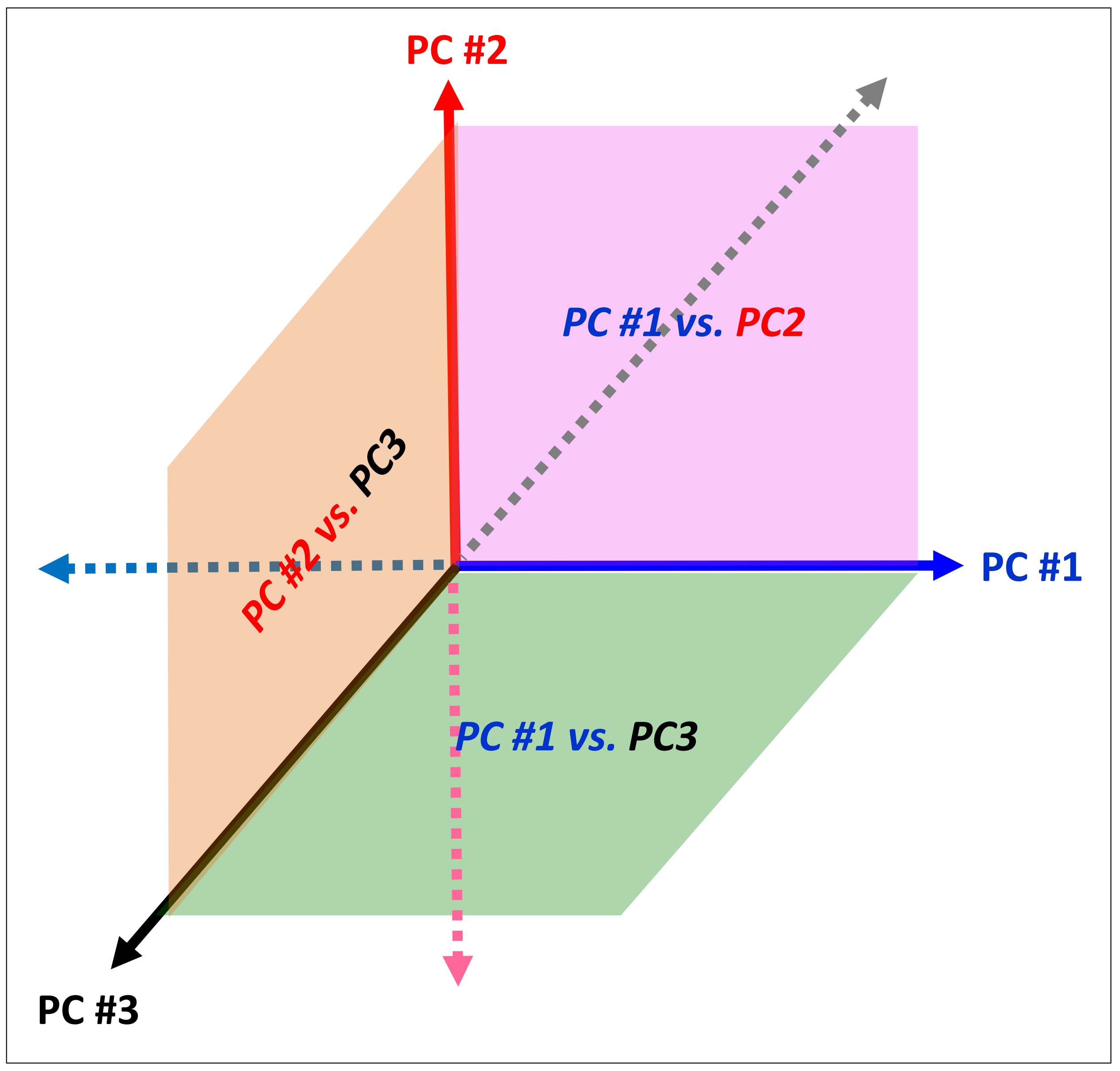


Figure 6. Schematic representation of three orthogonal Principal Components (solid lines) and planes defined by different pairs of the same three Principal Components.

PCA case-score figures can be used to identify potential **mixing lines** and **end-member** oil samples. Samples comprising a mixing line form a linear array on a PC1 vs. PC2 case-score figure, and on the analogous PC1 vs. PC3 case-score figure. Furthermore, putative end-member oil samples lie at both ends of the linear arrays on each case-score figure.

8. IDENTIFICATION OF EAGLE FORD OIL AND BUDA OIL MIXING LINES AND END MEMBERS, AND ALLOCATION OF COMMINGLED EAGLE FORD OIL SAMPLES

We used PCA case-score figures to identify potential **mixing lines** between oil samples produced from horizontal wells landed in the Eagle Ford Formation at the Burns Ranch field and oil samples produced from wells completed in the Buda Formation. **"Pseudo" end-member** samples of Eagle Ford oil and Buda oil also were identified – as well as oil samples produced from several Eagle Ford wells that appear to be **commingled mixtures** of the pseudo-end members (Figure 7). We also identified a second mixing line between two kinds of oil produced from the Buda reservoir.

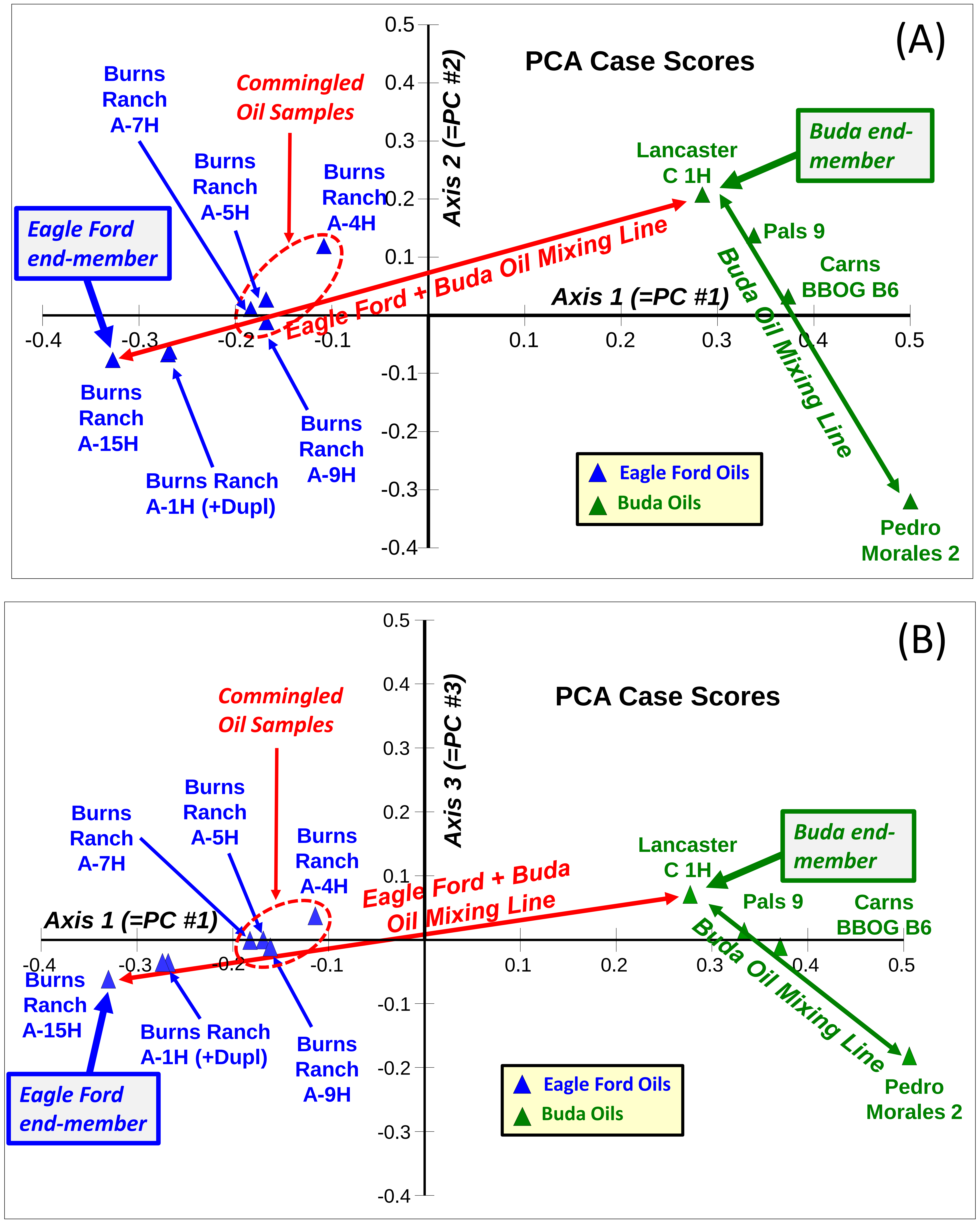
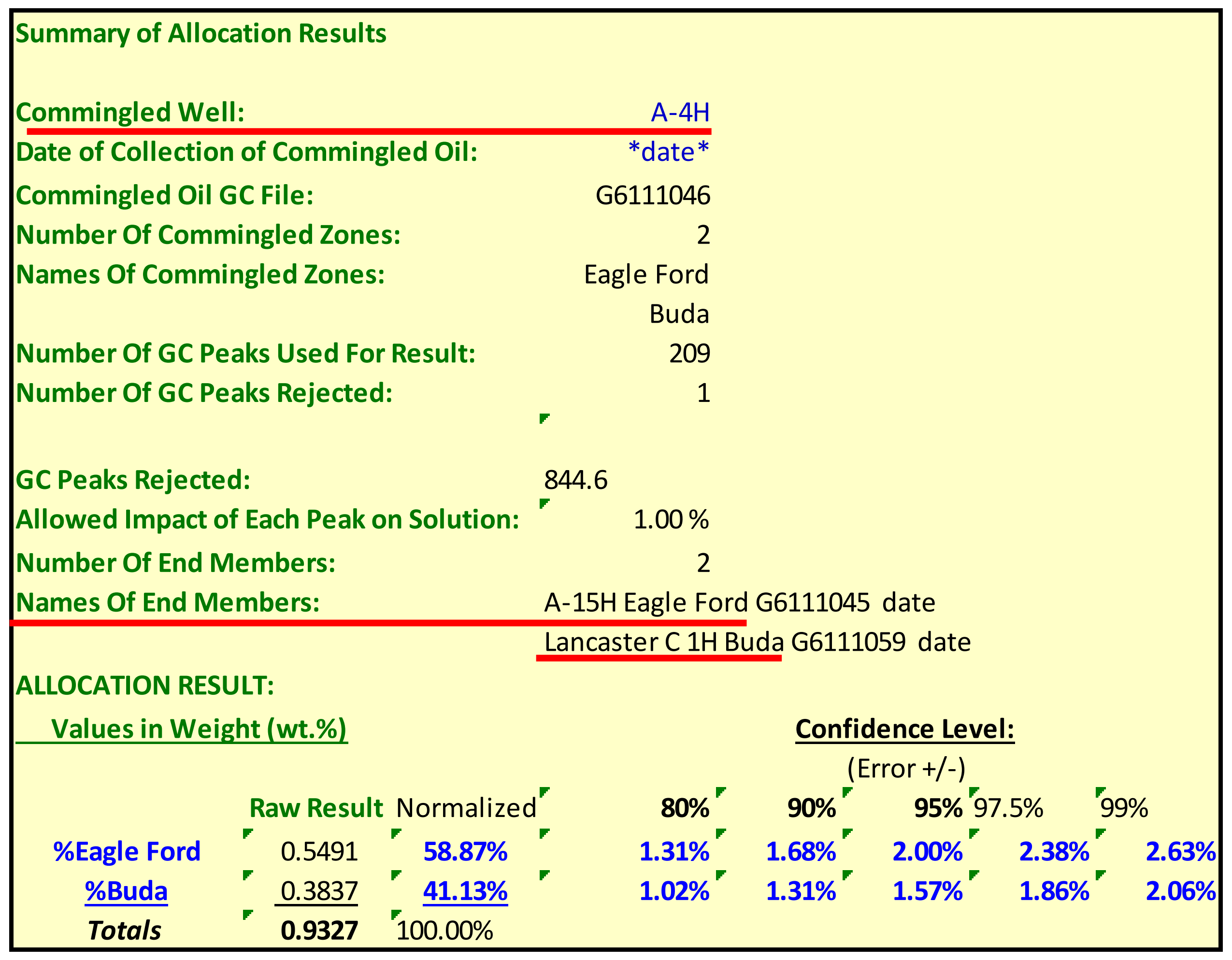


Figure 7. Mixing lines, pseudo-end member oil samples, and commingled oil samples identified on a PC1 vs. PC2 case-score figure (A) and on a PC1 vs. PC3 case-score figure (B).

9. ALLOCATING A COMMINGLED OIL SAMPLE PRODUCED FROM A HORIZONTAL WELL LANDED IN THE EAGLE FORD FORMATION

Commingled oil samples were allocated using ~100-250 HRGC **peak heights** (not peak-height ratios) as described in McCaffrey et al. (2011).

Table 1. Allocation Result for a Commingled Oil Sample Produced from the Burns Ranch A-4H Well (modified from Baskin et al. , 2013).



Summary of Allocation Results

Commingled Well:	A-4H
Date of Collection of Commingled Oil:	*date*
Commingled Oil GC File:	G6111046
Number Of Commingled Zones:	2
Names Of Commingled Zones:	Eagle Ford Buda
Number Of GC Peaks Used For Result:	209
Number Of GC Peaks Rejected:	1
GC Peaks Rejected:	844.6
Allowed Impact of Each Peak on Solution:	1.00 %
Number Of End Members:	2
Names Of End Members:	A-15H Eagle Ford G6111045 date Lancaster C 1H Buda G6111059 date

ALLOCATION RESULT:

Values in Weight (wt.%)

Confidence Level: (Error +/-)

	Raw Result	Normalized	**80%**	**90%**	**95%**	97.5%	99%
%Eagle Ford	0.5491	**58.87%**	**1.31%**	**1.68%**	**2.00%**	**2.38%**	**2.63%**
%Buda	0.3837	**41.13%**	**1.02%**	**1.31%**	**1.57%**	**1.86%**	**2.06%**
Totals	**0.9327**	100.00%					

The oil sample obtained from the Burns Ranch A-4H well is a **commingled mixture** that contains ≈59 wt% (±2.0 wt% at the 95% confidence level) of the type of oil produced from the Burns Ranch A-15H well and ≈41 wt% (±1.6 wt%) of the type of oil produced from the Lancaster C-1H well (Table 1). The Burns Ranch A-4H "Eagle Ford" oil sample contains a significant amount of oil that flowed from the underlying Buda reservoir.

10. ALLOCATING OILS PRODUCED FROM THE AUSTIN CHALK AND THE EAGLE FORD FORMATION ON THE SAN MARCOS ARCH USING OTHER PRODUCED OIL SAMPLES AND CORE-PLUG EXTRACTS OBTAINED FROM THE UPPER EAGLE FORD FORMATION

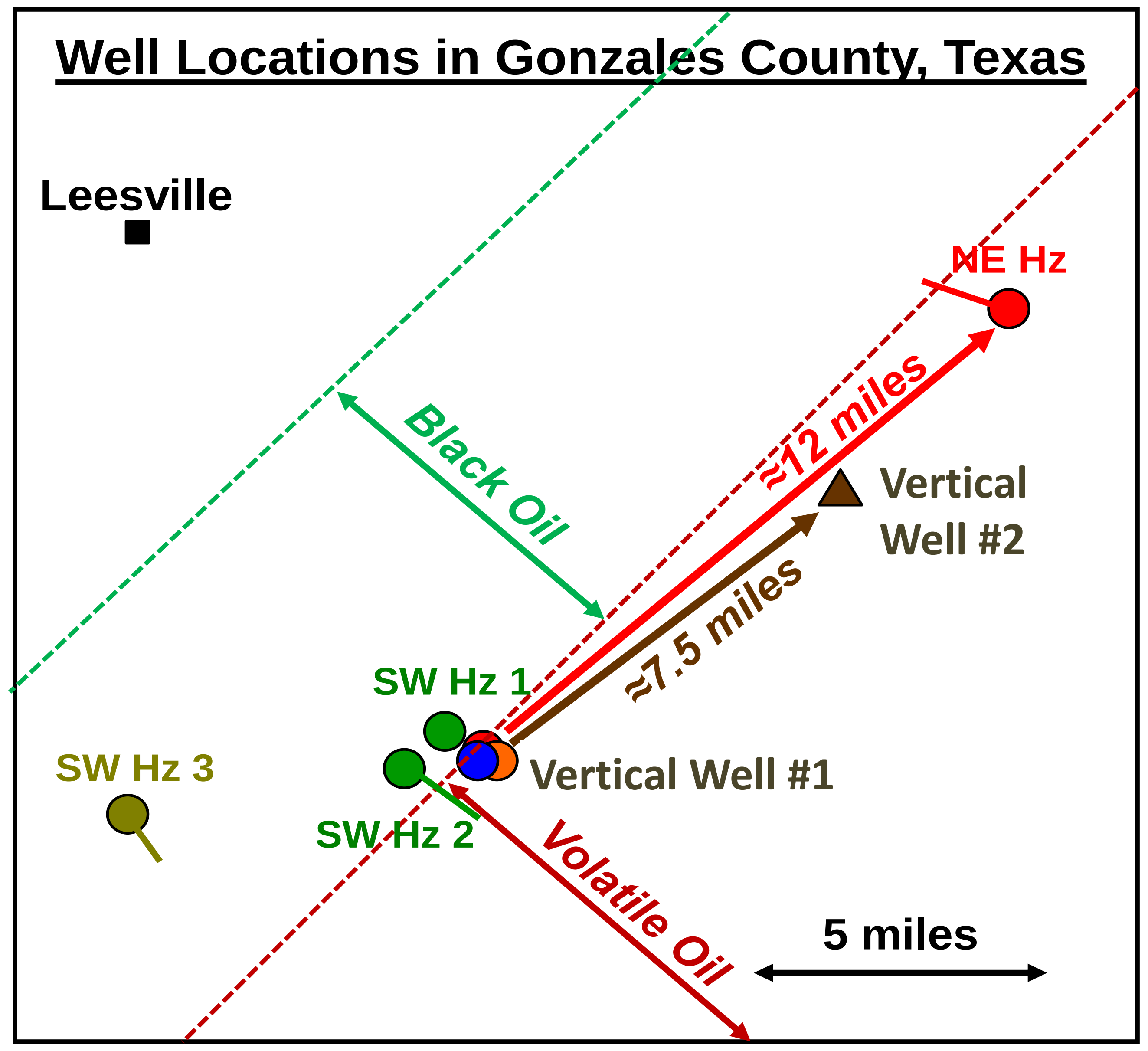


Figure 8. Map of vertical and horizontal wells where oil samples and core plugs were obtained on the San Marcos Arch.

Core plugs were selected from the Austin Chalk, the Upper Eagle Ford (UEF), and the Lower EF marl and clay-shale at Vertical Well #2. Core plugs also were selected from the UEF and the LEF marl at shallower Vertical Well #1 (Figure 8). The LEF marl is a very good oil-prone SR at VRE ≈0.70. The UEF and LEF clay-shale are good SRs that contain oil + gas-prone kerogen. The leaner Austin Chalk contains gas-prone or inert kerogen.

Oil samples produced from the Austin Chalk, UEF, and Buda Formation were obtained at Vertical Well #1. **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).

5. CLASSIFICATION OF THE AUSTIN CHALK, EAGLE FORD, AND BUDA OIL SAMPLES

The produced oil samples and core-plug extracts were classified by performing a HCA using 17 HRGC peak-height ratios that vary significantly. The samples are assigned to two distinct families. **Family #1** = the produced oil samples, plus extracts obtained from UEF core plugs at Vertical Well #1 and from the Austin Chalk at Vertical Well #2. **Family #2** = the extracts obtained from LEF marl and clay-shale core plugs selected at both vertical wells, and from UEF core plugs selected at Vertical Well #2 (Figure 9).

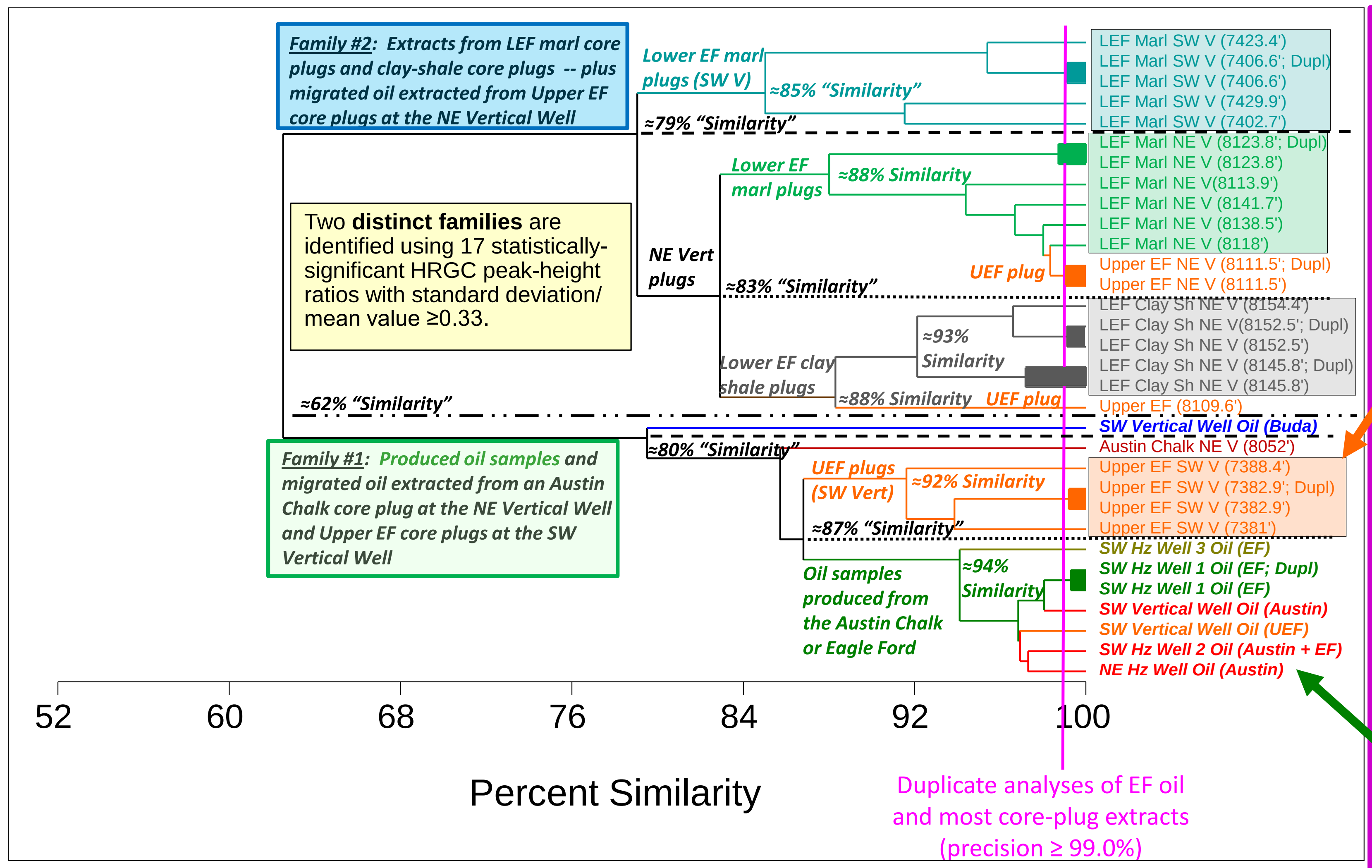


Figure 9. HCA classification of the produced oil samples and core-plug extracts.

Extracts obtained from three UEF core plugs selected at Vertical Well #1 form their own group. The produced oil samples form a distinct group that is most similar to those UEF core-plug extracts.

Extracts obtained from LEF marl and from clay-shale core plugs selected at Vertical Well #2 form distinct groups in Family #2, as do extracts obtained from LEF marl core plugs selected at Vertical Well #1 – an unexpected result because two geochemical source parameters indicate those marl core-plug extracts correlate to the produced oil samples (Kornacki, 2018).

11. IDENTIFICATION OF MIXING LINES, END MEMBERS, AND COMMINGLED OILS; ALLOCATION OF COMMINGLED PRODUCED OIL SAMPLES AND CORE-PLUG EXTRACTS

Several potential **mixing lines** among the produced oil samples and core-plug extracts are recognized on PC case-score figures. A mixing line among the oil samples is apparent only on the PC1. vs. PC3 diagram (Figure 10A). Allocation results indicate the following samples are commingled mixtures that formed during oil migration or production:

Oil Sample	wt% Austin Oil[1]	wt% UEF Oil[1]	wt% LEF Oil[2]	wt% Buda Oil[1]
Austin Chalk[1] (migration mixture)			74 ± 1.0	26 ± 1.0
SW Hz Well #1[3]			84 ± 1.6	16 ± 1.5
SW Hz Well #2[4]	53 ± 3.5	47 ± 3.6		
(production mixtures)				

[1] Oil sample produced from Vertical Well #1

[2] 23.4°API oil produced from SW Hz Well #3

[3] Hz well landed in the Lower Eagle Ford

[4] Hz well landed in the Upper Eagle Ford

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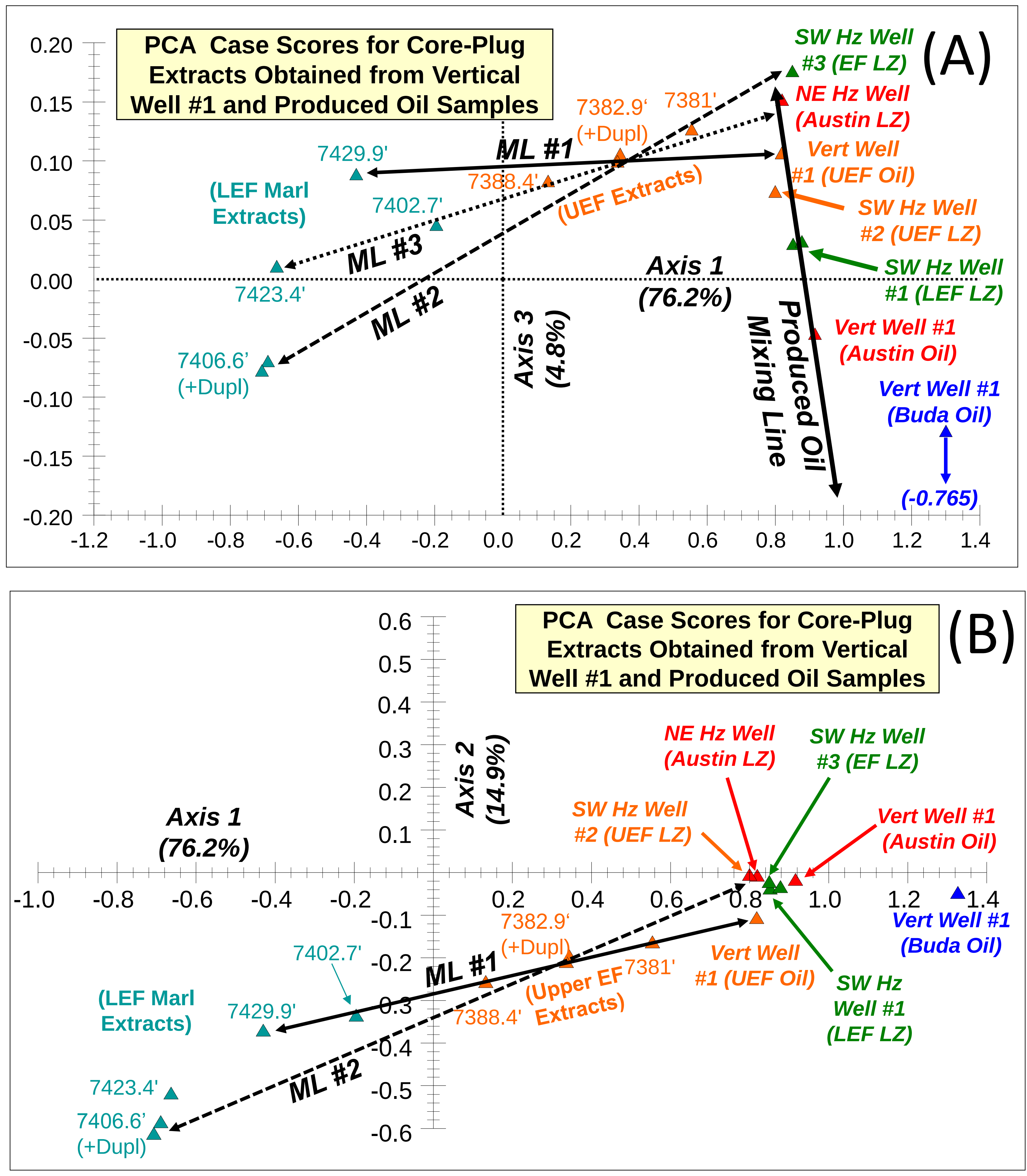

Figure 10. Mixing lines, end-member samples, and commingled samples identified on a PC1 vs. PC3 case-score figure (A) and on a PC1 vs. PC2 case-score figure (B).

The **basal UEF** reservoir at Vertical Well #1 apparently contains a mixture of oil generated by the oil + gas-prone kerogen present in that SR interval – plus a variable amount of migrated oil that was generated and expelled by underlying LEF marl SR beds (Figure 10). More LEF marl oil migrated vertically into the basal UEF reservoir near the contact with the LEF marl (which occurs at a depth of 7,390') than at a distance 7-9 ft above that contact (Table 2).

Table 2. Allocation Results for Several UEF Core-Plug Extracts Selected in Vertical Well #1.

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

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