

STERANE COMPOSITIONAL TRAITS OF BOWSER AND SUSTUT BASIN CRUDE OILS: INDICATIONS FOR THREE EFFECTIVE PETROLEUM SYSTEMS

By K.G. Osadetz¹, C. Jiang², C. A. Evenchick³, F. Ferri⁴,
L. D. Stasiuk¹, N. S. F. Wilson¹ and M. Hayes⁴

KEYWORDS: *Crude oil, natural gas, petroleum stains, seepages, Bowser-Sustut basins, organic geochemistry, solvent extracts, biomarkers, steranes, terpanes, gas chromatography-mass spectrometry.*

ABSTRACT

Crude oils extracted from Bowser Lake and Sustut groups have distinctive compositions that are inferred to be indicative of at least three effective petroleum systems that have generated, expelled and accumulated crude oil. Compositional differences among the three effective petroleum systems are illustrated by compositional variations of steranes, complicated molecules that have retained structural similarities to their inferred biological precursor, cholesterol. Oil stains occur widely, both geographically and stratigraphically. One compositional oil family is inferred to be derived from Stikine assemblage, the sub-Hazelton succession. This petroleum is derived from pre-Jurassic marine carbonate source rocks deposited in hypersaline to mesohaline environments. A second compositional oil family is derived from Mesozoic open marine source rocks, that are inferred to be within the upper Hazelton or lower Bowser Lake Group, as the lowest stratigraphic occurrence of these oils lies in marine slope deposits of Bowser clastic wedge. A third oil family is inferred to be derived from lacustrine Mesozoic source rocks occurs in northern Bowser and Sustut Basins, where it is probably derived from thick, often coaly, non-marine Bowser Lake successions. The occurrence and composition of these crude oils expand the petroleum prospectivity of the Bowser and Sustut basins by reducing petroleum system risks and indicating a possible petroleum system for Hazelton Group, which is now attributed petroleum potential.

INTRODUCTION

This report results from work performed as part of the project "Integrated Petroleum Resource Potential and Geoscience Studies of the Bowser and Sustut Basins", a collaborative research project of the BC Ministry of Energy and Mines (Oil and Gas Emerging Opportunities and Geoscience Branch), and the Geological Survey of

Canada (Evenchick *et al.*, 2003). The current multi-year project is multidisciplinary in scope and broad in geographic coverage, including the length and breadth of both the Bowser and Sustut basins. Primary activities include geological framework, energy resource studies, and petroleum resource assessment.

Previous petroleum assessment work of the region identified substantial petroleum potential while recognising that there are several poorly understood, but significant risks (Hannigan *et al.*, 1995). That study showed that there were significant play level risks associated with the inferred petroleum potential of the Bowser Basin. More recent GSC/BCMEM research resulted in a profound shift in perceptions of organic and thermal maturity patterns in the Bowser and Sustut basins (Evenchick *et al.*, 2002). The first regional organic maturity dataset illustrates that large areas, including the lowest stratigraphic levels of the Bowser Basin, have sufficiently low organic maturity levels to be favourable for the formation and preservation of crude oil. This fundamentally changed previous views that considered the high thermal maturity of some of the stratigraphically highest coals as a negative indication for hydrocarbon potential in all stratigraphic levels and all the geographic regions of the basins. The recent discovery of petroleum within the basin (Osadetz *et al.*, 2003a), as seepages or stains, provides information that eliminates play level risks associated with petroleum system function and reservoir occurrence. The results presented herein indicate that there are at least three operational petroleum systems, each with sources and crude oils of different molecular composition and stratigraphic characteristics operating in Bowser and Sustut basins. The results are consistent with the revised observations and models of thermal maturity and history. Integration of these data, models, and interpretations will increase the robustness of petroleum resource assessments in this potential frontier petroleum province.

¹Geological Survey of Canada: Calgary, 3303 33 St. NW, Calgary, AB, Canada, T2L 2A7

²Humble Geochemical Services Division, 218 Higgins Street, Humble, Texas 77338 U.S.A.

³Geological Survey of Canada: Pacific, 101-605 Robson St. Vancouver, BC, Canada, V6B 5J3;

⁴Resource Development and Geoscience Branch, BC Ministry of Energy and Mines, PO Box 9323, 6th Floor, 1810 Blanshard St., Victoria, BC, Canada, V8W 9N3

REGIONAL GEOLOGICAL OVERVIEW

The Bowser and Sustut basins are located in north-central British Columbia (Figure 1), in the Intermontane Belt of the Canadian Cordillera, a region of sedimentary diagenesis or low metamorphic grade (mainly greenschist facies) relative to the adjacent Omineca and Coast metamorphic and plutonic belts. They overlie Devonian to early Middle Jurassic strata of the allochthonous terrane Stikinia.

The basins comprise three stratigraphic successions with overlapping ages. The Bowser Lake Group is the lowest, ranging from upper Middle Jurassic to mid-Cretaceous. It constitutes a major clastic depositional wedge that includes strata deposited in distal submarine fan, slope, shallow marine shelf, deltaic, fluvial, and lacustrine environments (*e.g.* Tipper and Richards, 1976; Evenchick *et al.*, 2001). It was deposited directly on Stikinia, a volcanic arc that includes Jurassic upper Hazelton Group clastic successions. The Lower to mid-Cretaceous Skeena Group occurs south of the Bowser Lake Group with uncertain stratigraphic relationships. Skeena Group strata were deposited in marine and nonmarine environments, and are intercalated with volcanic successions (Tipper and Richards, 1976). The mid-to Upper Cretaceous Sustut Group, a fluvial and lacustrine foreland basin succession, unconformably onlaps the Hazelton and Bowser Lake groups that are deformed in older Skeena Fold belt structures. The Skeena Fold Belt subsequently involved and deformed the Sustut Group (Eisbacher, 1974; Figure 2).

All 3 successions and underlying Stikinia are deformed in the Skeena Fold Belt, a thin skinned contractional fold and thrust belt of Cretaceous and possibly early Tertiary age (Evenchick 1991). Northeast vergent open to close folds of about 100 to 1000 m wavelengths are the dominant structures at exposed levels, but larger wavelength folds often outlined by anticlinoria and synclinoria in Bowser Lake Group are associated with structural culminations and depressions inferred to be controlled by the involvement of Stikine Assemblage volcanic and clastic strata. The fold hinges trend northwest dominantly, but domains of northeast fold hinge trends occur in western Skeena Fold Belt (*ibid.*). Hinterland verging thrusts, in the vicinity of boundary between Bowser Basin and Sustut Basin (Evenchick and Thorkelson, in press), define a triangle zone (Gordy *et al.*, 1977), similar to major productive and prospective structures in many thrust and fold belts (MacKay *et al.*, 1996).

CRUDE OIL OCCURRENCE

New field work and the analysis of existing samples have identified, extracted, and characterized twenty crude oil occurrences from locations in Bowser and Sustut basins (Table 1, Figure 2). Numerous additional

indications of crude oil staining and petroleum fluid inclusions occur with the Bowser and Sustut basins, but only twenty samples (Table 1) are characterized here. Petroleum occurrences include:

1. Tsatia Mountain, (NAD 27, UTM Zone V E442468 N6380068), a breached oil field in Muskaboo Creek Assemblage Bowser Lake Group (GSC Extract X9693 and X9694; Osadetz *et al.*, 2003);
2. Sandstone in the roof of the triangle zone north of Cold Fish Lake (NAD 27, UTM Zone V E511100 N6396070), Tango Creek Formation Sustut Group (GSC Extract 9746);
3. Footwall of the Crescent Fault near the confluence of Buckinghorse Creek and Spatsizi River (NAD 27, UTM Zone V E525670 N6366320), Eaglenest (deltaic) assemblage of the Bowser Lake Group (GSC Extract X9731);
4. Amoco Ritchie a-3-J/104-A-6, one of the only two petroleum exploration wells in the basin, shows extensive oil stains which were extracted from samples at depths of 2115.7'; 4337.0'; 4723.4'; 6745.0' (GSC Extracts X9742-X9745);
5. Twelve diverse samples from the northern Bowser and Sustut Basins (between 57.4284° N to 57.7803°N and 127.7689° W to 130.0625° W; GSC Extracts X9790 to X9801);
6. New field examples of rocks potentially stained with crude oil have also been identified during sample drilling for paleomagnetic samples (Evenchick *et al.*, 2003). Oil films were present in the circulating fluid during paleomagnetic sampling of all Stikinia rocks sampled at Oweegee Dome. Oil films were present in a large number of lithologies through this antiformal culmination, including limestone, volcanic flows, volcanoclastic turbidites and conglomerates in Hazelton Group and lower units, as well as from Bowser Lake Group sandstone at Mount Ritchie (Figure 2, *ibid.*). These samples remain to be extracted and characterized, but they might reasonably be expected to resemble oil samples from the Ritchie wells;
7. In addition, to the stains noted above there are confirmed flammable natural gas seeps of biogenic methane into Tatogga Lake (Osadetz *et al.*, 2003) that will be reported elsewhere (Evenchick *et al.*, in prep).

All these indications demonstrate that petroleum (both crude oil and natural gas) occurs in Bowser and Sustut basin. The existing resource assessment suggests that significant petroleum resources and large pool sizes can be expected (Hannigan *et al.*, 1995), but only

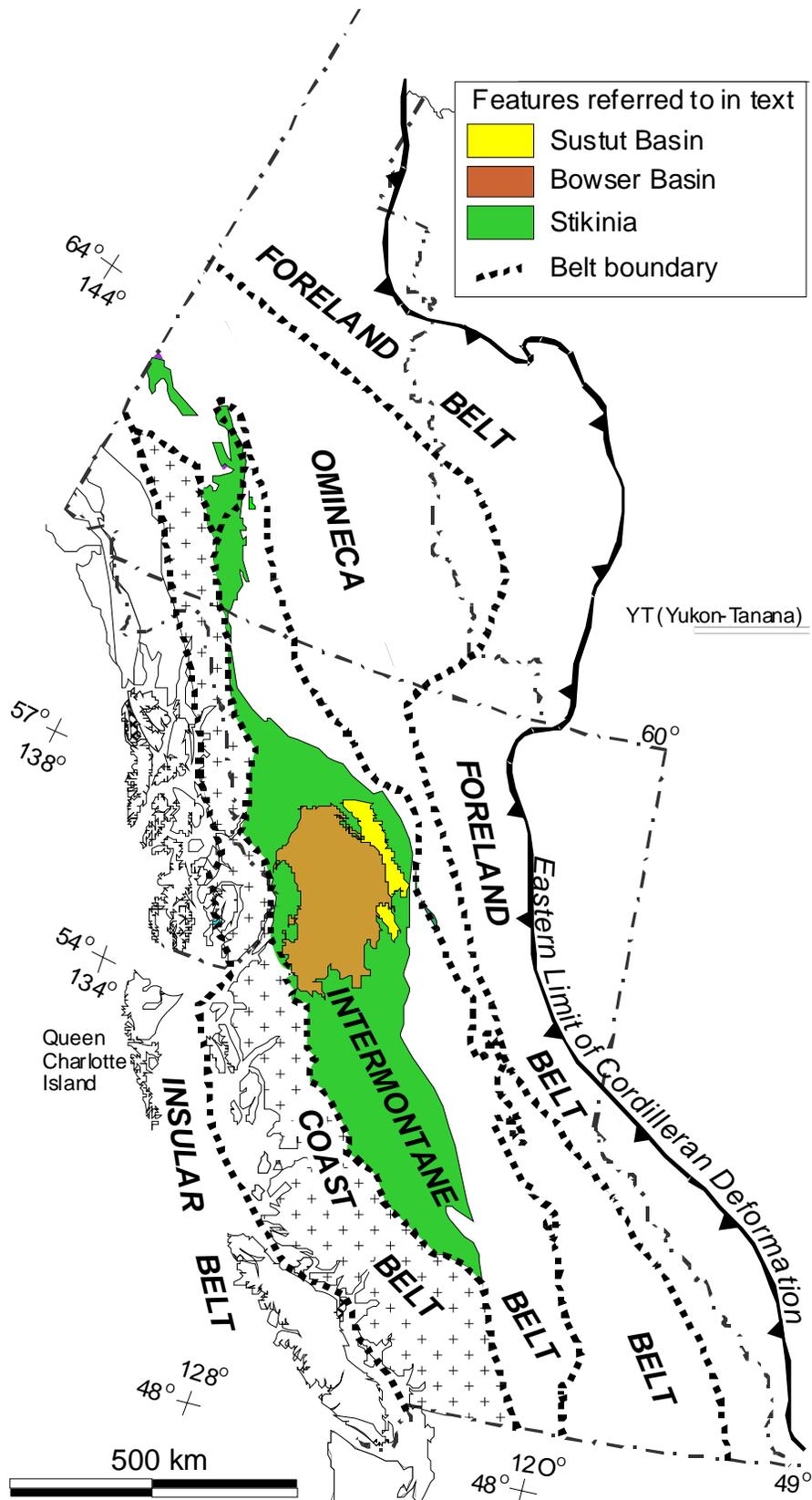


Figure 1. Location of the Bowser and Sustut basins on a base map showing the morphogeological belts of the Canadian Cordillera.

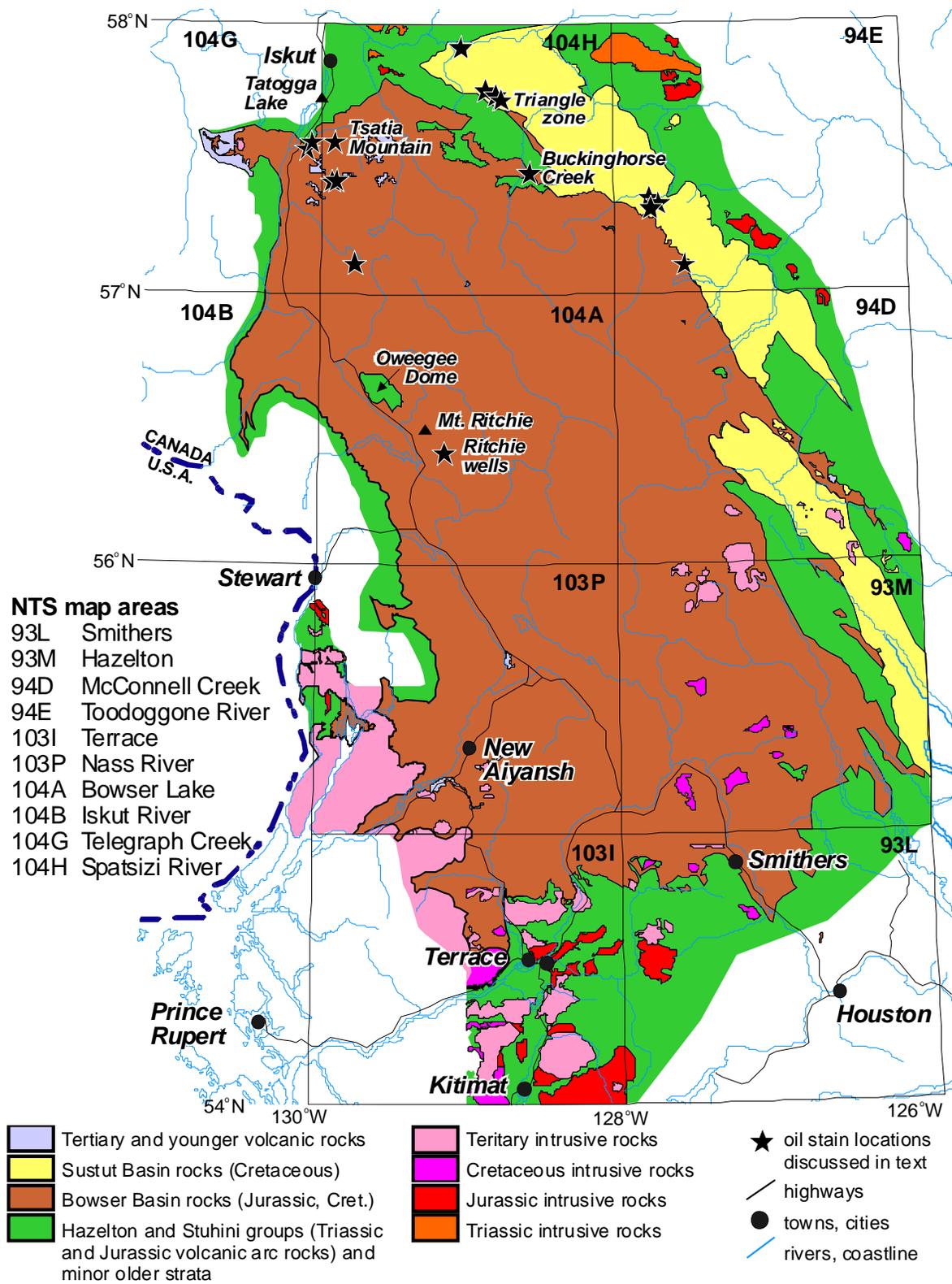


Figure 2. The locations of select crude oil samples discussed in text shown on a regional map of the Bowser and Sustut basins. The locations of all samples are listed in Table 1.

Table 1: Crude oil stain and fluid inclusion sample locations

Extract #	Latitude (°N)	Longitude (°W)	Depth	Map Unit
X9693	57.5613	129.9616	outcrop	Bowser Lake Gp; Muskaboo Creek Assemblage
X9694	57.5613	129.9616	outcrop	Bowser Lake Gp; Muskaboo Creek Assemblage
X9731	57.4408	128.5724	outcrop	Bowser Lake Gp; Eaglenest Assemblage
X9742	56.4188	129.1531	644.8 m	Bowser Lake Group
X9743	56.4188	129.1531	1321.9 m	Bowser Lake Group
X9744	56.4188	129.1531	1439.6 m	Bowser Lake Group
X9745	56.4188	129.1531	2055.8 m	Bowser Lake Group
X9746	57.5613	129.9616	outcrop	Sustut Group; Tango Creek Fm.
X9790	57.9247	129.1408	outcrop	Sustut Group; Tango Creek Fm.
X9791	57.5559	130.0481	outcrop	Bowser Lake Gp; Todagin Assemblage
X9792	57.1124	129.7686	outcrop	Bowser Lake Gp; Todagin Assemblage
X9793	57.4284	129.9309	outcrop	Bowser Lake Gp; Skelhorne Assemblage
X9794	57.4322	129.8974	outcrop	Bowser Lake Gp; Skelhorne Assemblage
X9795	57.3179	127.7667	outcrop	Sustut Group; Tango Creek Fm.
X9796	57.3137	127.7329	outcrop	Sustut Group; Tango Creek Fm.
X9797	57.1170	127.5309	outcrop	Bowser Lake Gp; Eaglenest Assemblage
X9798	57.7310	128.7963	outcrop	Sustut Group; Brothers Peak Fm.
X9799	57.7803	128.8793	outcrop	Sustut Group; Brothers Peak Fm.
X9800	57.5460	130.0625	outcrop	Bowser Lake Gp; Skelhorne Assemblage
X9801	57.3060	127.7689	outcrop	Sustut Group; Tango Creek Fm.

exploratory drilling will confirm the existence of a significant undiscovered petroleum resource.

PETROLEUM CHARACTERIZATION USING MOLECULAR COMPOSITIONAL TRAITS

Crude oil compositional characteristics reflect kerogen paleoecology, depositional environments, diagenesis, and maturity. Differential expulsion, migration, and post accumulation affects processes like catagenesis, biodegradation and water washing can also affect crude oil composition (Peters and Moldowan, 1993; Waples and Machihara, 1990; Seifert and Moldowan, 1986, 1981, 1978). Therefore it is important to distinguish source characteristics from migration and post-accumulation effects before inferring depositional and diagenetic characteristics directly from crude oils.

Extracts studied herein exhibit three distinguishable and distinctive compositional associations, or family groups, defined by persistent compositional characteristics that are exhibited by a variety of fractions and compounds, but which are especially well illustrated by steranes, the focus of this discussion.

Phytolic acid side chains from chlorophyll molecules indicate a particular phototrophism. The acyclic isoprenoid compounds pristane (Pr) and phytane (Ph), which are ubiquitous compounds in crude oils, are commonly derived from these side chains of chlorophyll molecules, although other sources for these compounds exist (Figure 3; Volkman and Maxwell, 1986). Low Pr/Ph is commonly inferred to indicate water column anoxia, especially when accompanied by even-odd n-alkane predominance (Welte and Waples, 1973). High Pr/Ph ratios are commonly interpreted as indicative of oxic water columns (Volkman and Maxwell, 1986).

Steranes, both regular and rearranged, are common biological markers in oils. Acid clays in the depositional

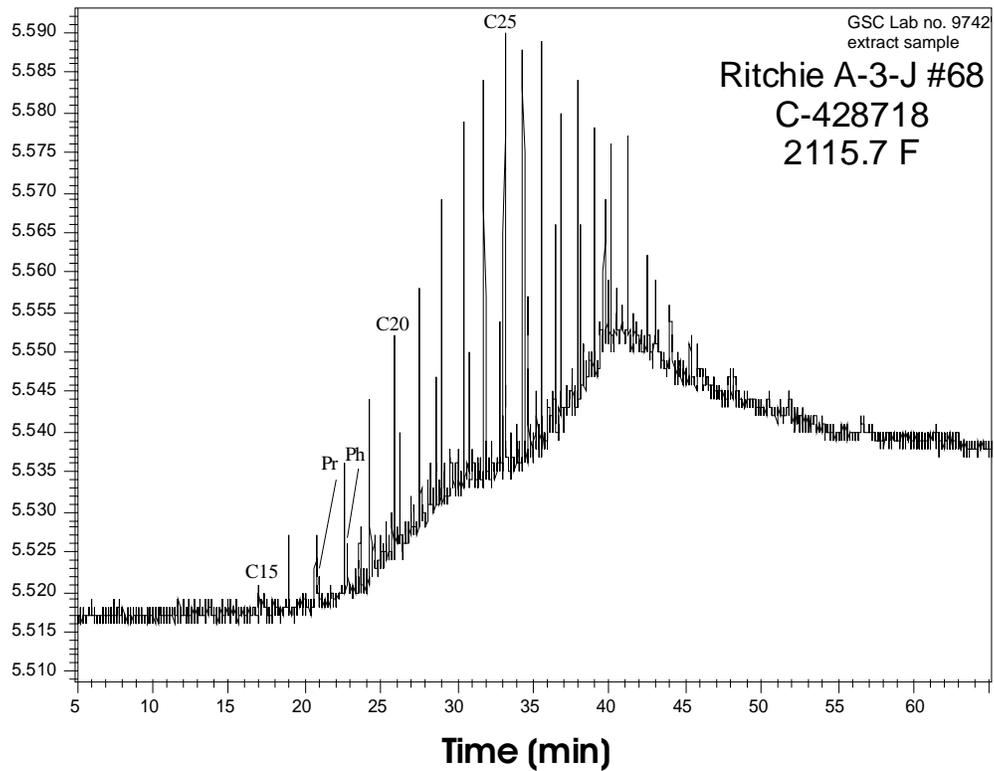
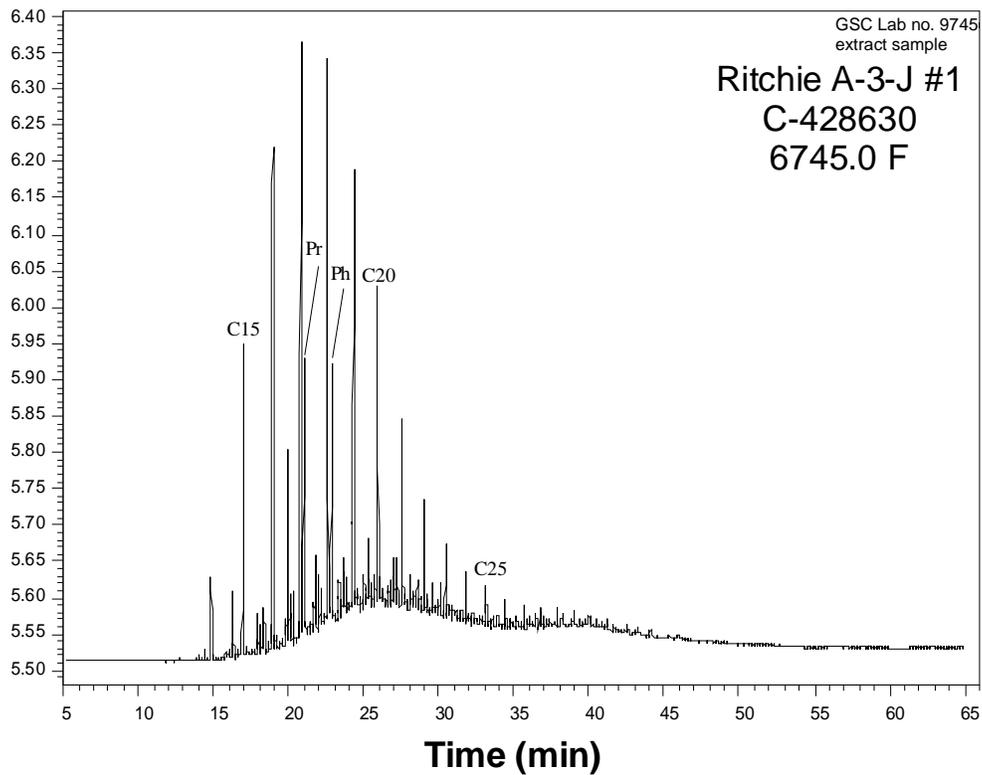


Figure 3. Illustrative saturate fraction gas chromatograms (SFGC) of two solvent extract samples from the Ritchie A-3-J well at 6745.0 feet (2055.8 m, top) and 2115.7 feet (644.8 m, bottom)(Figure 2). All figures show detector response (y-axis) as a function of time since injection on the chromatographic column (x-axis). The obvious SFGC compositional differences between these two samples are interpreted as due primarily to biodegradation of the shallower crude oil sample by aerobic bacteria.

environment can control early diagenetic reactions that result in sterane rearrangement via unsaturated intermediates to produce diasteranes (Figure 4; Sieskind et al, 1979; Rubinstein *et al.*, 1975). Low relative diasterane abundances, like those in some carbonate sourced petroleum systems are generally interpreted to indicate a clay starved depositional environment (i.e. a "carbonate" source rock), although many "carbonate" source rocks have diasterane/regular sterane ratios like those attributed to "clastic" source rocks (Osadetz *et al.*, 1992). A biological source of diasteranes is unlikely, but the association of anomalously high diasteranes in carbonate rocks with evaporitic depositional environments suggests a relationship (Clark and Philp, 1989).

Strongly reducing depositional environments are required to preserve organic matter and form kerogen in sedimentary petroleum source rocks. Since strongly reducing conditions can persist below the sediment-water interface, even in the absence of water column anoxia, euxinic sediments do not directly indicate water column environmental conditions. However, some biological compounds to source rock kerogen, notably phytolonic acid side chains of chlorophyll and bacteriohopane-tetrol

are commonly inferred to be affected by reduction and oxidation reactions in the water column, prior to, or at the earliest stages of, their incorporation into the sediment (Peters and Moldowan, 1993). Peters and Moldowan (1991) suggest that C₃₂ to C₃₄ hopane prominences could result from either redox reactions controlled by the deposition environment or from precursors molecules other than bacteriohopane-tetrol. The first alternative is preferred because C₃₄ hopane and C₃₅ hopane prominence commonly follows source rock depositional environment and paleoecology (Osadetz *et al.*, 1992). This results in a water column chemistry indicator that is preserved in compounds that are a common trace component of crude oils (Figure 5; Peters and Moldowan, 1991). The higher the carbon number of predominant extended hopanes the stronger and more persistent the water column anoxia.

RESULTS

Select gross and molecular compositional results of the twenty examined samples appear in Table 2. All subsequent illustrations of gas chromatograms and mass chromatograms show detector response (y-axis) as a

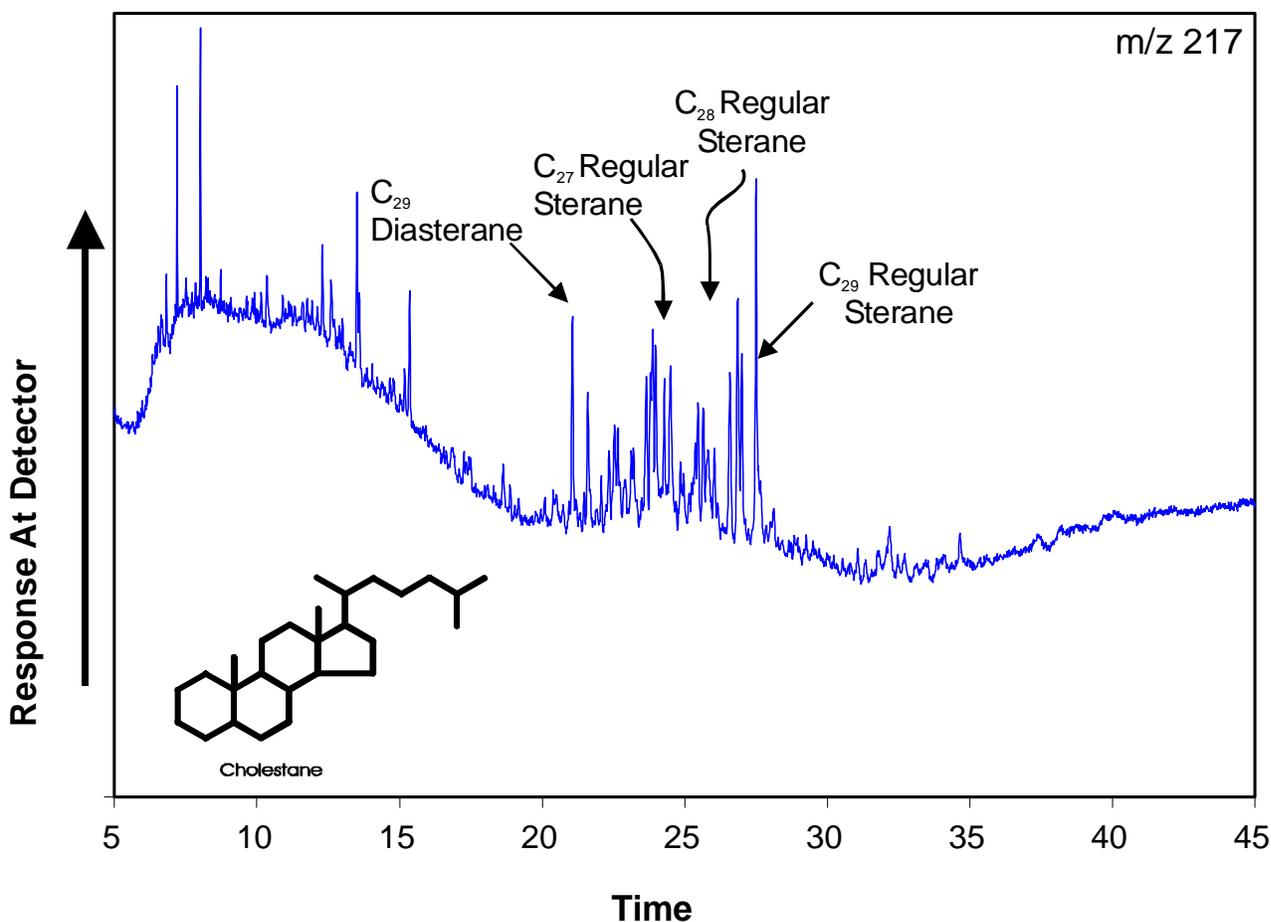


Figure 4. An example m/z 217 mass chromatogram showing the relative abundance of both regular and rearranged, or dia-, steranes in solvent extract sample X9693, from a sample of Muskaboo Creek Assemblage bioclastic sandstone at Tsatia Mountain.

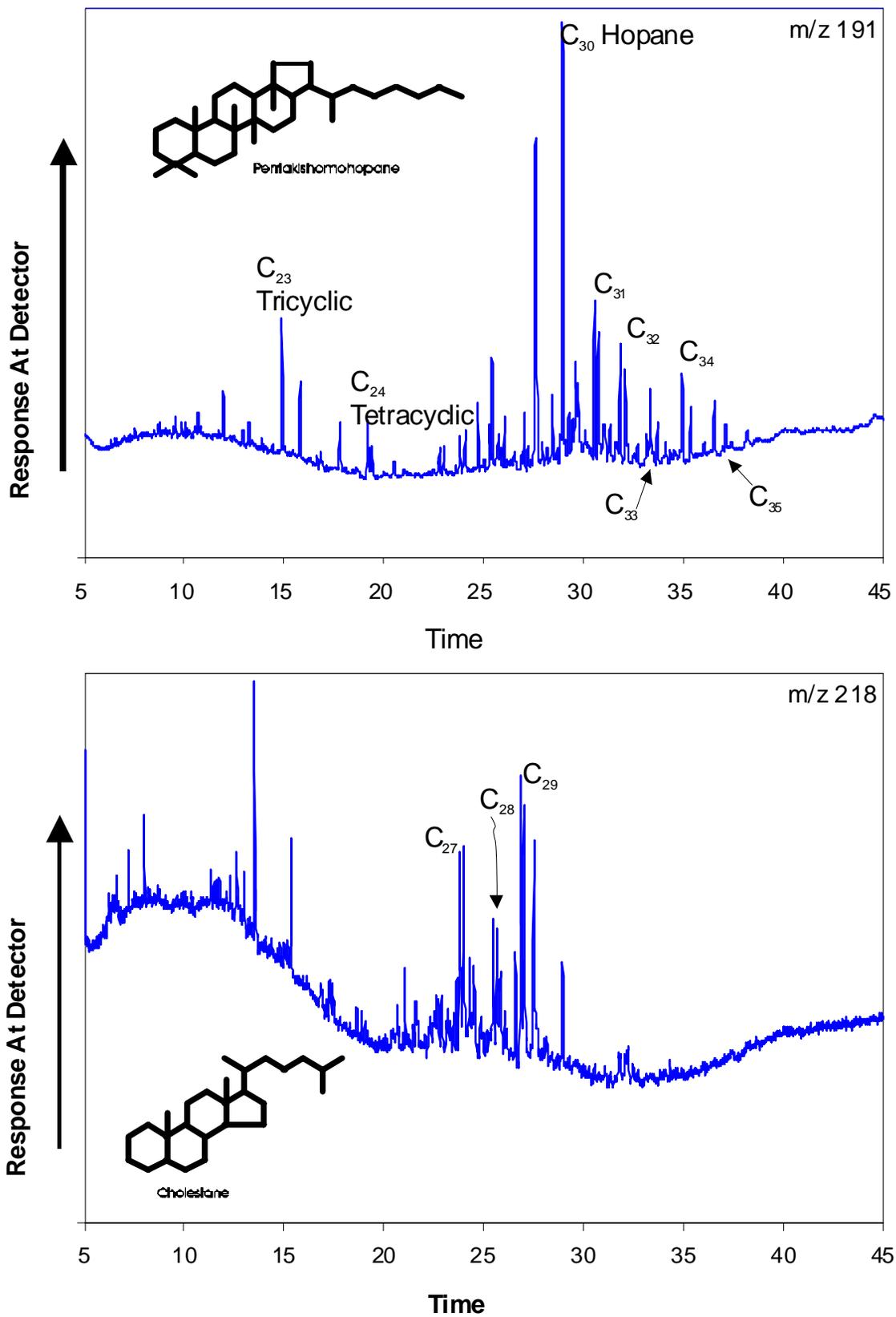


Figure 5. An example m/z 191 (terpanes, Top) and 218 (regular steranes, Bottom) mass chromatogram in solvent 5extract sample X9693, from Muskaboo Creek Assemblage bioclastic sandstone at Tsatia Mountain.

function of time since injection on the chromatographic column (x-axis). Compounds are identified by both standard elution order and by full scan triple sector GCMS operating in MS-MS mode. All samples have been characterized optically or petrographically as being stains or petroleum fluid inclusions. The low hydrocarbon yields and low HC% values are due to the small recoverable volumes (Table 2). This is expected considering the exposure of both outcrops and old well cuttings to processes of dissipation and alteration resulting from their exposure to the elements, especially in light of the inferred low densities and expected volatility of the hydrocarbons (Osadetz *et al.*, 2002).

SELECT CRUDE OIL MOLECULAR COMPOSITIONAL TRAITS

Molecular compositional differences among the samples are diverse, but they can be characterized by consideration of select compound variations. The observed variations are interpreted using standard techniques and previous studies to distinguish variations due to the alteration, specifically biodegradation, so that other variations due primarily to source can be isolated and interpreted. The variation of biological marker compounds, like steranes and terpanes, within the sample set are observed and interpreted to be unaffected by alteration, allowing interpretation of compositional variations attributed to source rock age (regular steranes, Grantham and Wakefield, 1988), lithology (diasteranes/regular steranes, Seiskind *et al.*, 1979; hopane prominence, Osadetz *et al.*, 1992) and depositional environment (Peters and Moldowan, 1991) that form the basis of compositional family and petroleum system definition.

Figure 3 illustrates the range of Saturate Fraction Gas Chromatogram (SFGC) compositions observed in the samples. Both samples are from the Ritchie A-3-J well at 6745.0 feet (2055.8 m, Figure 3, top) and 2115.7 feet (644.8 m, Figure 3, bottom; Figure 2) and both have similar biological marker compositions. Solvent extract X9745 (top) exhibits a normal crude oil response dominated by normal alkanes, derived from cell wall phospholipids and the irregular isoprenoid, most noticeably pristane (Pr) and phytane (Ph). The low amplitude baseline “hump” defines the envelope of a complicated mixture of coeluting compounds. Solvent extract X9742 (bottom) exhibits a biodegraded crude oil response dominated by normal alkanes that are paired, for samples with longer elution times than nC₂₀, with a homologous series of alkylcyclohexanes and methylalkylcyclohexanes that were identified by GC-MS-MS experiments not discussed herein. Sample X9742 also exhibits a high amplitude baseline “hump” of more complicated coeluting compounds. Note especially the relative change in response of the “hump” relative to compounds eluting prior to and after nC₂₀ between the two samples. The sterane compositions of these two samples are essentially similar (Table 2, Figures 4, 5, 6) illustrating that the lower molecular weight saturate fraction composition has been altered by the preferential removal of normal alkanes. Such compositional variations are commonly inferred to be indicative of biodegradation (Peters and Moldowan, 1993; Osadetz *et al.*, 1992)

The sample set compositional variation can be illustrated using a few key compounds. The most illustrative variations are shown by the regular and rearranged steranes (Figure 4). An example m/z 217 mass chromatogram showing the relative abundance of regular and rearranged, or dia-, steranes in solvent extract sample

**TABLE 2:
SELECT GROSS AND MOLECULAR COMPOSITIONAL RESULTS FROM BOWSER BASIN CRUDE OILS**

Sample No.	TOC (%)	(ppm of rock)	Extract (% of TOC)	HC (%)	R+A (%)	Sat/Aro	Pr/Ph	C ₂₉ St Dia/Reg	% C ₂₇	% C ₂₈	% C ₂₉	C ₂₇ /C ₂₉	C ₂₈ /C ₂₉
X9693	BD	2385	N/A	10.8	85.0	1.0	N/A	0.22	26	21	53	0.49	0.40
X9694	BD	22500	N/A	8.9	80.0	1.0	N/A	0.26	32	19	48	0.67	0.39
X9731	BD	N/A	N/A	N/A	N/A	N/A	N/A	0.76	42	26	31	1.35	0.83
X9742	BD	5500	N/A	4.6	87.7	0.3	N/A	0.54	30	29	40	0.76	0.73
X9743	0.10	396	40	7.9	86.8	2.0	N/A	0.56	25	33	42	0.59	0.80
X9744	0.01	771	771	10.7	57.1	0.8	0.44	0.64	22	33	44	0.50	0.75
X9745	5.05	579	1	27.3	58.2	0.6	1.11	0.55	26	34	40	0.66	0.86
X9746	0.05	1179	236	5.4	75.0	4.0	0.69	0.52	30	29	41	0.73	0.71
X9790	4.69	4442	9	4.7	90.6	0.1	1.29	0.57	16	18	66	0.24	0.28
X9791	0.88	1897	22	3.6	86.4	1.0	0.86	0.65	41	27	31	1.32	0.87
X9792	0.74	2857	39	3.9	85.0	0.4	0.67	0.76	41	27	32	1.28	0.86
X9793	1.07	4080	38	4.9	73.5	0.3	0.97	0.61	40	27	33	1.22	0.83
X9794	19.15	9238	5	6.2	90.2	0.7	1.67	0.38	21	24	55	0.38	0.43
X9795	8.07	8600	11	7.4	84.5	0.2	4.49	0.27	7	19	73	0.10	0.26
X9796	3.26	6657	20	8.2	82.0	0.4	2.59	0.32	16	22	62	0.26	0.35
X9797	43.28	29875	7	15.7	83.7	0.2	4.56	0.23	5	25	70	0.07	0.35
X9798	0.78	4903	63	2.0	89.5	0.5	0.7	0.54	36	26	37	0.97	0.71
X9799	0.53	3448	65	12.0	81.5	0.3	0.56	0.37	25	30	46	0.53	0.64
X9800	0.52	1832	35	8.1	84.3	0.9	1.04	0.77	38	27	35	1.10	0.77
X9801	3.19	3701	12	10.2	86.3	0.3	1.87	0.19	9	19	72	0.13	0.27

X9693 is from Muskaboo Creek Assemblage at Tsatia Mountain. Steranes are derived from cholestane-like molecules that act as common cell wall rigidifiers in eucaryotic organisms. The presence of diasteranes is an indicator of depositional environment and source rock lithology (Sieskind et al, 1979; Rubinstein *et al.*, 1975).

Two important groups of biological marker are the terpanes (m/z 191, Figure 5: Top) and regular steranes (m/z 218, Figure 5: Bottom). Their occurrence is also illustrated by mass chromatograms from solvent extract sample X9693, from Muskaboo Creek Assemblage at Tsatia Mountain. The m/z 191 mass chromatogram illustrates terpanes, which are primarily derived from bacteriohopanetetrol, a cell wall rigidifier in prokaryotic organisms (Peters and Moldowan, 1993). The ratio of similar carbon number hopanes in the homologous group of compounds that occurs to the right of the C30 hopane peak as annotated double peaks is controlled by depositional environment physical conditions (Peters and Moldowan, 1991). This sample shows that C34 hopanes are prominent, due to the accumulation of the source rock in an environment where anhydrite or gypsum was accumulating (Osadetz *et al.*, 1992). The m/z 218 mass chromatogram illustrates regular steranes that were probably derived primarily from cholesterol. The ratio of C28 to C29 steranes is known to increase with geological age in marine depositional environments, due to biochemical evolution in the marine biosphere (Grantham and Wakefield, 1998). The observed ratio of C28/C29 steranes, combined with the standard interpretation of the m/z 191 mass chromatogram indicates that the source rock of this oil stain is a sub-Hazelton carbonate source rock deposited in submarine hypersaline to mesohaline depositional environments, and probably occurring in the underlying Stikine succession.

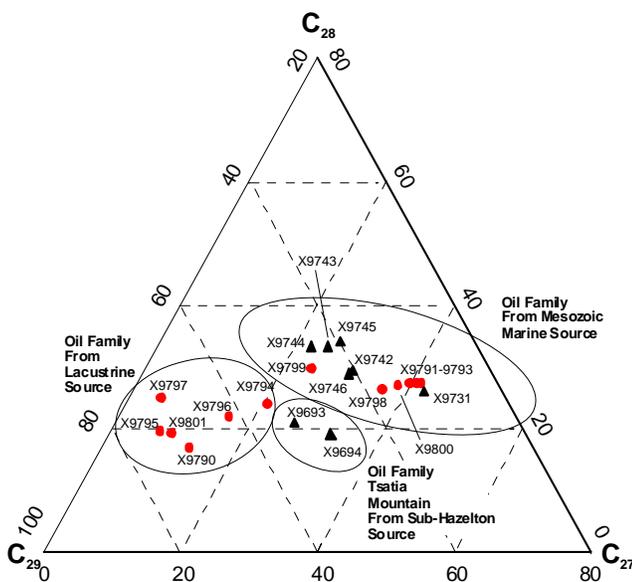


Figure 6. A ternary diagram illustrating compositional variations and affinities of all twenty solvent extract samples using the relative abundance of C₂₇-C₂₈-C₂₉ regular steranes (Table 2). The three oil families are identified.

A ternary diagram shows the variations and affinities of all twenty samples using the relative abundance of C₂₇-C₂₈-C₂₉ regular steranes (Figure 6, Table 2). The biodegradation of some oils (Figure 3) does not affect regular sterane compositions, such that observed variations can be attributed primarily to source rock compositional differences. This figure illustrates the presence of the three oil families identified. One, composed of two extracts from Tsatia Mountain (X9693, X9694) is inferred using terpane and sterane compositional characteristics to be derived from a carbonate source in the underlying Stikine succession, as discussed above. Using similar standard interpretations (Peters and Moldowan, 1993) we interpret the steranes and terpanes of the other samples. The second compositional family includes samples from the Amoco Ritchie a-3-J/104-A-6 at depths of 2115.7'; 4337.0'; 4723.4'; 6745.0' (GSC Extracts X9742-X9745), the Tango Creek Formation sample from the Triangle zone (GSC Extract X9746), the Eaglenest assemblage sample from Buckinghorse Creek (GSC Extract X9731), as well as six samples from other locations in the northern Bowser basin region (GSC Extracts X9791-93 and X9798-80, Table 1) which have compositional characteristics that suggest derivation from an open Mesozoic marine source rock. This potential source facies probably lies in the upper Hazelton or lower Bowser Lake groups, as the lowest stratigraphic occurrence of these oils lies in slope and shelf facies of the Bowser Lake Group. A third oil family composed of six samples from the group of twelve diverse samples from northern Bowser Basin (GSC Extracts X9790, X9794-97 and X9801) is distinguished by having lower C₂₇ regular steranes and generally higher C₂₉ regular steranes compared to all other samples. This oil compositional family is inferred to have a non-marine, possibly lacustrine source in Bowser Lake or Sustut groups (Peters and Moldowan, 1993). The transitional position of samples X9794 and X9796, do not preclude the possibility that they could be mixtures of the two oil families inferred to have Mesozoic source rocks. This is possible since the geographic range of the two end-member compositions of the Mesozoic marine and non-marine source oils overlaps. However, other evidence presented below suggests that mixing is not important.

A cross plot of the ratios C₂₉ diasteranes to regular steranes and ratio of regular C₂₈ steranes to C₂₉ steranes (Figure 7) shows additional compositional variations within families using variation of diasteranes/regular steranes (Sieskind et al, 1979; Rubinstein *et al.*, 1975). Those oils inferred to have a non-marine Mesozoic source have an overlapping range of diasterane/regular sterane ratios to those inferred to have Mesozoic marine sources, however the range of non-marine source oil compositions is illustrated by X9790, which is one of the samples that is most different from the oils inferred to have marine Mesozoic sources. Therefore, it is unlikely that the samples X9794 and X9796 are mixtures of any significant proportion. A cross plot of the ratios C₂₉ diasteranes to

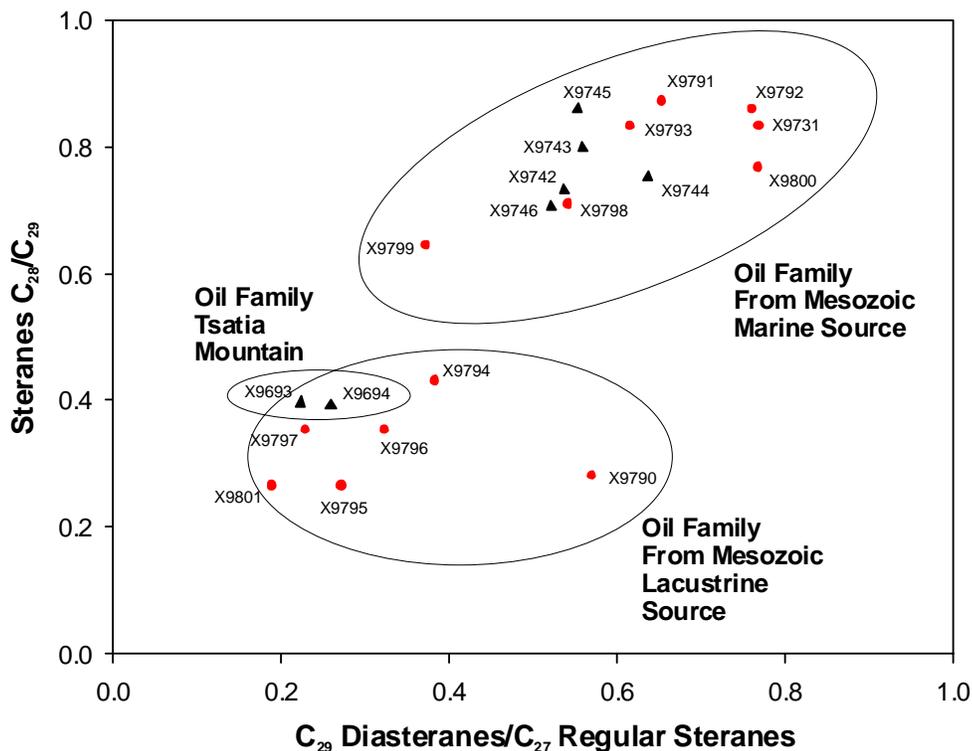


Figure 7. A cross plot of the ratios C_{29} diasteranes to C_{27} regular steranes and ratio of regular C_{28} steranes to C_{29} steranes showing that the compositional variations within families, as typified by the variation of diasteranes/regular steranes.

regular steranes and the ratio of pristane and phytane from the SFGC illustrates that the compositional distinction between the two interpreted Mesozoic oil families is also reflected by other compositional traits (Figure 8). Insufficient pristane and phytane were observed in the oils inferred to be sourced from the Stikine assemblage strata (X9693; X9694) to allow their characterization using pristane and phytane, however, they are distinguished from most Mesozoic sourced oils by their generally higher saturate to aromatic hydrocarbon ratio (Table 2).

DISCUSSION

The interpretation that biodegradation has altered the composition of some crude oils at or near the surface is important, but not surprising. The Amoco Ritchie a-3-J/104-A-6 well has a porous interval containing a resistive fluid that is either "by-passed petroleum pay" or fresh water. The nature of the wireline-log resistivity anomaly is not diagnostic. Some crude oil extracts from this well are clearly biodegraded (Figure 3), as a result of aerobic bacterial degradation that implies a connection with oxygenated, probably fresh and meteoric water, which like hydrocarbons, is electrically resistive. In the same well Koch (1973) reported other petroleum shows including both dry and wet gas in cuttings samples at depths <2600' where the gas detector indicated >40 units, compared to background readings of 10-20 units. Therefore, the nature of the resistivity anomaly in the well

remains unresolved. Regardless, the combined observations are important since the wireline logs indicate the presence of porous zones in some of the deepest strata in Bowser Lake Group, while the oil stains indicate an effective petroleum system in the same region. The results are consistent with the revised thermal maturity model (Evenchick *et al.*, 2002).

The analysis of the molecular composition of these oil stains and seepages has identified at least three distinct compositional crude oil families. One oil family is inferred to be derived from carbonate source rocks in underlying Stikinia. The second and third oil families are inferred to be derived from Jurassic or younger sources in the Hazelton-Bowser-Sustut successions, one of which has the characteristics of a marine source, and the other which has compositional characteristics of a non-marine, or lacustrine, source. The source rocks of these petroleum systems have not been identified explicitly, nor have the oils been correlated to solvent extracts from potential source rocks, although potential source rock intervals have been identified in a variety of stratigraphic positions (Evenchick *et al.*, 2002; Osadetz *et al.*, 2003b). However, the significant number of petroleum stains and their association with structures that could be traps for petroleum, as at the Ritchie well, Tsatia Mountain and in the roof of the triangle zone all point toward a complete removal of play level risks for both petroleum system and reservoir. This suggests that a revised petroleum assessment would be even more encouraging than the existing one (Hannigan *et al.*, 1995).

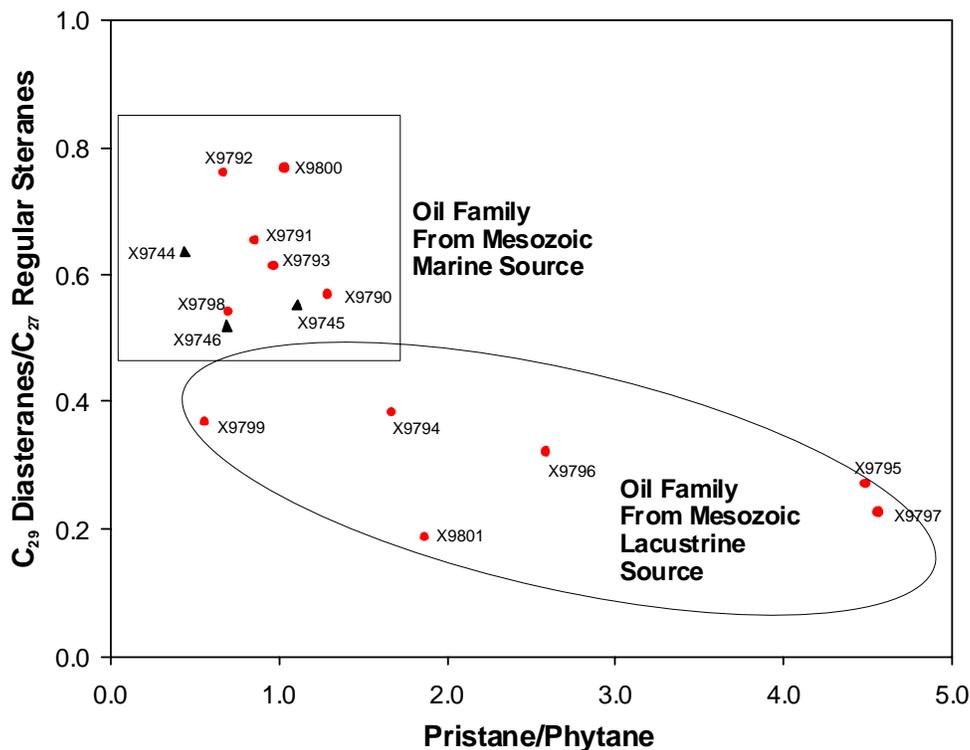


Figure 8: A cross plot of the ratios C_{29} diasteranes to C_{27} regular steranes and ratio of pristane (Pr) and phytane (Ph) from the saturate fraction gas chromatogram (SFGC) that illustrates how compositional distinctions between the two Mesozoic oil families is reflected by additional compositional traits.

CONCLUSIONS

Oil stains occur widely, both geographically and stratigraphically, with only the northern half of these basins being investigated. Twenty crude oil stains and petroleum fluid inclusions have been extracted from Bowser Lake and Sustut group rocks and their compositions have been characterized. The molecular compositions of these samples are interpreted to show that there are at least three compositionally distinct oil families representative of three effective petroleum systems in Bowser and Sustut basins.

Molecular compositional differences can be characterized by sterane compositional variations using standard techniques and previous studies, once the effects of alteration -- specifically biodegradation, are discounted. One compositional oil family is inferred derived from the sub-Hazelton succession. A second compositional oil family derived from normal Mesozoic marine source rocks is inferred derived from the upper Hazelton or lower Bowser Lake groups. A third oil family derived from lacustrine Mesozoic source rocks is inferred to occur in the Bowser Lake Group.

The occurrence and composition of these crude oils expand the petroleum prospectivity of Bowser Basin by reducing petroleum system risks and indicating a possible

petroleum system for Hazelton Group. The preservation of crude oils is also a strong confirmation of the revised thermal maturity model for the basin (Evenchick *et al.*, 2002). Existing petroleum resource assessments (Hannigan *et al.*, 1995) do not attribute petroleum potential to sub-Bowser successions indicating a need for revision.

ACKNOWLEDGEMENTS

We thank Sneh Achal, Rachel Robinson, and Marina Milovic for their technical assistance in the production of the data employed here. GSC colleagues Mark Obermajer, Maowen Li and David Ritcey provided helpful discussions and technical assistance in the preparation of this paper. This is Geological Survey of Canada contribution #2003313.

APPENDIX 1: ANALYTICAL PROCEDURES

Anhydrous Pyrolysis

Rock-Eval/TOC is a useful screen for recognizing sources and stained lithologies. Rock samples suspected or identified as having crude oil stains or petroleum fluid inclusions were pyrolyzed using Rock-Eval/TOC (Table 2), to determine total organic carbon content (Table 2; Espitalie *et al.*, 1985; Peters, 1986; Tissot and Welte, 1978, p. 443-447). The Rock-Eval/TOC analysis gives five parameters: S1, S2, S3, TOC and Tmax. The S1 parameter measures free or adsorbed hydrocarbons volatilized at moderate temperatures (300°C). S2 measures the hydrocarbons liberated during a ramped heating (300-550°C at 25°C/min.). The S3 parameter measures organic CO₂ generated from the kerogen during rapid heating (300-390°C at 25°C/min.). Milligrams product per gram rock sample, the equivalent to kilograms per tonne, is the measure of all these parameters. Total Organic Carbon (TOC) is measured and reported in weight per cent. Tmax, the temperature corresponding to the S2 peak maximum temperature is measured in °C.

Rock-Eval/TOC parameters have significance only above threshold TOC, S1 and S2 values. If TOC is less than about 0.3% then all parameters have questionable significance and the experiment suggests no potential. Oxygen Index (OI), S3/TOC, has questionable significance if TOC is less than about 0.5%. OI values greater than 150 mg/g TOC can result from either low TOC determination or from a mineral matrix CO₂ contribution during pyrolysis. Both Tmax and Production Index (PI = S1/(S1+S2)), have questionable significance if S1 and S2 values are less than about 0.2. Results can be affected by mineral matrix effects. These either retain generated compounds, generally lowering the S1 or S2 peaks, while increasing Tmax, or by liberating inorganic CO₂ and increasing S3 and OI. Mineral matrix effects are important if TOC, S1 and S2 are low, an effect not significant in this study.

Solvent Extract Gross Composition

The amount and composition of solvent extractable bituminous material, including crude oil stains and petroleum fluid inclusions was obtained by extracting the bitumen from the rock sample using the Soxhlet technique (Table 2). Solvent extracts were fractionated using packed column chromatography following a method effectively similar to that published by Snowdon (1978). The resulting gross composition can be used to identify crude oil stains or to characterize source rock richness and maturity. Normalized solvent extract hydrocarbon (HC)

yield, quoted in milligrams extract per gram organic carbon (mg/g TOC), is a richness indicator. HC yields less than 30 mg/g TOC suggests no source rock potential. Those between 30 and 50 mg/g TOC suggest marginal potential. HC yields between 50 and 80 mg/g TOC show good potential. Greater values indicate excellent potential. Hydrocarbon percentage criteria for maturity are commonly OM Type and lithology independent. Stained samples are those with more than 55% HC's and lower values are characteristic of petroleum source rocks, if sufficient material is available, which is not the case for this study. Less than 20% HCs' characterizes thermally immature sources, 25%, but less than 45% HCs' is the interval of marginal maturity with higher values occurring during the the main HC generation stage.

Solvent Extract Molecular Composition

The extractable bitumen was deasphalted by adding an excess of pentane (40 volumes) and then fractionated using open column liquid chromatography. Saturate hydrocarbons were analysed using gas chromatography (GC) and gas chromatography - mass spectrometry (GCMS). A Varian 3700 FID gas chromatograph was used with a 30 m DB-1 column coated with OV-1 and helium as the mobile phase. The temperature was programmed from 50°C to 280°C at a rate of 4°C/min and then held for 30 min at the final temperature. The eluting compounds were detected and quantitatively determined using a hydrogen flame ionization detector. The resulting saturate fraction chromatograms (SFGC) were integrated using *Turbochrom* software. GCMS was performed in both single ion monitoring and full scan modes on both saturate and aromatic hydrocarbon fractions of solvent extracts, although only select saturate fraction compositional characteristics obtained from single ion monitoring experiments are reported here. Single ion monitoring GCMS experiments were performed on a VG 70SQ mass spectrometer with a HP gas chromatograph attached directly to the ion source (30 m DB-5 fused silica column used for GC separation), or under similar analytical conditions. The temperature, initially held at 100°C for 2 min, was programmed at 40°C/min to 180°C and at 4°C/min to 320°C, then held for 15 min at 320 °C. The mass spectrometer was operated with a 70 eV ionization voltage, 300 mA filament emission current and interface temperature of 280°C. Terpane and sterane ratios reported herein were calculated using m/z 191 and m/z 217 and m/z 218 mass chromatograms.

REFERENCES

- Clark, J. P., and Philp, R. P. (1989): Geochemical characterization of evaporite and carbonate depositional environments and correlation of associated crude oils in the Black Creek Basin, Alberta. *Bulletin of Canadian Petroleum Geology*, v. 37, no. 4., pages 401-416.

- Eisbacher, G.H.(1974): Sedimentary history and tectonic evolution of the Sustut and Sifton basins, north-central British Columbia; *Geological Survey of Canada*, Paper 73-31, 57 pages.
- Espitalie, J., Deroo, G. and Marquis, F. (1985): Rock Eval Pyrolysis and Its Applications. Preprint; Institut Francais du Pétrole, Geologie No. 27299, 72 p. English translation of, La pyrolyse Rock-Eval et ses applications, Première, Deuxième et Troisième Parties, *in Revue de l'Institut Francais du Pétrole*, v. 40, p. 563-579 and 755-784; v. 41, pages 73-89.
- Evenchick, C.A. (1991): Geometry, evolution, and tectonic framework of the Skeena Fold Belt, north-central British Columbia; *Tectonics*, v. 10, page 527-546.
- Evenchick, C.A., Poulton, T.P., Tipper, H.W., and Braidek, I. (2001): Fossils and facies of the northern two-thirds of the Bowser Basin, northern British Columbia; *Geological Survey of Canada*, Open File 3956.
- Evenchick, C.A., Ferri, F., Mustard, P.S., McMechan, M., Osadetz, K. G., Enkin, R., Hadlari, T., and McNicoll, V. J. (2003): Recent results and activities of the Integrated Petroleum Resource Potential and Geoscience Studies of the Bowser and Sustut Basins project; in *Current Research, Geological Survey of Canada, A-13*, 11 pages.
- Evenchick, C.A., Hayes, M.C., Buddell, K.A., and Osadetz, K.G. (2002): Vitritine reflectance data and preliminary organic maturity model for the northern two thirds of the Bowser and Sustut basins, north-central British Columbia. Geological Survey of Canada, Open File 4343 and *B.C. Ministry of Energy and Mines*, Petroleum Geology Open File 2002-1.
- Evenchick, C.A., Osadetz, K.G., Ferri, F., Mayr, B., and Snowdon, L. R., (in prep.): A Natural Seepage of Biogenic Methane in the Intermontane Belt (Bowser Basin) of the Canadian Cordillera. *Bulletin of Canadian Petroleum Geology*, v. XX, no. X., p. XXX-XXX.
- Evenchick, C.A. and Thorkelson, D.J. (in press): Geology of the Spatsizi River map area, north-central British Columbia, *Geological Survey of Canada Bulletin 577*.
- Gordy., P.L., Frey, F.R., and Norris, D.K. (1977): Geological guide for the C.S.P.G. 1977 Waterton - Glacier Park Field Conference. - *Canadian Society of Petroleum Geologists*, Calgary.Grantham, P. J., and Wakefield, L. L.(1988): Variations in the sterane carbon number distributions of marine source rock derived crude oils through geological time, *Organic Geochemistry*, v. 12, no. 1, pages 61-73.
- Hannigan P. K., Lee, P. J. and Osadetz, K. G. (1995): Oil and gas resource potential of the Bowser-Whitehorse area of British Columbia, *Report to BCEMR*, March 1995, 72 pages.
- Koch, N. G. (1973): Central Cordilleran Region; in R. G. McCrossan ed., *The Future Petroleum Provinces of Canada - Their Geology and Potential*, *Canadian Society of Petroleum Geologists*, Memoir 1, pages 37-71.
- MacKay, P. A., Varsek, J. L., Kubli, T. E., Dechesne, R. G., Newson, A. C., Reid, J. P. (1996): Triangle Zones and Tectonic Wedges. *Bulletin of Canadian Petroleum Geology*, v.44, No.2, pages. I-1-I-5.
- Osadetz, K.G., Evenchick, C. A. , Ferri, F. , Stasiuk, L. D., and Wilson, N. S. F. (2003a): Indications for effective petroleum systems in Bowser and Sustut basins, north-central British Columbia. *in Geological fieldwork*, 2002; *B.C. Ministry of Energy and Mines*, Paper 2003-1, pages 257-264.
- Osadetz, K.G., Snowdon, L.R., and Obermajer, M. (2003b): ROCK-EVAL/TOC results from 11 Northern British Columbia boreholes. *Geological Survey of Canada*, Open File 1550 and *B.C. Ministry of Energy and Mines*, Petroleum Geology Open File 2003-1 (CD-ROM).
- Osadetz, K. G., Brooks, P. W., and Snowdon, L. R. (1992): Oil families and their sources in Canadian Williston Basin (southeastern Saskatchewan and southwestern Manitoba). *Bulletin of Canadian Petroleum Geology*, 40, pages 254-273.
- Peters, K. E. (1986): Guidelines for evaluating petroleum source rock using programmed pyrolysis. *American Association of Petroleum Geologists*, Bulletin, v. 70/3, p. 318-329.
- Peters, K. E., and Moldowan, J. M. (1993): *The Biomarker Guide*, Prentic-Hall, Englewood Cliffs, N. J., 363 pages.
- Peters, K. E., and Moldowan, J. M. (1991): Effects of source, thermal maturity, and biodegradation on the distribution and isomerization of homohpanes in petroleum. *Organic Geochemistry*, v. 17, no. 1, pages 47-61.
- Rubinstein, I., Sieskind, O., and Albercht, P. (1975): Rearranged sterenes in a shale: occurrence of simulated formation. *Journal of the Chemical Society*, Perkin Transactions I, pages 1833-1835.
- Seifert, W. K., and Moldowan, M. J. (1986): Use of biological markers in petroleum exploration; *in* R. B. Johns (ed.), *Biological Markers in the Sedimentary Record*. Amsterdam: Elsevier, pages 261-290.
- Seifert, W. K., and Moldowan, J. M. (1981): Paleoreconstruction of biological markers. *Geochimica et Cosmochimica Acta*, v. 45, pages 783-794.
- Seifert, W. K., and Moldowan, J. M. (1978): Applications of steranes, terpanes and monoaromatics to the maturation, migration and source of crude oils. *Geochimica et Cosmochimica Acta*, v. 42, pages 77-95.
- Sieskind, O., Joly, G., and Alberecht, P. (1979): Simulation of the geochemical transformation of sterols: superacid effect of clay minera. *Geochimica et Cosmochimica Acta*, V. 43, pages 1675-1679.
- Snowdon, L. R. (1978): Organic geochemistry of the Upper Cretaceous/Tertiary delta complexes of the Beaufort Mackenzie Sedimentary Basin. *Geological Survey of Canada*, Bulletin 291.
- Tipper, H.W. and Richards, T.A. (1976): Jurassic stratigraphy and history of north-central British Columbia; *Geological Survey of Canada*, Bulletin 270, 73 pages.
- Tissot, B. P., and Welte, D. H. (1978): *Petroleum formation and occurrence*; Springer-Verlag, Berlin, 538 pages.
- Volkman, J. K., and Maxwell, J. R. (1986): Acyclic isoprenoids as biological markers; *in* R. B. Johns (ed.), *Biological Makers in the Sedimentary Record*. Methods in Geochemistry and Geophysics, 24, Amsterdam: Elsevier, pages 1-42.
- Waples, D. W., and Machihara, T. (1990): Application of sterane and triterpane biomarkers in petroleum exploration. *Bulletin of Canadian Petroleum Geology*, v. 38, pages 357-380.
- Welte, D. H., and Waples, D. W. (1973): Über die Bevorzugung geradzahlgiger n-Alkane in *Sedimentgesteinen*. *Naturwissenschaften*, v. 60, pages 516-517.