Distribution and type of organic matter in Cretaceous to Tertiary source rocks in Soroosh and Nowrooz fields, Persian Gulf

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Abstract

Detailed organic petrography analysis were conducted on drill core and cutting samples from the Nahr Umr (Middle Albian), Burgan (Lower Albian) and Ratawi (Hauterivian) formations on the Soroosh and Nowrooz fields, NW part of the Iranian sector of the Persian Gulf. The thermal maturity of the Middle Albian Nahr Umr Formation appears to have reached the top of the oil window. The underlying Burgan (Kazhdumi) Formation shows vitrinite reflectance values less than those within the Nahr Umr Formation. The Burgan organic matter is terrestrial in origin and appears to be formed in a coal measures part of the section. Lamalginite is not prominent within the Burgan samples that were examined. The vitrinite found is texturally immature. The association of low reflectance values and textural immaturity could be due to early impregnation with oil, presumably from deeper horizons within the section. The Ratawi samples are lithologically dominated by carbonate and contain abundant lamalginite macerals. Much of the lamalginite is unusual in having a diffuse form. Most of the lamalginite macerals are associated with free oil inclusions. The Ratawi Formation is within the zone of active oil generation at present. In textural terms, the closest similarity to the Ratawi is the organic matter in the Miocene Monterey Formation from the west coast of the USA. The lamalginite differs from that found in lacustrine facies, and from that present in some prominent algal- rich Mesozoic source rocks such as the Kimmeridge Clay.

Keywords: *Organic petrography, Vitrinite reflectance suppression, Cretaceous rocks, Soroosh and Nowrooz fields, Persian Gulf.*

Introduction

Source rock study including evaluating its organic-richness, quality and thermal maturity is significant from hydrocarbon generation, migration and entrapment point of view. The purpose of this study is to characterize the dispersed organic matter (DOM) and assess thermal maturity of organic matter (OM) present in suite of rock samples from Soroosh and Nowrooz fields located in northwestern Persian Gulf. Detailed organic petrography analyses and reviewing the published data (Bashari, 2008; Paymani, 2003) enabled source rock evaluation and prediction of oil generation windows for Nahr Umr (Middle Albian), Burgan/Kazhdumi (Lower Albian) and Ratawi (Hauterivian) formations. This study also investigates the cause of vitrinite reflectance suppression noticed in some samples and discusses the basis for a frequently cited cause of suppressed vitrinite reflectance: bitumen or oil impregnation of vitrinite (Jones and Edison, 1978; Raymond and Murchison, 1991; Barker, 1991; Mukhopadhyay, 1994; Taylor *et al*., 1998; Carr, 2000). By definition, both materials are soluble in organic solvents and are part of extractable organic matter (EOM) yield during solvent extraction. Bitumen is thought to be an intermediate product generated by kerogen maturation that in turn breaks down to form oil, gas and an insoluble residue (pyrobitumen) (Tissot & Welte, 1984; Lewan, 1985)

The locations of the fields are shown in Fig. 1. A generalized stratigraphic section is given in Fig. 2.

Geological setting

Nowrooz field is located about 90 km WNW of Kharg Island in the northern part of Persian Gulf, about 50 km NNW of Soroosh and some 20km NNW of the *Aboozar* fields (Fig. 1). The structure has NNE-SSW trending elongate anticline measuring approximately 20 km by 5 km. The reservoir rocks are Albian sandstones of the Burgan Formation (Fig.2). The structure has a pronounced southern culmination and is faulted along its crest. Significant crestal collapse is present over the northern culmination which has lower structural relief compared to the southern culmination (Ghazban, 2007). *Soroosh* field is a domal structure located about 80 km west of Kharg Island, and produce oil from the Burgan Formation. The Burgan sands and shales (equal to Nahr Umr Formation) were deposited during a transgressive-regressive phase under shallow marine, littoral, to inner shelf environmental conditions with deltaic influence (Motiei, 1993). In Soroosh oil field, the proportion of sand (Kazhdumi Formation) increases considerably and sand facies occurs between a lower and upper interbedded shale-limestone unit (Mina *et al*., 1967).

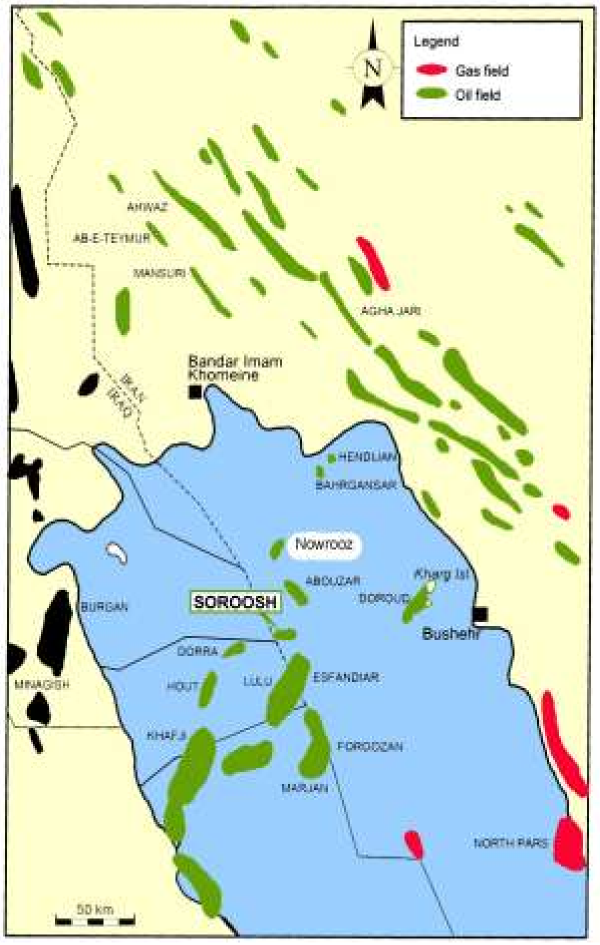

Figure 1: Location Map of the Soroosh and Norooz fields in northern Persian Gulf (Bashari, 2008).

Materials and methods

A total of eighteen samples were collected from three boreholes (Nowrooz-16, Soroosh-02 and Soroosh-17). Samples from three wells drilled in the northern part of the Persian Gulf were examined to determine the vitrinite reflectance and to describe the organic matter assemblages that are present.

Two of these wells are from the Soroosh field, and one well (three Burgan cores) is from the Nowrooz field. Nine samples from cuttings and nine samples from cores.

Age		Stratigraphic Units: Offshore Iran	Stratigraphic Units: Kuwait SE Iraq
Pliocene Quaternary		Bakhtiari Fm	Dibdibba
		Agha Jari Fm	
Miocene		Mishan	Lower Fars
		Gacharsan Fm	
		Amsari Fm	Ghar
Oligocene			
Eocene	Upper	Jahrum Fm	Dammam
	Middle		
	Lower	Pabdeh Fm	Rus
Palaeocene			Umm Er Radhuma
Cretaceous	Maastrichtian	Gurpi Fm	Tayarat
	Campanian		Bahra
	Santonian	Ilam Fm	Gudair
	Coniacian		
	Turonian	Sarvak Fm	Magwa
	Cenomanian		Ahmad
			Wara
	Albian		Mauddud
		Kazhdumi Fm	Burgan/Nahr Umr ●
	Aptian	Dariyan Fm	Shu'aiba
	Neocomian	Gadvan Fm	Zubair
		Fahliyan Fm	Ratawi ●
			Minagish
Jurassic	Late	Surmeh Fm	Hith/Gotnia
	Middle		
	Early	Neyriz Fm	
Triassic		Khaneh Kat Fm	

● Source Rock

Figure 2: Simplified stratigraphy of Northern Persian Gulf (Bashari, 2008).

Preparation and mounting of samples

The samples were dried at about 105°C, then placed in silicone moulds and mounted to make briquettes suitable for polishing. The samples were bound using a cold-setting polyester resin. Polyester is preferred to the epoxy resins used by many laboratories because it has a polishing hardness closer to that of organic matter and sedimentary rocks that have a clay matrix. Examination of the duplicate samples indicated no significant difference between the two different procedures.

Grinding and polishing

Grinding was undertaken using silicon carbide wet and dry papers, irrigated with water. Final grinding was done with a metal impregnated 20 micron diamond lap. Coarse polishing was done with 20 micron silicon carbide rolling abrasive. Fine polishing was done using first chromium sequioxode and then gamma alumina on a velvet cloth laps with a variable speed lap. Normal polishing speed for this stage is about 50 r.p.m. This polishing agent and lap combination gives moderate polishing relief and controlled polishing relief is useful during identification of macerals.

Reflectance measurements

Reflectance measurements were made in accordance with AS 2486. A Leitz MPV 1.1 photometer, mounted on a Leitz Orthoplan microscope, was used. Measurements were made using a 50x NPL oil immersion objective lens. The OPAK illuminator must be set so that the Berek prism is in the light train and the polarizer in the 45-degree position. A 10x ocular was
used to project the image onto the field stop adjacent to the photometer. Total magnification from the system on to the photometer stop is 500x (organic petrographic analyses were made by Alan Cook, Keiraville Konsultants, New South Wales, Australia).

The field stop that is located in the mounting from the stabilized light source was set to illuminate a square of about 30 microns square on the sample. For measurements, the combination of settings for the stabilized quartz iodine lamp and the photomultiplier tube (PMT) voltage was set to give a readout that is essentially a direct reading of reflectance. This is done during calibration with the standards. The measuring stop in front of the photometer was set to an aperture giving a back projected image size on the sample of about 2 microns by 3 microns.

The standards used are the McCrone spinel (0.42%) yttrium aluminium garnet (0.90%) and the gallium gadolinium garnet (1.72%). Calibration runs were taken before and after each set of reflectance measurements or at any other time when there was evidence of drift. The main cause of rapid change is the presence of small air bubbles that rise into the oil from pores within the samples. Checking for air bubbles is done directly by introducing the Bertrand lens to the light path where a polarizing binocular tube is fitted. Rotation of the stage can also aid in the detection of bubbles as the density differences cause the bubbles to move as a result of centrifugal forces. Temperature in the room with the photometer was kept within a range of 23°C ±2°C to ensure that the immersion oil has a refractive index (n_e=1.518) within the required limits.

Mean maximum reflectances were measured. To obtain these, after a vitrinite field had been acquired, the stage was rotated until a maximum was obtained. The stage was then rotated 180 degrees to obtain a second maximum. Provided the two values are within about 5% relative, they were accepted and averaged. Therefore, the number of measurements taken is twice the number of fields reported as being measured. The overall mean, ranges and standard deviations were reported, together with descriptions of each sample, including estimated maceral abundances by volume. Variation of readings on rotation is usually associated with local tilt due to polishing relief or with coals, the development of desiccation cracks. A check on tilt can be made using the Bertrand lens. Although the effects of tilt cannot be eliminated, they can be minimised by setting the stage at the location where N-S run-out of the image using the Betrand lens is at a minimum.

Higher rank vitrinite or vitrinite-like material can show distinct to extreme bireflectance. Where reflectance is high but bireflectance low, this is normally evidence for contact alteration. With the polarizer in the light train, coke textures can normally be detected in the white light image. The use of partially or completely crossed polars provides a more sensitive test of the present of coke mosaic and mosaic size. Bireflectances are probably present in the deeper section, but did not prove useful in distinguished vitrinite (bireflecting) from inertinite (either isotropic or showing stress bireflectance).

Even after careful centring of the lens, stage run-out is typically about 0.002 to 0.003 mm. This means that where pairs of readings are made, although these are almost on the same area of vitrinite, the exact areas for the two component readings for each measurement may be slightly different. Thus the number of fields measured is effectively more than the number reported in the data listings. For this reason, means and histograms are more robust statistically than where single readings have been taken.

For samples with clearly defined vitrinite populations, the mean reflectance has stabilised after about 20 readings and the base number of fields measured (N) is usually 25. Where multiple populations or other complications are present, the number of fields should be increased provided sufficient fields could be found. Within the present sample suite, at least 25 fields could be found in all but one of the samples and over 40 fields were measured for one sample. Inertinite reflectances are reported. The inertinite measurements tended to be biased towards low reflecting inertinite.

Maceral analyses

The macerals were recognized following the classification used in ICCP 1994 and Taylor *et al*., (1998) with slight differences (see Appendix 1). The major differences related to the combination of terms for lower rank vitrinite macerals (termed huminite in Taylor *et al*., 1998) and to the macerals within alginite. The use of term vitrinite over the full range of rank or maturation simplifies descriptions and does not result in the loss of any information.

Point counts are reliable only where organic matter is at least a major component (>10% and desirably >25%) and this was not the case for most of the samples in the present suite. For samples with low organic matter abundance (the great majority of all of the samples in the present study), the errors associated with point counts become unacceptably high, unless very large numbers of points are counted. Therefore, visual estimates were made for abundances of organic matter. This was done using comparison charts.

Examinations in fluorescence-mode were made using the plane slip illuminator and fluorescence-mode was used for all fields for the samples where fluorescing liptinite was present. Fluorescence-mode illumination is also used to determine mineral fluorescence characteristics. Where organic matter is a minor component, abundance estimation is more reliable than the point-count technique.

Sequence during examination of sample

Samples were examined first using a low power air immersion lens in order to examine the overall textures. After immersion oil was placed on the sample, reflectance measurements are made as soon as possible. Experience shows that reflectance values can decrease following immersion in oil, usually after a period of some hours. Therefore, the possibility of this occurring was eliminated by making reflectance measurements within an hour of initial immersion. Some fluorescence examinations were undertaken concurrently with the measurement of reflectance, mostly for the lower vitrinite reflectance samples to check on the presence or absence of fluorescence from the vitrinite.

Following the measurement of reflectances, the samples were examined in fluorescence and white light modes to obtain the maceral analyses. For the samples with lower levels of maturation examination was made using both white light and fluorescence-modes.

Especially for samples that have present maturation levels within the oil generation window, fluorescence intensity tends to increase on exposure to the fluorescence excitation beam. For some of the early to mid-mature samples, some fields were subjected to prolonged irradiation to check on alteration properties of the organic matter and minerals. No marked alteration was noted. Oil haze was not prominent but appears to be present in some of the deeper samples.

Where abundance terms are used, these are defined as follows:

Category	**Percentage (by volume)**
Absent	0.0
Rare	<0.1
Sparse	0.1-0.4
Common	0.5-1.9
Abundant	2.0-9.9
Major	10.0-49.9
Dominant	50.0-100

Organic matter assemblages

Organic facies present

Organic matter ranges from sparse to major. Within the Tertiary section, organic matter is absent to rare with liptinite being present in the Ghar Formation.

In the Cretaceous samples, organic matter is generally more abundant compared to the overlying Tertiary and ranges from rare to major. Apart from the Burgan Formation, marine liptinite is the most prominent component (Plate 2).

The Ahmadi to Nahr section contains typical marine assemblages. Liptinite is typically the most abundant maceral group, but dispersed organic matter (dom) is rare to sparse.

The upper part of the Burgan contains lamalginite and some of the samples show evidence of a lacustrine origin. The sample from 2303.5 m in the Burgan Limestone contains *Botryococcus*-related telalginite. This alga forms resistant tests, that can be transported, but it has origin from non-marine settings and usually its presence indicates a lacustrine depositional setting (Cook & Struckmeyer, 1986).

The Burgan B samples contain common sporinite and vitrinite ranges from common to major. Two samples from the Burgan B coaly interval examined from Soroosh-17 were similar in facies to reference samples from Nowrooz-16. The organic matter assemblages are consistent with a fluvio-deltaic origin. This interval is illustrated in Plates 1 to 8. Most of the illustrations show the well-developed telovitrinite and some of the features that indicate textural immaturity (plate 5). Plates 1 and 2 shows telovitrinite with inclusions of resinite and a small v-shaped vein of exsudatinite and plates 3 and 4 exhibit detrovitrinite, sporinite and cutinite in claystone for Nowrooz-16, 2328.5 m, Burgan, Cretaceous sample under white reflected and fluorescence-mode respectively**.** Plate 6 shows the abundant oil inclusions that are present in some lithologies from the Burgan. A sample of Burgan reservoir sand was examined. Although the sand is dark, oil traces are difficult to observe and from this limited observation it appears that the oil within the reservoir is too mobile for easy examination using petrographic techniques. It should be noted that this apparent difficulty is unusual because oils within many other reservoirs can be observed easily.

The samples from Soroosh-02 are from the Ratawi Formation and show an abundance of algal material. Terrestrial influences are minor, but can be seen in Plates 7 and 8. Plate 7 illustrates the diffuse lamalginite that is the main component of the Ratawi samples (Bashari, 2008). Oil inclusions are prominent and it appears that the Ratawi is currently within the zone of active generation of oil (Paymani, 2003).

PLATES AND PLATE CAPTIONS

The Plates were taken using Kodak 400 ASA negative film and scanned at 2900 dpi from the negatives or at 300 dpi from 15x10 cm prints. The illustrations in this document were prepared from Jpeg files at 3 compression.

The Plates used were all taken using a 50x oil immersion objective. Where reflected white light and fluorescence-mode pairs are used the two plates are close to being in registration, with any differences being due to cropping during preparation of the Jpeg files.

The fluorescence of the liptinite is generally weak and the appearance has been enhanced during the photographic and digital processes that have been used to produce the Plates.

The Plates are organised in depth order, with exception of Plate 14, which was moved to keep reflected white light and fluorescence-mode plate together on the same page. The Plates were selected to illustrate both the range of organic matter present and to try to illustrate its variation within depth.

The following abbreviations are used in lettering the Plates:

Tv= telovitrinit, Dv= detrovitrinite, Lam= lamalginite, D lam= diffuse lamalginite,

Sp= sporinite, X= exsudatinite, O= oil, O haze= oil haze, Qtz= quartz

The numbers on some of the Plates relate to the reflectance of that part of the field.

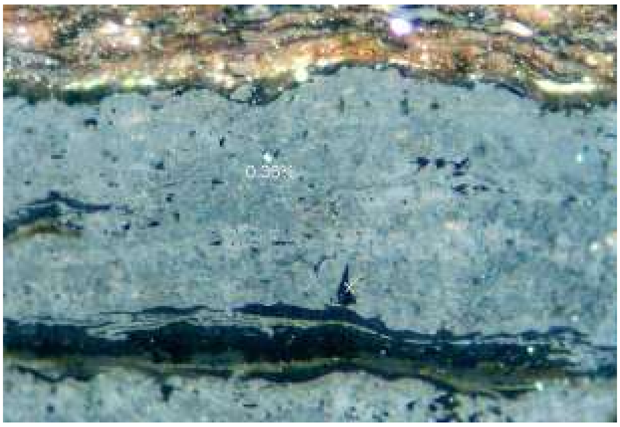

Plate 1: T9408, Soroosh-17 well, 2309 m, Cretaceous Burgan Formation. Telovitrinite with a reflectance of 0.36% and inclusions of resinite and a small v-shaped vein of exsudatinite. Reflected white light $\overline{R}_v$max 0.39%, field width 0.22 mm.

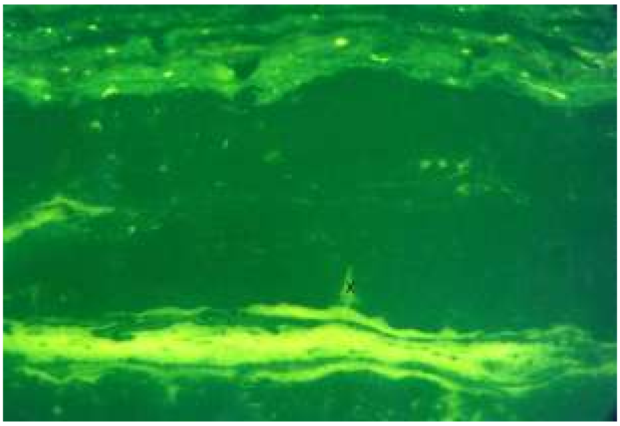

Plate 2: T9408, Soroosh-17 well, 2309 m, Cretaceous Burgan Formation. Same values as Plate 1, but in fluorescence-mode. Telovitrinite with inclusions of resinite and a small v-shaped vein of exsudatinite. Fluorescence-mode, $\overline{R}_v$max 0.39%, field width 0.22 mm.

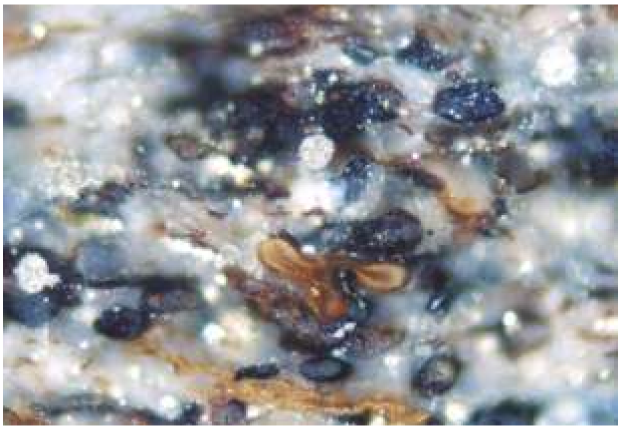

Plate 3: T9447, Nowrooz-16 well, 2328.5 m, Cretaceous Burgan Formation. Detrovitrinite, sporinite and cutinite in claystone. Reflected white light $\overline{R}_v$max 0.47%, field width 0.22 mm.

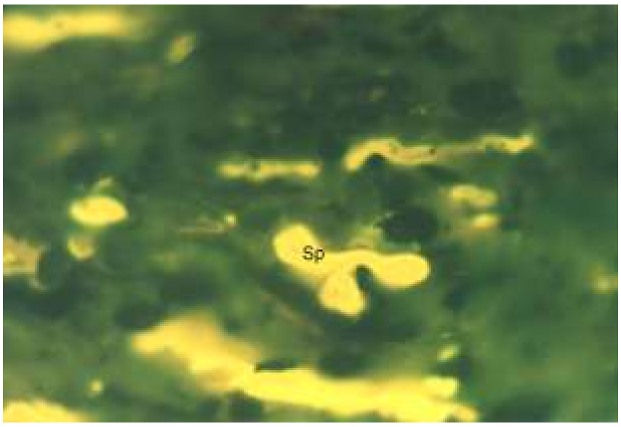

Plate 4: T9447, Nowrooz-16 well, 2328.5 m, Cretaceous Burgan Formation. Same values as Plate 3, but in fluorescence-mode. The liptinite is strongly fluorescing and this is consistent with the low values obtained for the vitrinite reflectance. Fluorescence-mode. $\overline{R}_v$max 0.47%, field width 0.22 mm.

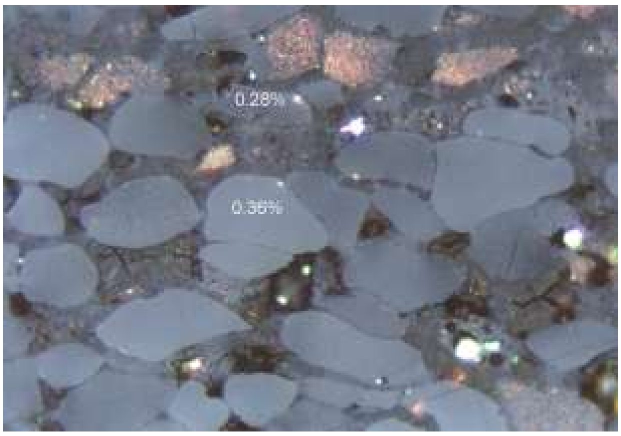

Plate 5: T9448, Nowrooz-16 well, 2350.1 m, Cretaceous Burgan Formation. Texturally immature telovitrinite. Reflected white light $\overline{R}_v$max 0.38%, field width 0.22 mm.

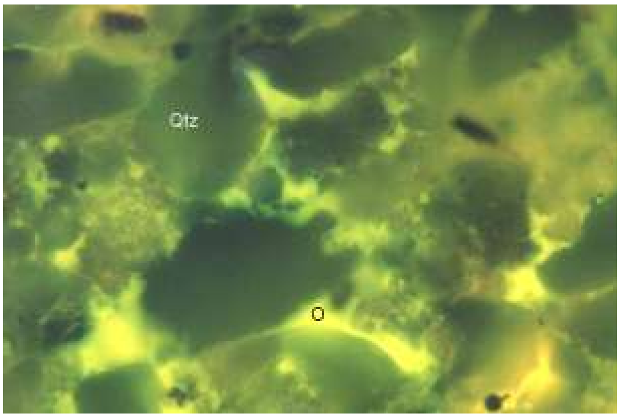

Plate 6: T9447, Nowrooz-16 well, 2328.5 m, Cretaceous Burgan Formation. Oil saturated siltstone. Fluorescence-mode. $\overline{R}_v$max 0.47%, field width 0.22 mm.

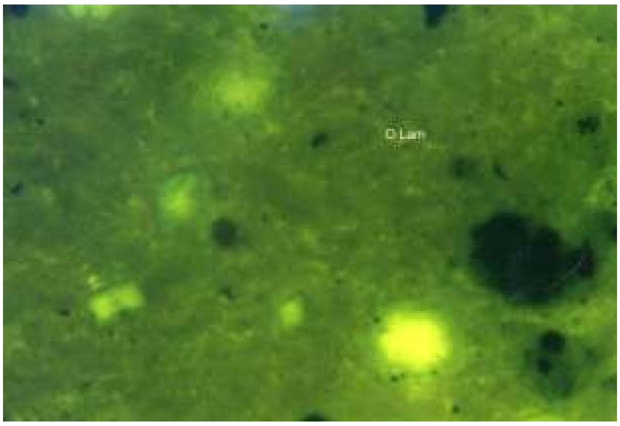

Plate 7: T9413, Soroosh-02 well, 3064 m, Lower Cretaceous Ratawi Formation. Carbonate with diffuse lamalginite. The bright orange oval area is probably an oil inclusions. Fluorescence-mode. Field width 0.22 mm.

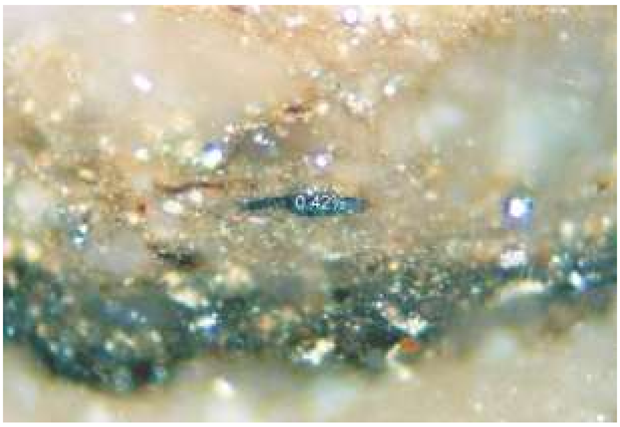

Plate 8: T9411, Soroosh-02 well, 2719 m. Lower

Cretaceous Ratawi Formation. Detrovitrinite with a reflectance of 0.42% and weakly fluorescing lamalginite in claystone. Reflected white light $\overline{R}_v$max 0.39%, field width 0.22 mm.

Reflectance Data

Vitrinite reflectance data were obtained from all of the Burgan samples and from three of the overlying Cretaceous section in Soroosh-17 and from one of the Ratawi Formation cores. Although vitrinite reflectance data are limited to the Cretaceous section, they appear to indicate that the top of oil generation window is currently about 2150 m. At the top of the Burgan, a mean vitrinite reflectance of 0.54% was obtained. Three samples below this contain common to abundant vitrinite but show lower vitrinite reflectance values that range from 0.51% at 2303.5 m to 0.36% at 2327.4 m. Below that, the basal shale shows a slightly higher mean vitrinite reflectance of 0.49%.

These values for the Burgan are similar to those found at similar depths in the Burgan cores from Nowrooz-16 and it is assumed that the effects found for Soroosh-17 are similar to those that occur within the Nowrooz-16 section.

Immature textures are found within the telovitrinite for both wells. The greater prominence of the immature textures seen in the Plates from Nowrooz-16 may be due to the presence of coal rather than shaly coal in the Nowrooz-16 samples. Fluorescence from telovitrinite is prominent both in Plate 2 (Soroosh-17) and in Plate 5 (Nowrooz-16).

The most likely explanation for both the low vitrinite reflectance values in the Burgan and the textural immaturity is that the oil was emplaced early within this unit and the fluid pressures have prevented the development of mature vitrinite textures.

This has implication both for the source of the oil and for the timing of generation. Although the Burgan is currently marginally mature for oil generation, it is unlikely that oil generated from the organic matter in the Burgan could preserve the cell textures. This would require that the oil had come from a deeper source and has migrated into the section before compaction to bituminous coal textures could occur. In general terms, this suggest emplacement of oil within the Burgan at depths of overburden less than about 1500 m.

Thermal history interpretation of VR data

Results of new vitrinite reflectance (VR) analyses carried out for this paper are summarised in Table 1.

Maximum paleotemperature estimates from the VR in Soroosh-02

Maximum paleotemperatures derived from the measured VR values and the equivalent VR values from the Lower Ratawi Formation, are summarized in Table 1.

Estimated temperature ranges from 62ºC for the measured VR data in sample GC 873-82.1 to 116ºC from inertinite reflectance in the same sample. A maximum paleotemperture of 100ºC is estimated from liptinite fluorescence observations.

A paleotemperature estimate of 62ºC from the single measured VR value in sample GC873-82.1 is anomalously low, being significantly less than the present temperature. Conversely, the estimate of 116ºC from inertinite reflectance in the same sample is higher than that the present day temperature, but this is not considered to be robust estimate as it is based on only a single measurement. On the other hand, the estimate of~100ºC over the sampled interval from liptinite fluorescence observations plots close to the present day temperature profile, suggesting that the Lower Ratawi Formation is currently at maximum paleotemperatures at the present day. This is consistent with the results obtained from more extensive data in the Soroosh-02 (Bashari, 2008). The Lower Ratawi Formation, in terms of type of organic matter, shares some similarities with algal-rich Mesozoic source rocks of the Kimmeridge Clay of NW Europe (Bray, *et al*., 1992; Cook, & Struckmeyer, 1986; Cook & Sherwood, 1990).

Vitrinite reflectance suppression in Soroosh-02 and Nowrooz-16

Mean random reflectance (Rv, in %) of normal vitrinite is an optical property of sedimentary organic matter (SOM) that is widely used in assessing the thermal history of organic matter leading to the evaluation of remaining hydrocarbon generation potential, among many other applications. However, over the last few decades, numerous studies suggest that besides thermal history, other factors, primarily operator bias in vitrinite selection, natural variations in maceral precursors and diagenesis, may act to suppress vitrinite reflectance. Through the process of primary and secondary hydrocarbon migration, vitrinite impregnation could occur by retention of internally generated bitumen within vitrinite or migration of externally generated bitumen into vitrinite (Hutton & Cook, 1980; Crick *et al*., 1988).

Table 1: Vitrinite reflectance measurements and maximum paleotemperature data for wells Soroosh-17, Soroosh -02 and Norooz-16.

Sample number	Depth (m)	Sample type	Stratigraphic subdivision	Stratigra-phic age (Ma)	VR Range (%)	Maximum Paleo-temperature (ºC)
Soroosh-17 GC873-3.1	400	cuttings	Bakhtiari-Agha Jari	5-2.6	5.80* 5.48-6.12	-
GC873-6.3	680	cuttings	Ghar Fm (L. Miocene)	24-15	-	-
GC873-11.1	1815	cuttings	Ahmadi (Sarvak) (Cenomanian)	94-91	1.42* 0.96-2.10	99
GC873-16.1	1956	cuttings	Ahmadi sh (Sarvak) (Cenomanian)	98-94	1.15* 0.80-1.60	72
GC873-23.1	1980	cuttings	Mauddud (Sarvak) (U. Albian)	99-98	0.34*	50
GC873-27.1	2148	cuttings	Nahr - Umr (Kazhdumi)(M. Albian)	101-99	0.50* 0.36-0.65	83
GC873-30.1	2175	cuttings	Dair lst (Kazhdumi) (M. Albian)	103-101	0.51* (0.39-0.65)	86
GC873-40.1	2220	cuttings	Burgan 'A' (Kazhdumi) (M. Albian)	104-103	0.54* (0.40-0.66)	92
GC873-49.1	2304	core	Burgan lst (Kazhdumi) (M. Albian)	105-104	0.51* (0.42-0.62)	85
GC873-50.1	2309	core	Burgan 'B' (Kazhdumi) (M. Albian)	106-105	0.39* (0.34-0.47)	62
GC873-52.1	2327	core	Burgan 'B' (Kazhdumi) (M. Albian)	106-105	0.36* (0.26-0.47)	55
GC873-55.1	2412	cuttings	Burgan basal sh (Kazhdumi) (M. Albian)	108-106	0.49* (0.31-0.62)	82
Soroosh-02 GC873-82.1	2719	cuttings	L. Ratawi (Fahliyan)	141-130	0.39* (0.33-0.47)	62
GC873-84.1	3052	cuttings	L. Ratawi (Fahliyan)	141-130	-	-
GC873-89.1	3064	cuttings	L. Ratawi (Fahliyan)	141-130	-	-
Nowrooz-16 GC873-58.1	2329	core	L. Ratawi (Fahliyan)	106-105	0.47* (0.38-0.64)	83
GC873-60.1	2350	core	L. Ratawi (Fahliyan)	106-105	0.38* (0.28-0.46)	65
GC873-62.1	2357	core	L. Ratawi (Fahliyan)	106-105	0.49* (0.40-0.58)	87

*Inertinite

Mean VR and inertinite-derived equivalent VR values (VRE) are plotted against depth (with respect to kb) (Fig. 3). The red square symbol in this plot represents the best estimate of VR analysis (0.57-0.60%) and the true VR level in the deepest sample was achieved based on the fluorescence observations.

As shown in Fig. 3, the VR profile is predicted on the basis of the Default Thermal History- i.e. the thermal history predicted for samples from this well if they have never been hotter than their present temperatures at any time in the past. This history is based on the burial history derived from the units intersected in the well (shown in Fig. 3), combined with the present-day thermal gradient of 31.6°C/km, derived from corrected BHT values as defined by Bashari (2008).

Two of the three measured VR values, all from the Kazhdumi sequence near TD, plot on or very near the predicted profile (Fig. 4), which suggests this formation at Nowrooz-16 has not been heated above the present-day temperatures at any time since deposition. The third value is lower, and is clearly anomalously low when compared with the two adjacent higher values. There appears to be a relationship between low VR and the abundance of telovitrinite in this sample, which was also noted for Soroosh-17. This anomalously low measured VR values are therefore attributed to some form of geochemical suppression, of unknown cause, although the presence of hydrogen-rich organic matter, high lipinite abundance and pervasive oil impregnations are possible explanations.

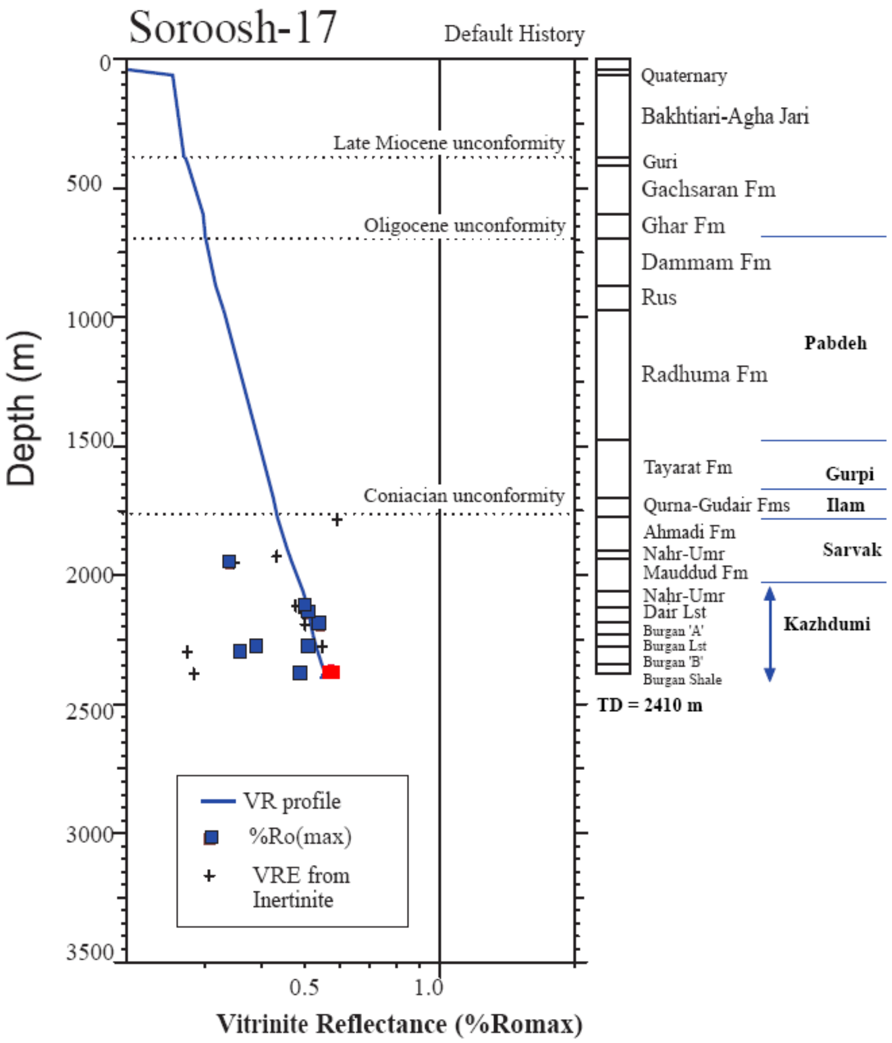

Figure 3: Measured and predicted vitrinite reflectance with respect to depth in the Soroosh-17, Northern Persian Gulf.

Evidence that samples have been hotter in the past in the Soroosh -17 well

About half of the measured VR and VRE values plot on, or close to, the profile predicted by the Default Thermal History in Fig. 3, with the remainder falling well below the profile. The remaining values that fall on the profile indicate that the sampled section, including the Burgan, is at, or close to, maximum paleotemperatures at the present-day. On the other hand, those values that plot well below the predicted profile are clearly inconsistent with the higher values at around the same depth and are interpreted as being either suppressed, or incorrectly measured. While caving contamination is possible in some samples, there are direct indications of VR suppression as discussed previously (e.g. presence of common liptinite macerals, oil droplets, possible bitumen impregnation), and this is the preferred interpretation. In this context, a VR level of 0.57 to 0.60% derived from the mode is regarded as representative of the level of maturation in sample GC873-55.1 compared with the mean level of 0.49%. On the other hand the mean measured VR levels of ~0.50 to 0.54% in the shallower Albian samples (GC873-27.1, -30.1, -40.1 and -49.1) are considered to be reasonable measures of the maturity level. VR levels derived from inertinite show a similar range to the associated true vitrinite, with the higher VRE values similar to the higher VR values, and similar comments apply.

Thus, there is no evidence from the measured VR and VRE values to suggest that the sampled units have been hotter in the past, and this interpretation is highly consistent with the interpretation of the AFTA carried out by Bashari (2008).

Evidence that samples have been hotter in the past in the Nowrooz-16 well

Two of the three measured VR values, all from the Kazhdumi sequence near TD, plot on or very near the predicted profile (Fig. 4), which at face value suggests that the section has not been heated above the present-day temperatures at any time since deposition. The third value is lower, and is clearly anomalously low when compared with the two adjacent higher values as reported by Duddy (2004). There appears to be a relationship between low VR and the abundance of telovitrinite in this sample, which was also noted for Soroosh-17. Oil cut was also noted from the telovitrinite, although there is no direct evidence that the presence of oil has lowered the reflectance of the telovitrinite. On the other hand, even the highest VR values are systematically lower than expected. These anomalously low measured VR values are therefore attributed to some form of geochemical suppression, of unknown cause, although the presence of hydrogen-rich organic matter, high liptinite abundance and pervasive oil impregnation are possible explanations.

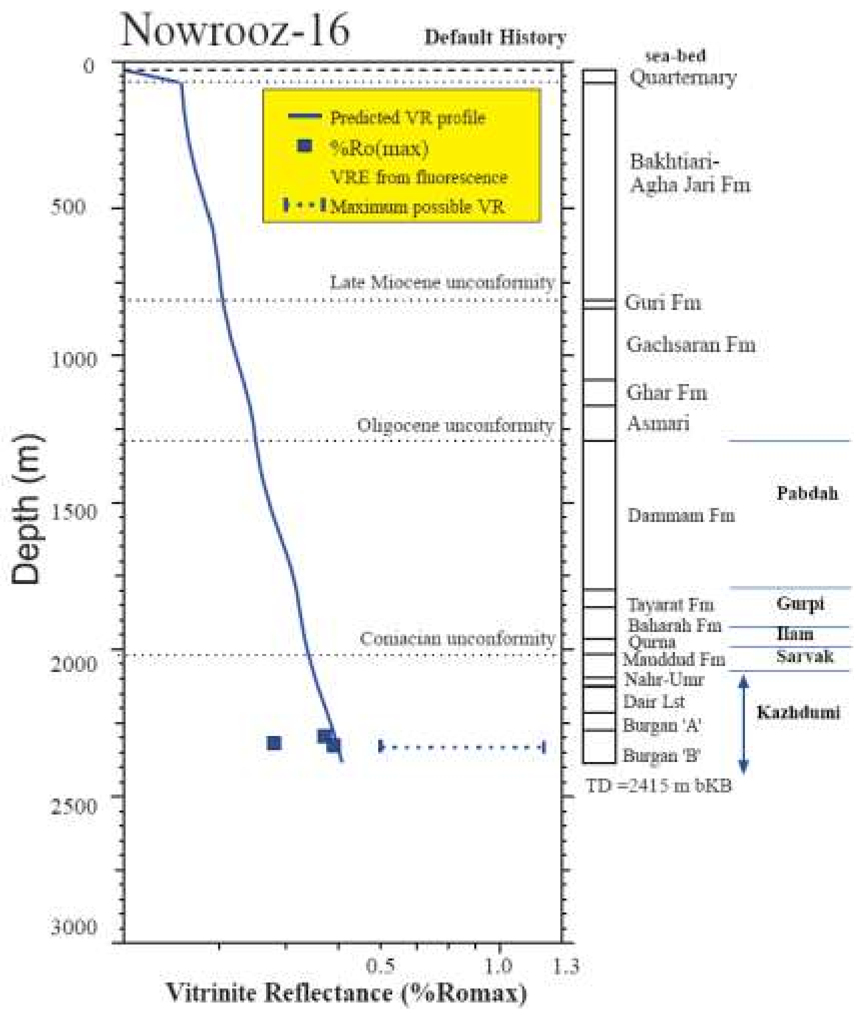

Figure 4: Vitrinite reflectance values from samples Noowrooz 16 well Persian Gulf, offshore Iran (summarized in Tables 2), plotted against depth (TVD rkb).

On the other hand, the fluorescence colours of the liptinite macerals in these samples would be consistent with somewhat higher VR levels than indicated by the measured vitrinite reflectance, with a possible equivalent VR range from 0.6 to 1.2% Ro (max) estimated for the Kazhdumi sequence. These VRE values plot above the predicted profile (Fig. 4), suggesting that this section has been hotter in the past, which is in better agreement with the AFTA results (Bashari, 2008).

Conclusions

The organic petrographic observations show that the Burgan (Kazhdumi) organic matter in Soroosh-17 and Nowrooz-16 is largely terrestrial in origin from a coal measures part of the section without much lamalginite. In contrast, the Fahlyian section (Lower Ratawi Formation) samples examined from Soroosh-02 are dominated by carbonate and contain abundant to major lamalginite. Much of the lamalginite is unusual in having a diffuse form and is associated with free oil inclusions. These observations are interpreted as indicating that the Fahlyian section (Lower Ratawi Formation) underlying the Soroosh reservoirs is currently within the zone of active oil generation.

The sections examined in Soroosh-17 and Nowrooz-16 appear to reach the top of the oil window in the Middle Albian Nahr Umr Formation. The underlying Burgan (Kazhdumi) shows a zone of vitrinite reflectance values that are lower than those within the Nahr Umr Formation. The vitrinite found is texturally immature. The association of low reflectances and textural immaturity could be due to early impregnation with oil, presumably from deeper within the section.

It is probable that the Lower Ratawi Formation is currently within the zone of active oil generation. In textural terms, the closest similarities to the Lower Ratawi Formation are with the organic matter that is present in the Monterey Formation from the west coast of the USA. The lamalginite differs from that found in lacustrine facies, and from that present in some prominent algal rich Mesozoic source rocks such as the Kimmeridge Clay of NW Europe.

Measured vitrinite reflectance data from all three wells sections indicate that the pattern of vitrinite reflectance distribution is complex. Reflectances that are assessed to be anomalously low are associated with both the Burgan B and with the Ratawi Formation. However, the causes of the lower reflectances are different for these two different units.

In the case of the Ratawi, the low vitrinite reflectance values are associated with abundant to major lamalginite. The association between low vitrinite reflectance values and abundant lamalginite is a well known process considered for vitrinite reflectance suppression.

The Burgan coaly unit also shows anomalously low reflectances. This tentatively is assigned to the presence of the oil charge in this unit which is an indication of early emplacement of the oil within this unit.

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APPENDIX 1. MACERAL CLASSIFICATION USED IN THIS STUDY

MACERAL GROUP	MACERAL SUBGROUP	MACERAL	SUB-MACERAL
VITRINITE	**TELOVITRINITE**	TEXTINITE	TEXTINITE A & B
		TEXTO-ULMINITE	TELINITE
		EU-ULMINITE	
		TELOCOLLINITE	COLLOTELINITE
	DETROVITRINITE	ATTRINITE	
		DENSINITE	
		DESMOCOLLINITE	
	GELOVITRINITE	CORPOGELINITE	
		PORIGELINITE	
		EUGELINITE	
INERTINITE	**TELO-INERTINITE**	FUSINITE	
		SEMIFUSINITE	
		FUNGINITE (Sclerotinite)	
	DETRO-INERTINITE	INERTODETRINITE	
		MICRINITE	
LIPTINITE		SPORINITE	
		CUTINITE	
		SUBERINITE	
		RESINITE	
		FLUORINITE	
		LIPTODETRINITE	
		ALGINITE	TELALGINITE
			LAMALGINITE
		BITUMINITE	
		EXSUDATINITE*	

NOTE: ICCP now uses the same divisions to the sub-group level (ICCP, 1995). At the maceral level, ICCP terminology is now moving to use a single system for low and moderate to high levels of maturation.

* Exsudatinite is a primary bitumen and should be included with other bitumens but at present is included by ICCP within the maceral system.