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Hydrocarbon Source Rock Potential of Eocene Forearc and Subduction Zone Strata, Southern Oregon Coast Range, U.S.A.

미국 오레곤 남부 에오세 전호상 및 섭입대 퇴적층의 탄화수소 근원암 가능성

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Abstract : The hydrocarbon source rock potential of the Eocene units in the southern Oregon Coast Range was evaluated by using the Rock-Eval pyrolysis. Most Eocene units in southern Oregon Coast Range are thermally immature and contain lean, gas-prone Type III kerogen. However, some beds (coals) are sufficiently organic-rich to be sources of biogenic and thermogenic methane discovered in numerous seeps. The overall hydrocarbon source rock potential of the southern Oregon Coast Range is moderately low. Several requirements for commercial accumulations of hydrocarbon, however, probably exist locally within and adjacent areas. Three speculative petroleum systems are identified. The first includes the southern part of the Oregon Coast Range near the border with the Mesozoic Klamath Mountains and is related to a proposed subduction zone maturation mechanism along thrust faults. The second is centered in the northern part of the range and may be associated with basin-centered gas in an over-pressured zone. The third occurs near the eastern border of the range where maturation is related heating by sills and migration of hydrothermal fluids associated with mid-Tertiary volcanism in the Western cascade arc.

Key words: Oregon Coast Range, Eocene, Rock-Eval, source rock, petroleum system

요 약 : 오레곤 연안 산맥 남부에 분포하는 에오세 퇴적층들에 대한 탄화수소 근원암 평가가 Rock-eval 열분석을 이용 수행되었다. 오레곤 연안 산맥 남부의 에오세 퇴적층 대부분은 가스성향의 Type III 케로겐들을 소량 포함하고 있으며, 열적으로도 미숙성 되었다. 그러나 탄층을 포함하여 일부 퇴적층은 인접 지역에서 발견되는 유기적 또는 열적으로 생성된 메탄 가스징들의 근원암이 될 수 있을 정도로 충분한 유기물들을 포함하고 있다. 오레곤 연안 산맥 남부의 에오세 퇴적층에 대한 탄화수소 근원암 평가는 전반적으로 낮게 평가된다. 그러나 오레곤 연안 산맥 남부 및 인접 지역에 상업적으로 생산될 수 있는 규모의 탄화수소 집적소들이 존재할 가능성이 있으며, 세 종류의 가능성 있는 석유 시스템이 인지된다. 가장 가능성이 높은 석유 시스템은 오레곤 연안 산맥 남부와 중생대 클라매쓰 산맥 북부의 인접 지역에 나타나며, 섭입대 성숙 메카니즘과 관련된 트러스트를 따라 발달하는 석유 시스템이다. 두 번째 가능성 있는 석유 시스템은 오레곤 연안 산맥 북부에 과압력대와 연관되어 발달될 수 있는 분지중심가스의 석유 시스템이며, 세 번째 석유 시스템은 오레곤 연안 산맥 서부에 나타나는 제3기 화산활동과 연계되어 생성된 열수용액들의 이동과 관입암체들에 의한 열적 숙성에 의한 석유 시스템이다.

주요어 : 오레곤 연안 산맥, 에오세, Rock-eval 열분석, 근원암, 석유 시스템

Introduction

The discovery of gas in 1979 at Mist field in the northwest Oregon has brought renewed interest in exploration of Eocene rocks throughout Oregon and Washington Coast Range (Newton, 1979; Fig. 1). Despite the increased interest, few studies of the hydrocarbon potential of the region have been conducted, but they have been primarily limited to the Washington Coast Range (Armentrout and Suak, 1985). The most recent evaluation of hydrocarbon potential of the Eocene strata, Oregon Coast Range was compiled by Niem and Niem (1990). This compilation pointed out the need for a more comprehensive study of the hydrocarbon source rock potential and a better understanding of the stratigraphic framework of the Eocene forearc and subduction zone strata, southern Oregon Coast Range.

This study attempts to characterize the hydrocarbon source rock potential of Eocene strata, southern Oregon Coast Range (Fig. 1). Three critical factors that include generative potential (quantity), potential type of hydrocarbons (oil and gas), and thermal maturity are extensively evaluated by using the Rock-Eval pyrolysis. This study will greatly contribute to a fundamental understanding of the hydrocarbon source rock potential of the southern Oregon Coast Range, providing basic information on spatial and temporal distribution of hydrocarbon source beds.

Regional Setting

The Oregon Coast Range is bounded on the south by the northern margin of the Mesozoic Klamath Mountains and is overlapped on the east by upper Eocene and Miocene calc-alkaline arc volcanics of the western Cascade Range (Fig. 2). An aggregate thickness of more than 7000 m of lower to

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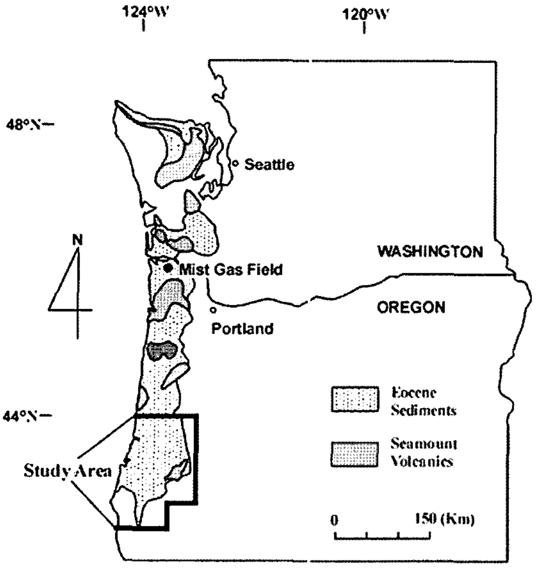

Fig. 1. General geologic map of the Oregon and Washington Coast Ranges. Study area includes the southern half of the Oregon Coast Range that comprises the Eocene forearc and subduction zone strata as well as seamount volcanics.

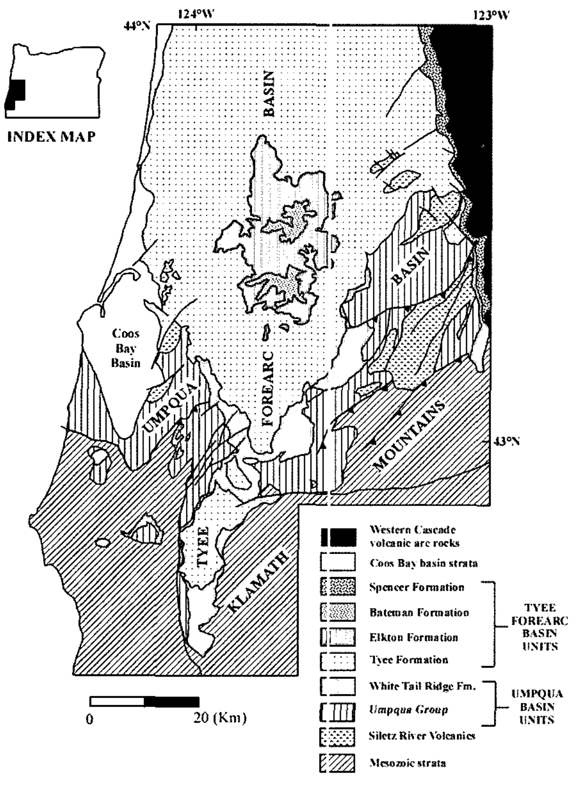

Fig. 2. General geology and tectonic features of the southern Oregon Coast Range. Note the NE-SW structural trend of the early Eocene Umpqua basin strata (Bushnell Rock and Tenmile formations; lower Umpqua Group) in fault contact with Paleocene to lower Eocene Siletz River Volcanics basement and Mesozoic terranes of the Klamath Mountains. Middle Eocene strata of the Tyee forearc basin (Tyee, Elkton, Bateman, and Spencer formations) and upper Eocene to middle Miocene strata of the Coos Bay basin display an N-S trend that is discordant with the early Eocene trend.

upper Eocene strata is preserved in the southern Oregon Coast Range. Two superimposed basins with different trends and geologic and tectonic histories are shown in the southern Oregon Coast Range: the NE-SW-trending early Eocene Umpqua basin and the N-S-trending late-early to late Eocene Tyee forearc basin (Fig. 2).

The older NE-SW-trending Umpqua basin strata represent a partially subducted accretionary wedge deposited in a trench or a rifted continental margin (Heller and Ryberg, 1983; Wells *et al.*, 1984). These strata overlie and, in part, interfinger with the Paleocene to lower Eocene Siletz River Volcanics, representing oceanic basaltic crust formed of seamounts and oceanic islands (Figs. 2, 3). When the seamount terrane was subducted beneath the North American margin, syn-tectonic fan-delta and shallow marine lithic sand and gravel were deposited along the southern margin of the basin as the Bushnell Rock Formation and the Slater Creek Member (Figs. 2, 3). The overlying Tenmile Formation represents a transgressive deposit that consists of lithic turbidite sand and slope muds (Figs. 2, 3). These fan-delta and turbiditic sediments were accreted to the Mesozoic Klamath Mountains terranes along a series of northward-verging, imbricate thrust faults (Figs. 2, 3). During the early Eocene, subduction ceased along the early Eocene trench, possibly because the thick buoyant oceanic seamount terrane clogged the subduction zone. The entry of seamounts into the subduction zone resulted in local uplift followed by subsidence. As a consequence, fluvial to deltaic lithic sand and gravel of the White Tail Ridge Formation filled irregular lows. These strata thin over submarine highs

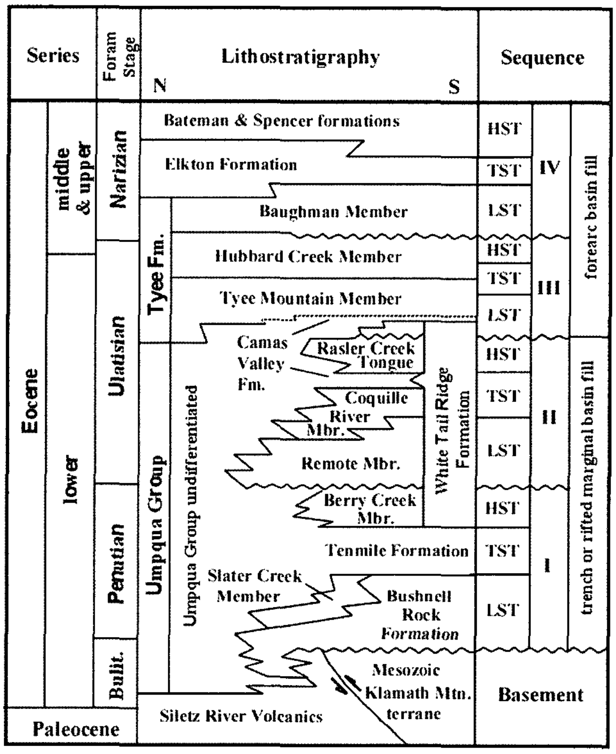

Fig. 3. Lithostratgraphy and sequence stratigraphy of the southern Oregon Coast Range.

created by intrabasin, imbricate thrust faults and are overlain by shelf to slope mudstone of the Camas Valley Formation (Fig. 3). The White Tail Ridge Formation is further subdivided into the Berry Creek, Remote, and Coquille River members and the Rasler Creek Tongue (Fig. 3). To the north, the laterally equivalent lithofacies of these formations is informally referred to as undifferentiated Umpqua Group, which is a thick sequence of lithic turbidite sand and deep-marine muds (Fig. 3). Paleomagnetic studies suggest that this convergent continental margin was also rotated clockwise as much as 50° by the late-early Eocene (Wells and Heller, 1988).

During clockwise rotation, a new subduction zone formed to the west beneath the present outer continental shelf and slope of Oregon, and a magmatic arc (i.e., Clarno Volcanics) developed in central Oregon. Subsidence of the area between the active western subduction zone and the magmatic arc created a forearc basin. Sand-rich, micaceous arkosic to volcano-lithic sediments derived from the granitic Idaho Batholith and Clarno volcanic arc were deposited in the Tyee forearc basin (Heller and Ryberg, 1983). These sediments form the upper-lower Eocene Tyee Formation (Fig. 2), which is composed of the Tyee Mountain, Hubbard Creek, and Baughman members (Fig. 3). Overlying the Baughman Member are slope muds of the Elkton Formation, which in turn are overlain by wave- to tide-dominated deltaic units of the Bateman and Spencer formations (Figs. 2, 3).

With the mafic forearc volcanism during late Eocene to middle Miocene, several transgressions and regressions occurred within the Tyee forearc basin (Niem *et al.*, 1992). These events are preserved in the thick upper Eocene to middle Miocene Coos Bay basin strata and the Western Cascade cal-calkaline volcanic arc rocks of the southern Oregon Coast Range (Fig. 2). Since the middle Miocene, the Coast Range block may have experienced additional clockwise rotation (up to 22°) due to back-arc spreading and extension of the Basin and Range Province (Wells and Coe, 1985; Wells and Heller, 1988).

Recent sequence stratigraphic application to the southern Oregon Coast Range indicates that the lower to middle Eocene strata can be divided into four third-order depositional sequences I to IV (Fig. 3; Ryu *et al.*, 1996). Each depositional sequence represents the consequence of the interplay between relative sea-level changes and tectonics (Ryu *et al.*, 1996). The oldest depositional sequence I includes the lower Umpqua Group (slope fan and basin-floor fan), the Bushnell Rock Formation and the Slater Creek Member (a prograding deltaic wedge and incised-valley fill), the Tenmile Formation (a back-stepping slope fan overlain by a shelf to slope mudstone), and the Berry Creek Member of the White Tail Ridge Formation (a prograding delta of the highstand systems tract). Depositional sequence II consists of the upper Umpqua Group (slope fan and basin-floor fan), the Remote Member (a prograding deltaic wedge and incised-valley fill), the Coquille River Member (a back-stepping tide-dominated deltaic wedge), the Camas Valley Formation (a shelf to slope mudstone), and the Rasler Creek Tongue (a prograding wave-dominated delta of the highstand systems tract). Depositional sequence III encompasses the Tyee Mountain Member (slope fan and basin-floor fan) and the Hubbard Creek Member (a shelf to slope mudstone of the transgressive systems tract and prograding nested channel sandstone of the highstand systems tract). The overlying depositional sequence IV contains the Baughman Member (a prograding deltaic wedge and incised-valley fill), the Elkton Formation (a shelf to slope mudstone), and the Bateman and Spencer formations (a prograding wave-dominated delta of the highstand systems tract).

Samples and Methods

More than 240 samples were collected and submitted for source rock analysis during the course of this study. They include all Eocene units in the southern Oregon Coast Range and several pre-Tertiary units in the adjacent Klamath Mountains. Most samples are fresh dark to medium gray mudstone, coal, and carbonaceous mudstone; one is from a block of micritic limestone in the pre-Tertiary (Cretaceous) mélange of the Klmath Mountains. In addition, source rock data for more than 1625 outcrop and well samples from earlier reports (e.g., Amoco (1983, 1985), Browning and Flanagan (1980), Brown and Ruth Laboratories, Inc. (1983), Law *et al.* (1984), Mobil Oil Corporation (1980), and Newton (1980)) are also incorporated in this study.

All submitted samples were analyzed by using the Rock-Eval II instrument at U. S. Geological Survey organic geochemistry laboratory in Denver, Colorado. The powered rock sample (about 100 mg) is first analyzed at 250°C for 5 minutes that thermally distills organic compounds from C_1 to about C_{32}. The released hydrocarbons are measured by a flame ionization detector (FID) and the amount is reported as S_1 (mg HC/g rock). Then programmed pyrolysis from 250°C to 600°C at 25°C/minute cracks the kerogen and heavy bitumen yielding organic compounds, water and carbon dioxide as well as other gases. Half the flow of gas goes to the FID to measure the generated hydrocarbons as S_2 (mg HC/g rock) and half goes to a carbon dioxide trap. The gases flow into a carbon dioxide trap from 250°C to 390°C. From 390°C to 600°C the evolved carbon dioxide is not collected. After completion of the programmed pyrolysis the carbon dioxide trap is heated and the released gas measured by a thermal conductivity detector (TCD) is reported as S_3 (mg HC/g rock). This amount of CO_2 is a function of the oxygen content of the organic matter. Next the crucible is moved to another furnace where it is heated to about 590°C in air (oxidizing atmosphere). The carbon dioxide (and carbon monoxide catalyzed using CuO to carbon dioxide) evolved is measured as S_4 by the TCD. S_4 is the residual (inert) organic carbon and is also add to S_1 and S_2 to calculate the Total Organic Carbon (TOC). T_{max} (°C) is the temperature where the maximum amount of S_2 hydrocarbons is generated. T_{max} is a function of kerogen type and thermal maturity.

Measured pyrolysis values are usually not interpreted directly but in conjunction with other parameters. For example, S_1

and S_2 are typically interpreted in relation to the Total Organic Carbon value. Hydrogen Index (HI) is the ratio of S_2/TOC (mg HC/g C) which is correlative with the H/C ratio of the kerogen: HI = 694 (H/C − 0.29) − 800 (O/C), (Orr, 1983). Values typically range from 0 to 900. Oxygen Index (OI) is the ratio S_3/TOC that is correlative with the O/C ratio of the kerogen. Values typically range from 0 to 300. Thus, HI and OI are indicators of kerogen type analogues to the van Krevelen diagram (H/C vs. O/C) and whether the source rock is oil or gas prone (Peters, 1986).

Vitrinite reflectance was determined on splits of selected rock samples from the sample set. First the dispersed organic matter was separated from the sample by centrifuging the mixture of rock powder and zinc bromide solution (Barker and Pawlewicz, 1986). After decanting off the organic matter into another centrifuge tube, it was rinsed and centrifuged three times and then dried. The dried organic matter was set in resin on a standard petrographic slide, and after drying; the slide was trimmed with a thin section saw and polished on a lap wheel. Reflectance readings were taken under oil immersion using 546 nm light and a 3 micron sensing spot. Ideally 50 readings are taken on terrigeneous organic material (Type III kerogen) with the lowest reflectance but the actual numbers of readings taken depend upon the abundance of terrigenous organic matter in the sample.

Source Rock Evaluation

Source Rock Generative Potential

Most of the 1869 surface and subsurface samples contain low to very low total organic carbon (Fig. 4A). The average TOC value is approximately 0.85 weight percent. The overall distribution of TOC is skewed towards lower values (less than 0.5 weight percent) with approximately 95 percent of all samples falling into the poor to fair (non-source to marginal) source rock category (i.e., less than 1.0 weight percent TOC). Only 59 samples (less than four percent of samples analyzed) have TOC values greater than 1.0 weight percent, which rate these as good to very good source rocks (Fig. 4A). Most of these samples are carbonaceous mudstones and silty coals from LST of depositional sequence II and IV (White Tail Ridge Formation, Baughman Member, Bateman Formation, and Spencer Formation; 21 samples), some slope mudstones from the transgressive deep marine sequences of Sequences II, III, and IV (Camas Valley Formation, Hubbard Creek Member, and Elkton Formation; 13 samples), and a few deep basinal mudstone from turbidite sequence of Sequence I (the Umpqua Group; 13 samples) (Fig. 5). Some pre-Tertiary Klamath Mountain terrane samples also have greater than 1.0 weight percent TOC (carbonaceous shale in Cretaceous Whitsett Limestone; 1 sample: undifferentiated Myrtle Group mudstone; 5 samples) (Fig. 5).

The S_1 and S_2 yields liberated during pyrolysis are a useful measurement to evaluate the generative potential of source rocks (Peters, 1986; Law *et al.*, 1984). Approximately 95 percent of the samples analyzed have less than 1.0 mg HC/g rock (Fig. 4B). Pyrolysis $S_1 + S_2$ yields less than 6.0 mg HC/g rock are generally considered to be source rocks with poor to fair generative potential; yields greater than 6.0 are common in known hydrocarbon source rocks (Peters, 1986). Thus, Rock-Eval pyrolysis $S_1 + S_2$ yields also indicate that most samples analyzed are poor in generative potential, including some basinal and slope mudstone units that rated as good and very good source rock based on TOC (i.e., 2 to 3%; compare Fig. 5 and Fig. 6). Although high in total organic carbon, much of this carbon is inert and does not yield much free hydrocarbon upon pyrolysis (or heating). Therefore, those samples are rated as poor source rocks. The samples that have the best potential as source rocks, as indicated by $S_1 + S_2$ values > 6.0 (shaded area of Fig. 6), are all coals.

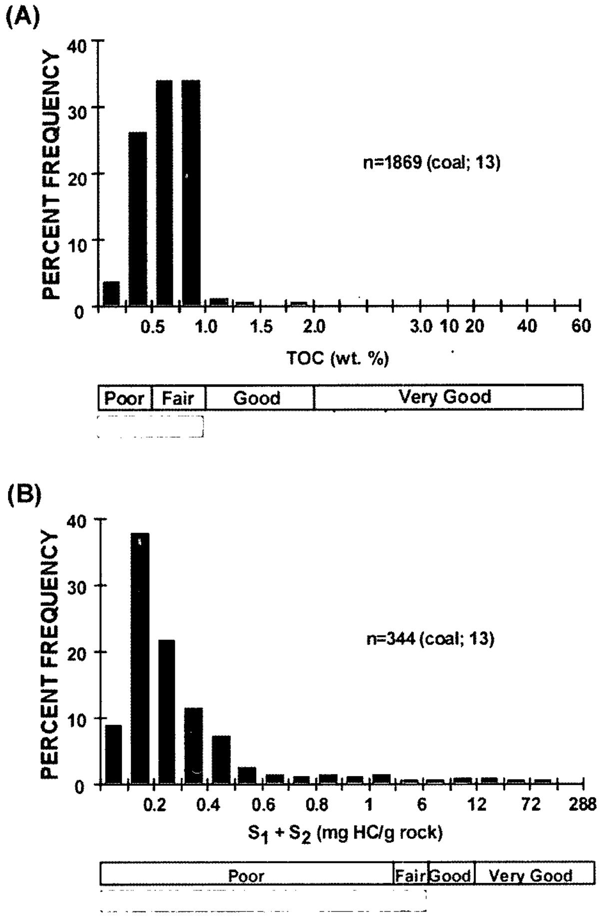

Fig. 4. (A) Summary of distribution of Total Organic Carbon (TOC) for all southern Oregon Coast Range samples. (B) Pyrolysis $S_1 + S_2$ yields. Approximately 95 percent of samples fall in the poor to fair categories (Peters, 1986). Stippled area represents 95% distribution of samples.

Type of Hydrocarbon Generated

A binary plot of whole rock hydrogen indices (S_2/TOC) and oxygen indices (S_3/TOC) can be used to classify the dominant type of organic matter (i.e., gas- or oil-prone) in potential source rocks (Tissot and Welte, 1978; Fig. 7). Most

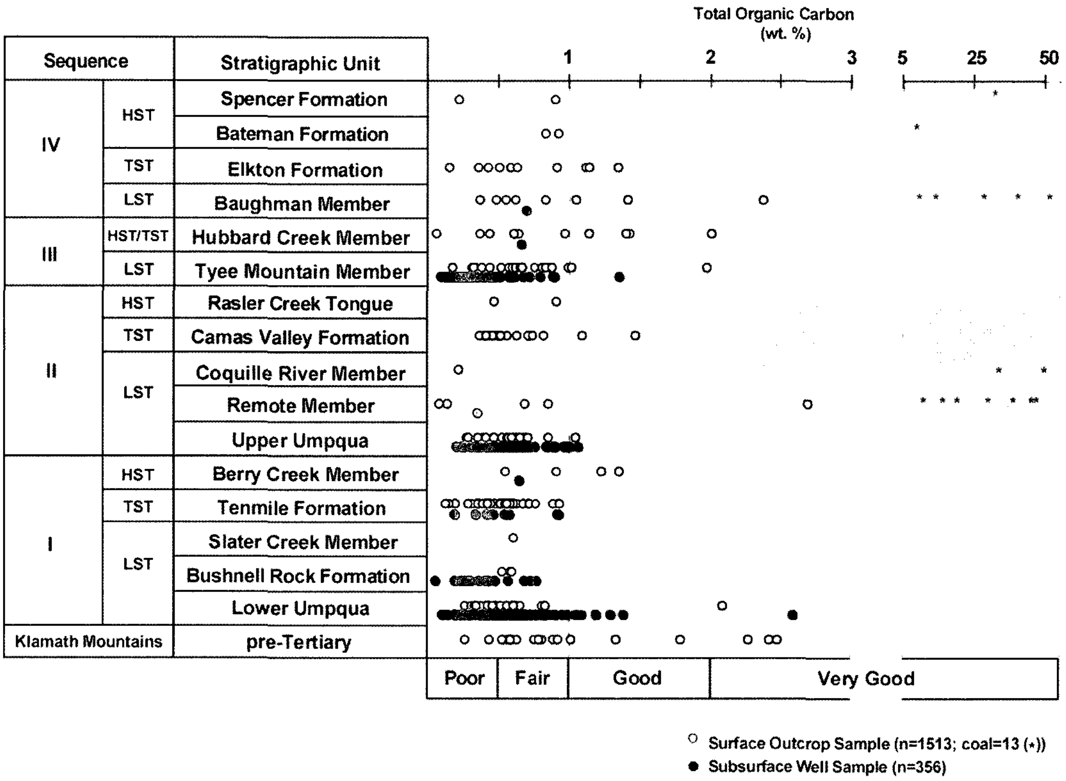

Fig. 5. TOC values as a function of stratigraphic unit. Coals and carbonaceous mudstones (*) of deltaic sequences commonly rate as good to very good potential source rock in the southern Oregon Coast Range. Some deep basinal mudstone sequences of the Umpqua Group include good to very good potential source rock. Pre-Tertiary organic-rich source rocks (>1% TOC) are from the Cretaceous Whitsett Limestone and Cretaceous/Jurassic Myrtle Group.

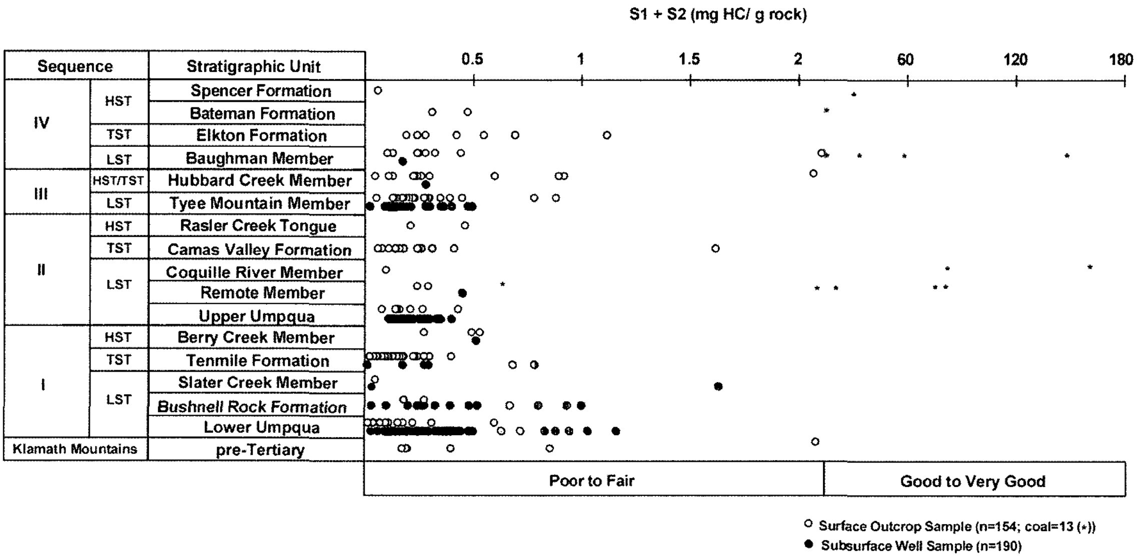

Fig. 6. Pyrolysis $S_1 + S_2$ yields as a function of stratigraphic unit. Coals and carbonaceous mudstones (*) in the deltaic members of Sequences II and IV rate as good to very good potential source rocks (stippled area) in the southern Oregon Coast Range.

of 320 surface and subsurface samples plot in the field of very low hydrogen indices and low oxygen indices. This suggests that the organic matter in nearly all samples is Type IV (very limited or marginal potential for gas) or Type III (gas-prone) organic matter. Fifteen samples, however, plot in the field between Type II (oil-prone) and Type III (gas-prone) organic matter.

Rock-Eval pyrolysis studies indicate, however, that high

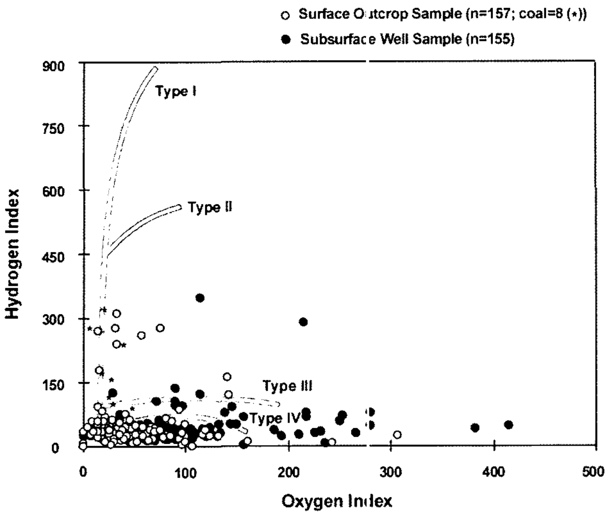

Fig. 7. Van Krevelan diagram (Hydrogen Index (HI) versus Oxygen Index (OI)), showing the hydrocarbon-generative type. Most samples plot in the Type III (gas-prone) and Type IV (very limited or marginal potential for gas) fields, but a few samples plot in the field between Type II (oil-prone) and Type III (gas-prone).

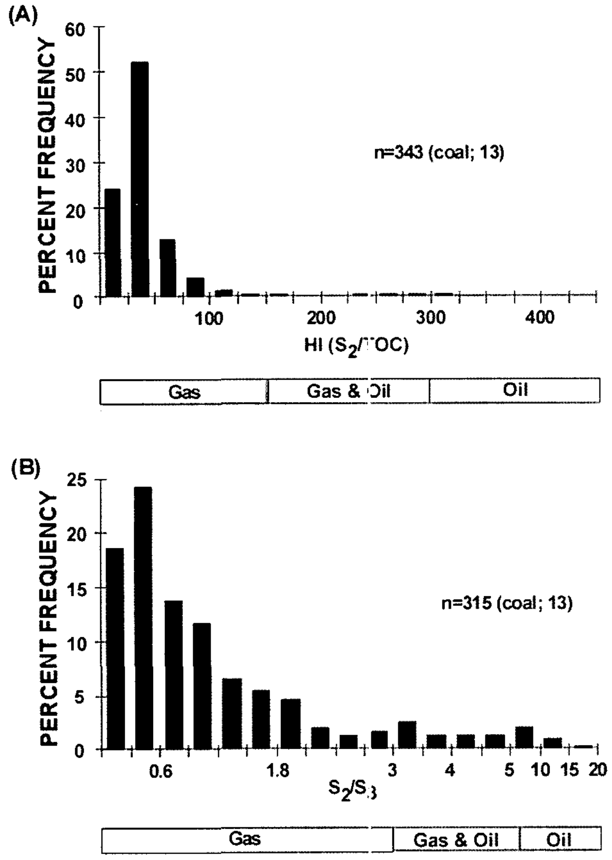

Fig. 8. (A) Overall distributions of hydrogen index and (B) pyrolysis S_2/S_3 yields. Most samples are gas-prone, but a few samples are oil- and gas-prone (Peters, 1986). Stippled area represents 95% distribution of samples.

oxygen index with low hydrogen index and low TOC (<0.5%) in argillaceous or mud-rich samples is directly influenced by a variety of variables such as CO_2 released from carbonate minerals in the matrix or absorption of oxygen by clay minerals (Peters, 1986). In addition, outcrop samples are likely to show higher S_3 and lower S_1 and S_2 values due to oxidation, during weathering, resulting in high values for oxygen index (Durand and Monin, 1980). In order to avoid the possible inaccuracy of oxygen index values, the type of organic matter is now generally classified on hydrogen index only. The distribution of hydrogen index values for all samples is shown in Fig. 8A. Approximately 75 percent of the samples analyzed have a hydrogen index less than 50. A hydrogen index of 50 is typical of organic matter with very limited to marginal potential to generate dry gas (methane). This fraction falls in or close to the field of Type IV organic matter, which is residual organic matter (i.e., inertinite) recycled from older strata (Tissot *et al.*, 1974). The remaining 20 percent of samples plots between hydrogen index values of 50 and 150, indicating the potential for dry gas only (Type III, Tissot *et al.*, 1974). Only five percent of the samples have a hydrogen index greater than 150, typical of organic matter with the potential to generate oil or wet gas (Type II or Type III organic matter, Tissot *et al.*, 1974).

Stratigraphic distribution of hydrogen index values shows that oil- and wet gas-prone organic matter occurs mostly in coal-bearing deltaic sequences (Sequences II and IV) and in a few thin mudstones of the Bushnell Rock Formation, Slater Creek Member, Tyee Mountain Member, and Hubbard Creek Member (Fig. 9). The Cretaceous Whitsett limestone is also considered a source rock capable of generating oil and wet gas. Unfortunately, the potential of this unit as a source rock is limited because it is present only as isolated blocks in Mesozoic mélange (Dothan Formation of Ramp, 1972). Most other samples (lower Umpqua, Bushnell Rock, Tenmile, Camas Valley, Tyee Mountain, Hubbard Creek, Elkton, Bateman, and Spencer) are only gas-prone. Thus, potential source rocks in the southern Oregon Coast Range have only limited ability to produce natural dry gas. A similar conclusion was reached by Law *et al.* (1984).

Other source rock analyses to determine the types of hydrocarbons which could be generated are visual kerogen typing and C_{15}^{+} extract with gas chromatography (Figs. 10, 11). These analyses were conducted by oil companies and by geochemistry consultants on fewer samples and mostly on lower Umpqua Group and Tyee Mountain Member samples from exploration wells in southern Oregon Coast Range (Well data are tight-hole). Microscopic inspection indicates that most kerogen in marine and non-marine mudstone samples is terrestrial herbaceous pollen and structured woody material (Brown and Ruth Laboratories Inc., 1983; Long, 1994; Fig. 10). This type of kerogen is mainly vitrinite which tends to be gas-prone (Tissot and Welte, 1978). Some deep-marine mudstone in the lower Umpqua Group has higher concentrations of oil-prone alginite and exinite. Some lower Umpqua samples have high concentrations of inertinite,

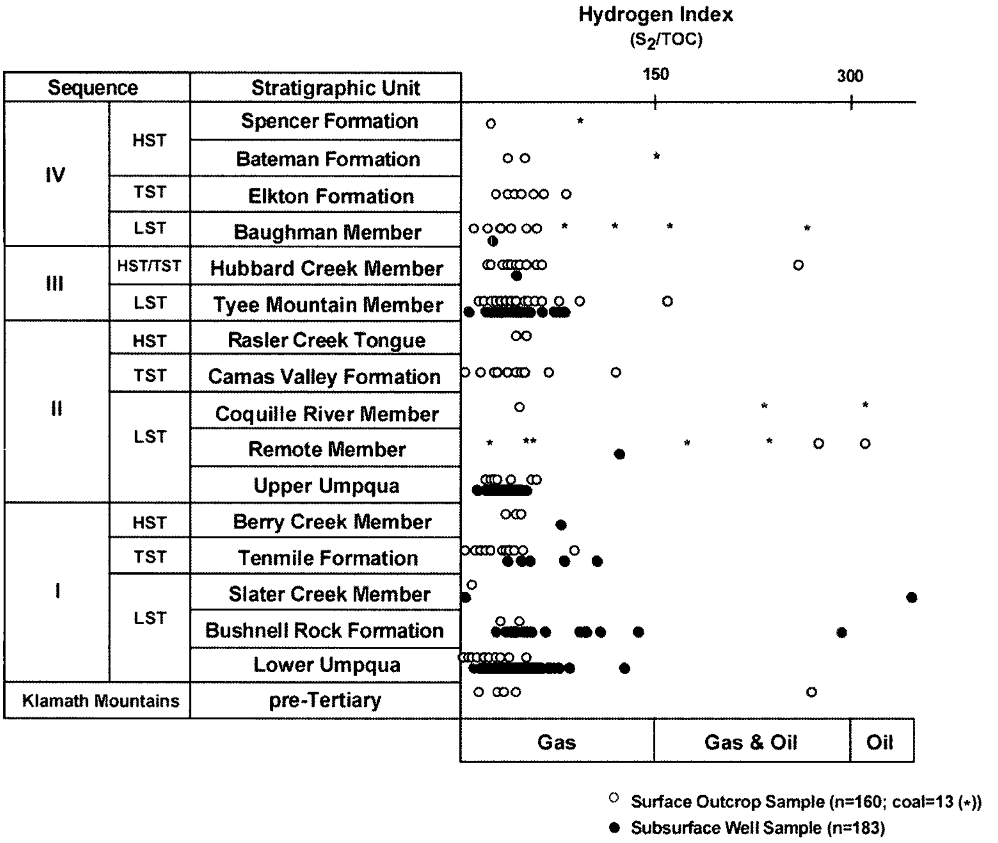

Fig. 9. Hydrogen Index values as a function of stratigraphic unit. Most samples are gas-prone, but a few samples plot in the gas and oil prone area (Peters, 1986). Gas and oil prone source rocks of Sequence III (Tyee Mountain and Hubbard Creek members) are deep-marine mudstones in the northern part of the study area. Also two subsurface samples from the exploration wells (Well data are tight hole) indicate that some mudstones in the Bushnell Rock Formation and Slater Creek Member are oil prone. Also a carbonaceous mudstone interbed in the Cretaceous Whitsett Limestone is gas and oil prone. Note coals and carbonaceous mudstones (*) of deltaic members of Sequences II and IV are generally gas and/or oil prone.

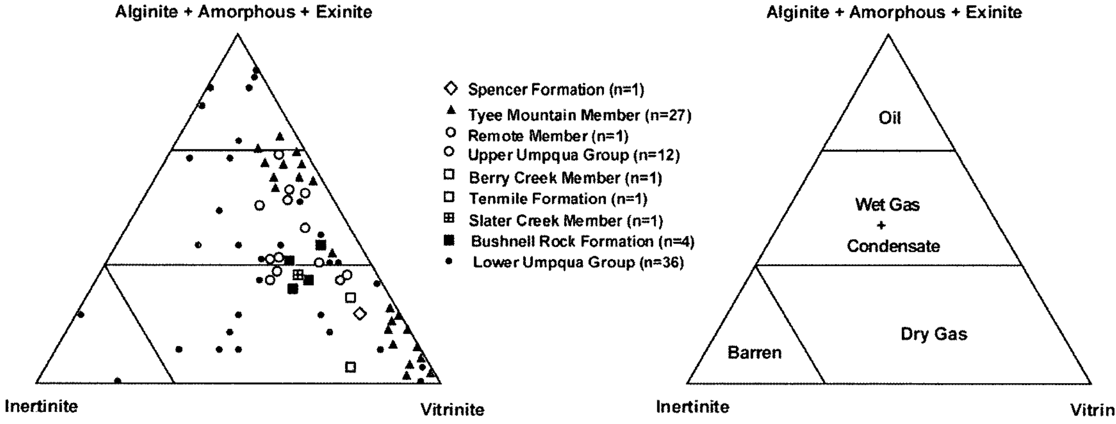

Fig. 10. Visual kerogen analyses from 84 southern Oregon Coast Range samples. Most samples are from exploration wells (Well data are tight-hole). Comparison of these data with the reference diagram (Tissot and Welte, 1978) indicates that most organic matter in Eocene strata is dry and wet gas-prone. However, a few samples of lower Umpqua Group are oil prone.

suggesting recycling of organic matter.

Level of Thermal Maturity

Most·analyzed samples (95%) show vitrinite reflectance values less than 0.8% R_o (Fig. 12A). They generally cluster around 0.5 to 0.7% R_o, merely marginal levels of oil and wet gas generation and significantly below the generation level of dry gas at 1.0% R_o for Type III organic matter (Fig. 12A).

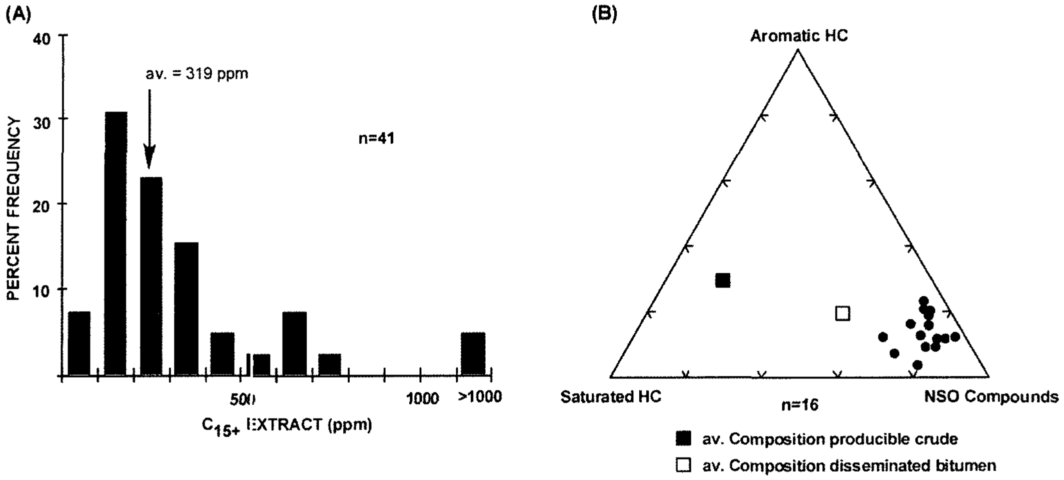

Fig. 11. (A) C_{15}^+ extract levels of subsurface samples from five exploration wells (Well data are tight-hole) and (B) General composition of C_{15}^+ bitumen extracts. All analyzed samples (mainly from the Tyee Mountain Member and the lower Umpqua Group) contain low amounts of extractable C_{15}^+ bitumen. Two samples (the lower Umpqua Group and the Tyee Mountain Member) contain high amounts (>1,100 ppm) of extractable C_{15}^+ bitumen. Note the bitumens are low in aromatic and saturated hydrocarbons comparing to the average values of gross composition of crude oils or "typical" source rock bitumens compiled by the French Petroleum Institute (Tissot and Welte, 1978).

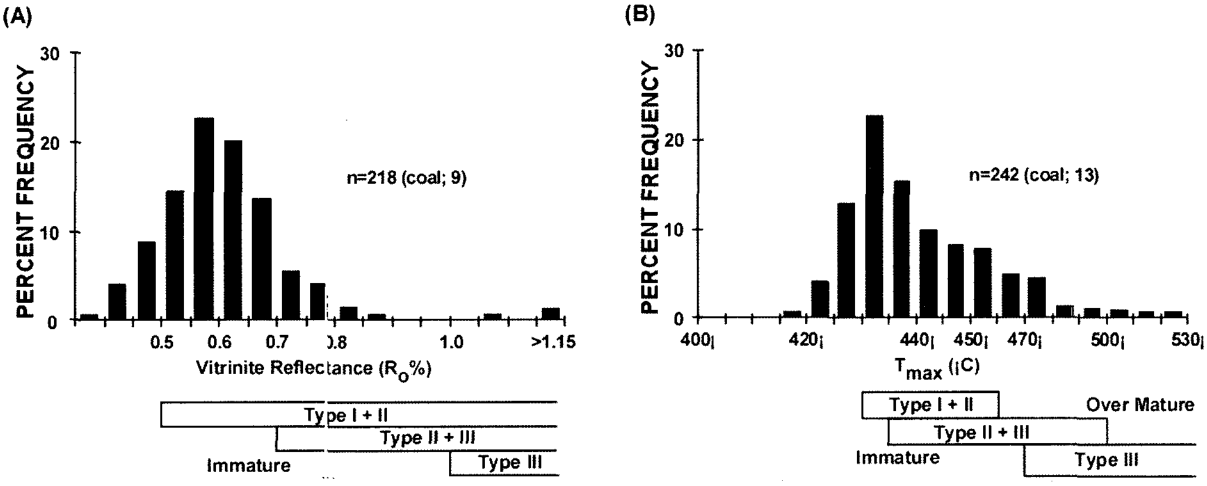

Fig. 12. Overall distribution of Vitrinite Reflectance (A) and T_{max} (B) for southern Oregon Coast Range samples. Stippled area represents 95% distribution of samples. Maturation scale from Espitalie (1985).

The top of the maturation window varies with the type of organic matter from 0.5 to 1.0% R_o; the bottom of the window varies from 1.4 to 3.5% R_o (Tissot and Welte, 1978; Espitalié, 1985). Thermogenic (metagenic) dry gas is thought to be generated at vitrinite reflectance values above 1.0% R_o for woody or terrestrial Type III kerogen. The distribution of vitrinite reflectance (% R_o) data suggests that most Eocene units and some pre-Tertiary units are not sufficiently mature to generate thermogenic (metagenic) gas and are marginally mature for oil and wet gas (condensate). However, vitrinite reflectance values for some samples are greater than 0.7, which indicates that Type II and Type III kerogens are sufficiently thermally mature to produce wet gas and oil (Figs. 12A, 13).

Generally, vitrinite reflectance values increase with depth due to increase in geothermal gradient and increasing absolute age of the rock with depth (e.g., Fig. 13). The White Tail Ridge and post-White Tail Ridge strata (Sequences II, III, and IV) are largely immature, whereas pre-White Tail Ridge strata (Sequence I) are marginally mature to immature for Type II and Type III kerogen (Fig. 13). Deeper burial, attributable to underthrusting, may also have resulted in maturing some of these subduction zone strata (i.e., Sequence I). Other exceptions to the generalization that Eocene units are immature and submature, however, do occur (Fig. 13). For example, two mudstone samples of lower and upper Umpqua Group have

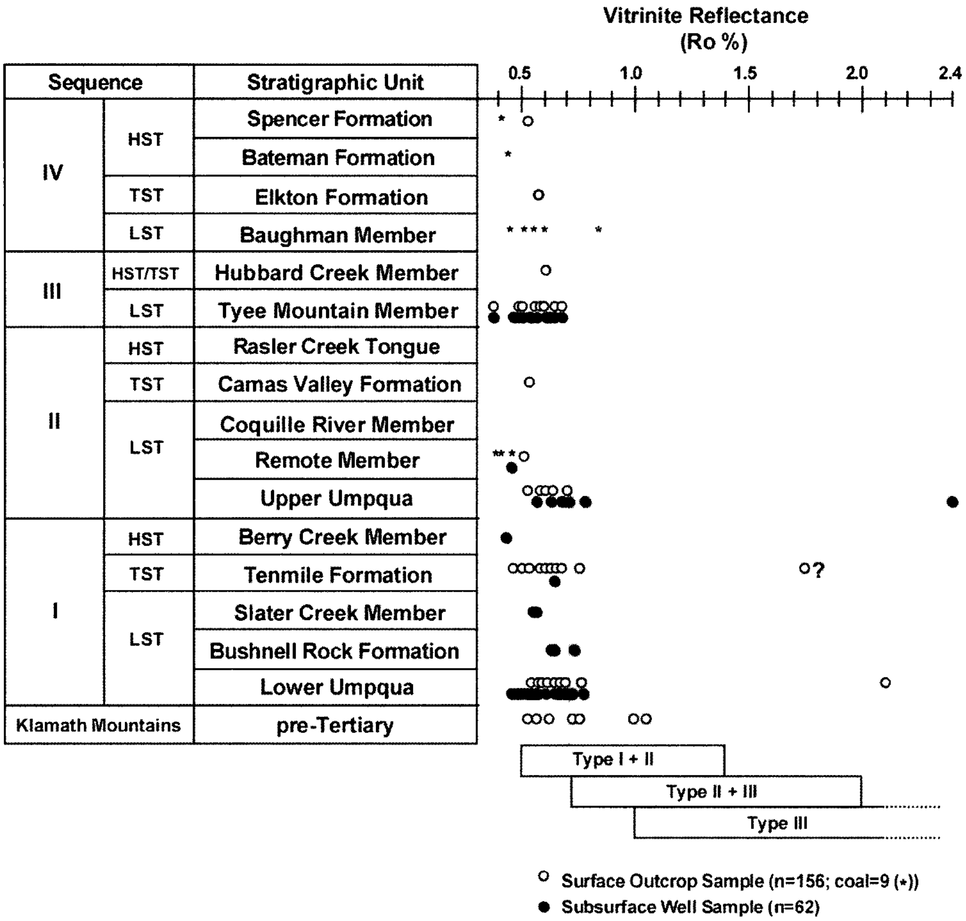

Fig. 13. Vitrinite reflectance values as a function of stratigraphic unit and increasing depth. Note the vitrinite reflectance value increases with depth. High vitrinite reflectance values (2.1 and 2.4 %Ro) of lower and upper Umpqua Group are due to basaltic intrusions. Data point for 1.75 %Ro in the Tenmile Formation is from Law *et al.* (1984), but exact location is not available and stratigraphic unit is questionable. Stippled area represents maturation level for Type II and Type III organic matter.

very high vitrinite reflectance values of 2.4 and 2.1 (Fig. 13). These two samples are mudstones baked by basaltic sills (1) in subsurface and (2) in an exposure near Dickinson Mountain.

Thermal maturity of organic matter in the analyzed samples is also evaluated based on the T_{max} of the S_2 peak (Fig. 12B). The maturation range of T_{max} varies for different types of organic matter (Tissot and Welte, 1984). The range of variation of T_{max} is narrow for Type I kerogen, wider for Type II, and much wider Type III kerogen due to the increasing structural complexity of the organic matter (Tissot *et al.*, 1987). The maturation level of Type I and II organic matter ranges from 430°C to 470°C; this range also represents "the oil window" (Tissot *et al.*, 1987; Peters, 1986). The onset of maturity for Type III terrestrial organic matter is 465°C to 470°C; T_{max} greater than 470°C represents the dry gas-zone (Tissot *et al.*, 1987; Peters, 1986). Most samples (95%) in Rock-Eval pyrolysis yielded T_{max} values less than 470°C (Fig. 12B). They generally group from 425°C to 445°C, significantly below the maturation window of dry gas-prone terrestrial Type III organic matter (Fig. 12B). Therefore, almost all units are thermally immature to generate dry gas from Type III organic matter. However, locally in some deep wells and in outcrop (Fig. 14) Umpqua Group units are marginally mature for Type II and Type III organic matter, whereas the same units farther north and overlain by thicker sections of sedimentary rock are thermally immature. These data suggest that areas in the southern part of the basin were once more deeply buried but have been subsequently uplifted and stripped of overlying sedimentary rock (e.g., Coos Bay upper Eocene to middle Miocene (?) strata).

T_{max} values generally increase as a result of increasing burial depth (i.e., older, more deeply buried rocks have higher T_{max} values) (Fig. 14). In general, the trend of increasing T_{max} is similar to the vitrinite reflectance. That is, the older White Tail Ridge and pre-White Tail Ridge strata are marginally mature to mature, and all of the younger post-White Tail Ridge strata are dominantly immature to marginally mature with respect to Type II and Type III kerogen (Fig. 14).

Although thermal maturity (i.e., R_o and T_{max}) usually increases linearly with depth and with higher burial temperatures, anomalous variations can result from unconformities, faults, erosion of overlying units, and other local factors (e.g., flash

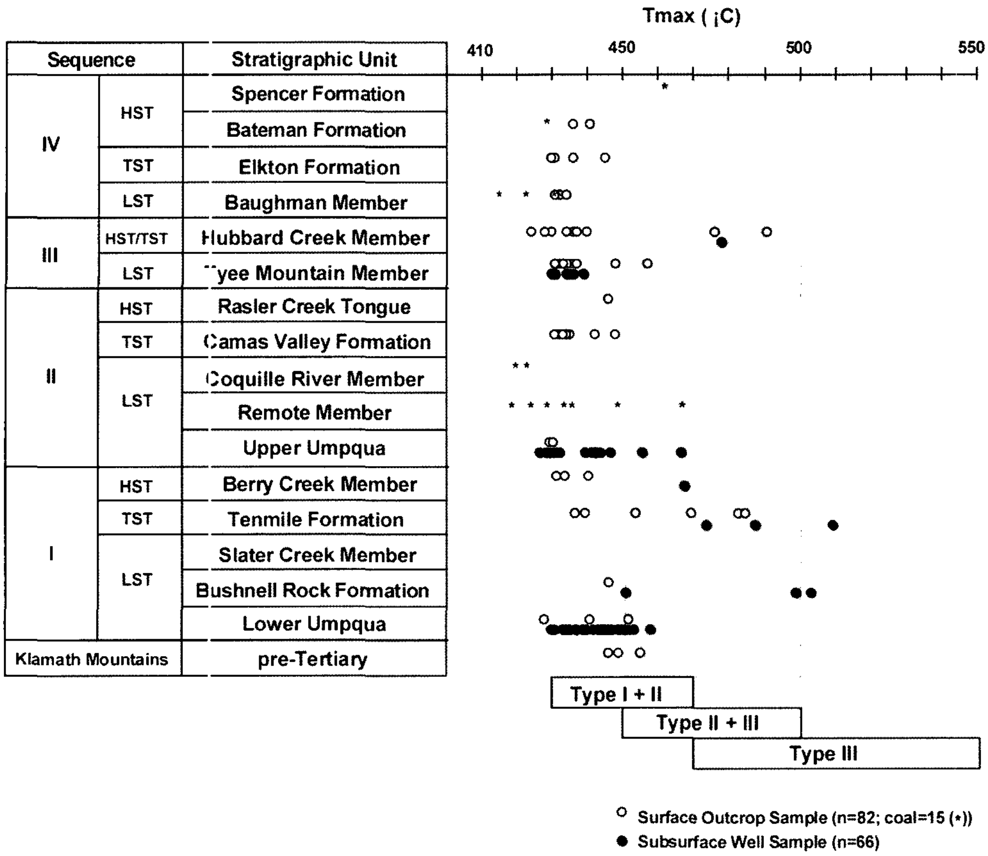

Fig. 13. Vitrinite reflectance values as a function of stratigraphic unit and increasing depth. Note the vitrinite reflectance value increases with depth. High vitrinite reflectance values (2.1 and 2.4 %Ro) of lower and upper Umpqua Group are due to basaltic intrusions. Data point for 1.75 %Ro in the Tenmile Formation is from Law *et al.* (1984), but exact location is not available and stratigraphic unit is questionable. Stippled area represents maturation level for Type II and Type III organic matter.

heating by intrusion of basalt sills) and from changes in the relative abundance and type of organic matter (e.g., recycled) (Peters, 1986).

Natural Gases in the Southern Oregon Coast Range

Natural gas has been reported from 42 localities in the southern Oregon Coast Range. Many seeps issue from coal-bearing units (e.g., White Tail Ridge Formation) and from lower Umpqua units in thrust fault zones. The gas appears to be methane from coals and carbonaceous overbank mudstone and sandstone in these units. Natural gas also was detected in the Mesozoic terranes of the northern Klamath Mountains (e.g., Dothan Formation of Ramp, 1972).

Kvenvolden *et al.* (1995) show that both thermogenic and biogenic natural gas is present in the southern Oregon Coast Range. These gases are predominantly methane (C_1; >99%) with minor to trace amounts of C_2, C_3, C_4, and C_5 (Kvenvolden *et al.*, 1994). The C_1/C_2+C_3 ratios of this methane are high (i.e., 290 to >100,000), typical of dry gas. Thermogenic natural gases typically contain isotopically heavy methane; these gases have $\delta^{13}C$ values of −33.3 and −50.6‰ and δD values of −155 and −134‰. These thermogenic gases are thought to be derived from more deeply buried and tectonically deformed source rocks which have undergone thermal alteration (i.e., metagenesis) (Kvenvolden *et al.*, 1995). In contrast, biogenic gases are characterized by isotopically light methane; these biogenic gases have $\delta^{13}C$ values of −64.8, −63.9, and −64.9‰ and δD values of −245, −207, and −123‰. The biogenic gases are thought to have formed *in situ* through microbial reduction or early diagenesis of thermally immature coals and carbonaceous mudstone (Fig. 15A).

Thermogenic gases (mainly metagenic dry methane C_1) are found in water wells in pre-Tertiary mélange and broken formation (Dothan Formation) in the northern Klamath Mountains (S_{18} and S_{19} on Fig. 15). One sample has an isotopic composition that appears to be a mixture of biogenic and thermogenic methane. The isobutane to normal butane ratios of gas samples collected in these Klamath Mountain water wells is similar to absorbed gas released by crushing rock samples from outcrop (Kvenvolden *et al.*, 1995). In the northern Klamath Mountain, thrust faults between blocks of locally thermally matured Dothan strata and/or subducted Umpqua turbidites and mudstone may serve as conduits for migration of thermally mature gas into the overlying thermally

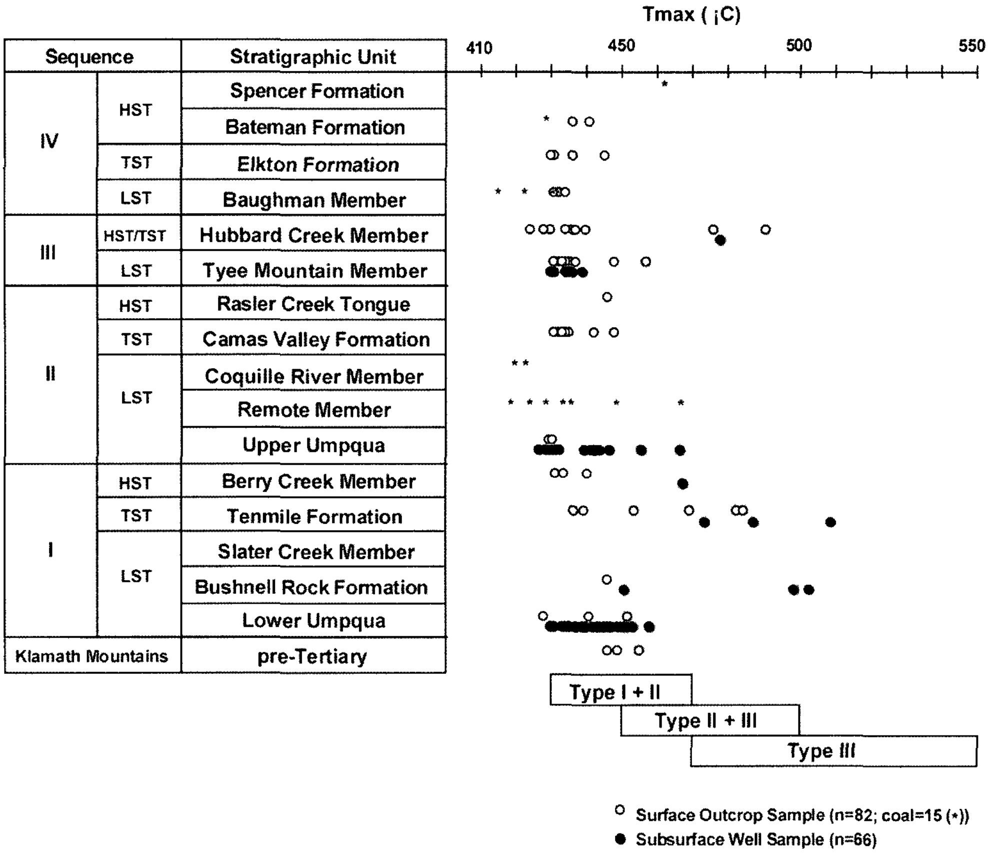

Fig. 14. Pyrolysis T_{max} values of southern Oregon Coast Range units as a function of stratigraphic unit and depth. Stippled area represents maturation level for Type II and Type III organic matter. Reliable T_{max} values only ($S_2 > 0.2$ and TOC > 0.5).

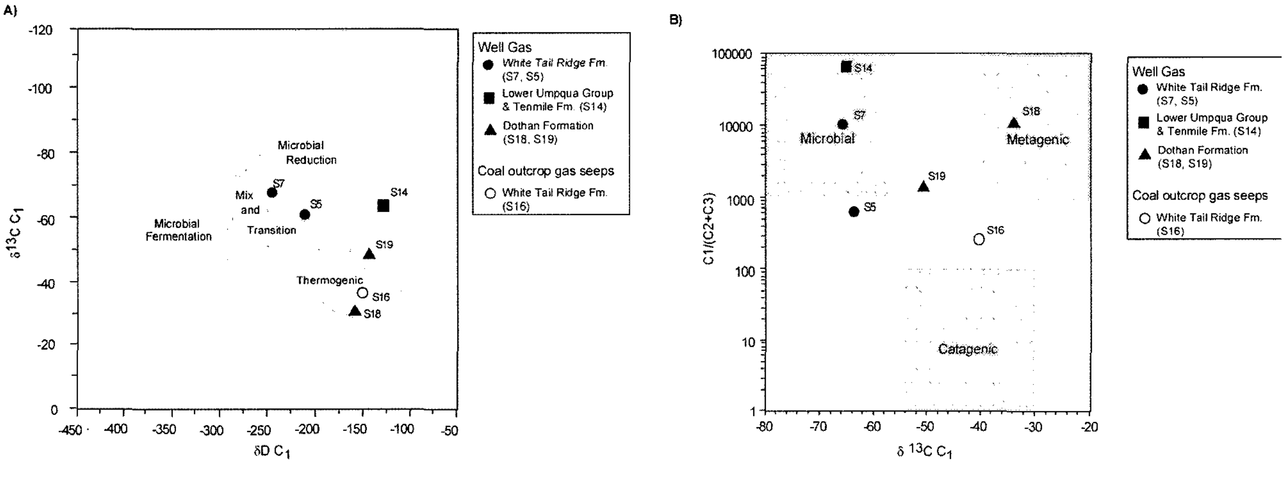

Fig. 15. A) $\delta^{13}C$ C_1 (‰) versus δD C_1 (‰) plot of thermogenic and biogenic methane from natural seeps and water wells. (B) C_1/C_2+C_3 versus $\delta^{13}C$ C_1 (‰) plot of methane from natural seeps and water well gas samples, showing peak generation areas of microbial (biogenic), metagenic, and catagenic gases (from Kvenvolden *et al.*, 1995).

immature strata of the Umpqua Group (Kvenvolden *et al.*, 1995). Some gas issues from fractures and joints in lower Umpqua turbidite strata associated with these thrusts (Niem and Niem, 1990).

Biogenic methane, on the other hand, is prevalent in Lookingglass Valley and Camas Valley, especially west of Melrose (e.g., S5 and S7 on Fig. 15). Small pockets of methane gas are encountered by shallow water wells. The biogenic gas may be coal bed methane from subbituminous coals and carbonaceous mudstones in the deltaic Remote and Coquille

River members (Kvenvolden *et al.*, 1995). Microbial dry methane also occurs in thin-bedded slope mudstone and turbidites of the Tenmile Formation in Camas Valley (S14 on Fig. 15).

Some thermally immature coals (i.e., $R_o < 0.6\%$ and $T_{max} < 435°C$) in these units, however, contain thermogenic gas (S16 on Fig. 15) that may have migrated up faults and microfractures from underlying thermally matured Klamath Mountain rocks and/or from more deeply buried and subducted lower Umpqua strata (Kvenvolden *et al.*, 1994). Metagenic dry methane derived from Type III organic matter normally requires a much higher level of maturation (i.e., $R_o > 1.4$ and $T_{max} > 470°C$) than normally observed in southern Oregon Coast Range and northern Klamath Mountains. The occurrence of dry metagenic methane with a thermogenic isotopic signature in thermally immature Coquille River coals (e.g., $R_o < 0.7\%$) (Fig. 15) may be the result of heretofore unexplained isotopic fractionation or diffusion processes *in situ* in these coals. Thermally immature coals in the Coos Bay basin also release methane that has thermogenic carbon and deuterium isotopic signatures (Kvenvolden *et al.*, 1994; 1995). Dry natural methane with both thermogenic and biogenic isotopic signatures is common throughout the Pacific Northwest (e.g., Armentrout and Suek, 1985; Stormberg, 1992; Johnson *et al.*, 1993; Kvenvolden *et al.*, 1989). The principal source rocks appear to be coals and/or lean source rocks of marine origin in which the organic matter is mostly gas-prone Types III and IV similar to the southern Oregon Coast Range strata.

Source Rock Potential and Maturation Mechanism

The samples with the highest total organic carbon content (>2.0 weight percent) are listed in Table 1. The samples are grouped by formation and ranked by generative potential. All the coals and carbonaceous mudstones in the deltaic units rate as very good potential source rock for gas and possibly oil based on the total organic carbon content (Table 1). Also one sample from the Whitsett Limestone is ranked as potential source rock (Table 1). The dark micrite containing pelagic foraminifers and coccoliths emits a petroliferous odor when broken and is interbedded with carbonaceous mudstone. However, these Cretaceous (Albian-Aptian) limestones occur as isolated scattered small blocks in the Mesozoic mélange and thus are geographically very limited as source rock.

For an organic-rich source rock to become an effective source rock, it must have reached a maturity level sufficient to generate hydrocarbons (Tissot and Welte, 1978). Two binary plots of hydrogen index versus maturation (i.e., T_{max} and R_o) show the hydrocarbon-generative type (i.e., gas or oil or mixed) of potential source rocks and levels of maturation

Table 1. Source rock samples that have the best generative potential in southern Oregon Coast Range

UNIT	SAMPLE NO.	ROCK TYPE	TOC	HI (S_2/TOC)	T_{max}	R_o
Spencer	R-92-027	Coal	Very Good	Gas	Immature	Immature
Bateman	R-89-172	Coal	Very Good	Gas & Oil	Immature	N/A
Baughman	Law *et al.* (1984)	Coal	Very Good	Gas & Oil	Immature	Immature
Baughman	N-92-1001	Coal	Very Good	Gas	Immature	N/A
Baughman	Law *et al.* (1984)	Coal	Very Good	Gas & Oil	Immature	Immature
Baughman	Browning & Flanagan (1980)	Coal	Very Good	?	Immature	N/A
Baughman	R-89-044	Coal	Very Good	Gas	Immature	N/A
Baughman	Browning & Flanagan (1980)	?	Very Good	?	Immature	N/A
Hubbard Creek	RN-90-144	Siltstone	Very Good	Gas & Oil	Immature	N/A
Coquille River	N-90-358	Coal	Very Good	Gas	Immature	N/A
Coquille River	RN-91-099	Coal	Very Good	Gas & Oil	Immature	N/A
Remote	RN-91-270	Coal	Very Good	Gas & Oil	Mature	Immature
Remote	KL-93-14-	Coal	Very Good	Gas & Oil	Immature	Immature
Remote	Law *et al.* (1984)	Coal	Very Good	Gas	Immature	Immature
Remote	R-92-017	Coal	Very Good	Gas	Mature	Immature
Remote	N-91-116	Coal	Very Good	Gas	Immature	N/A
Remote	KL-93-13-	Coal	Very Good	Gas	Immature	Immature
Remote	RN-91-391	Coal	Very Good	Gas	Immature	N/A
L. Umpqua	subsurface	Mudstone	Very Good	Gas	Immature	N/A
L. Umpqua	N-91-131	Mudstone	Very Good	Gas	Immature	N/A
Pre-Tertiary	Law *et al.* (1984)	Mudstone	Very Good	Gas	Immature	Immature
Pre-Tertiary	Law *et al.* (1984)	Mudstone	Very Good	Gas	Immature	Immature
Pre-Tertiary	KL-93-11-5	Limestone	Very Good	Gas & Oil	Immature	Immature

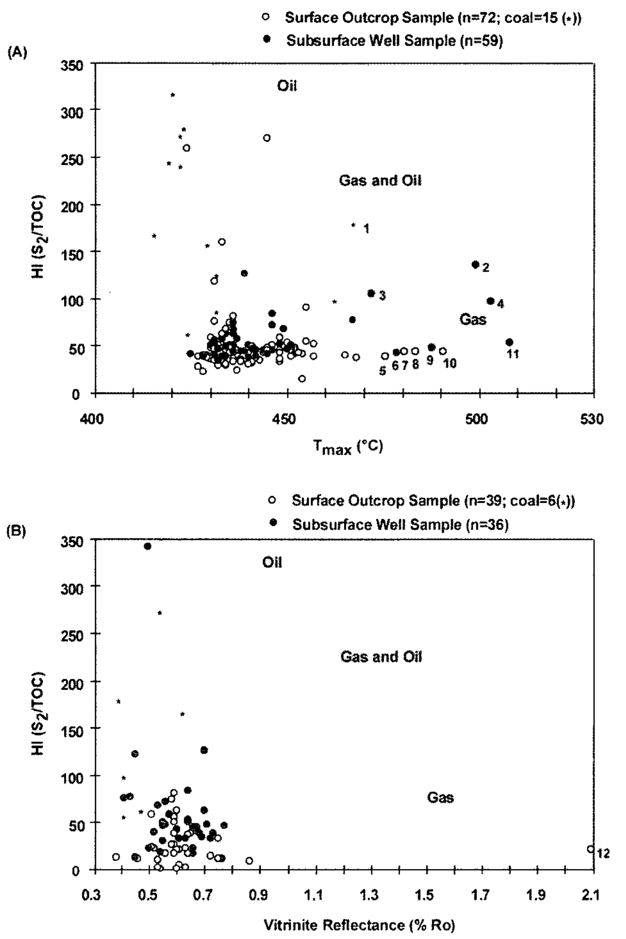

Fig. 16. Plots of (A) Hydrogen Index (HI) versus pyrolysis T_{max} values and (B) Hydrogen Index (HI) versus vitrinite reflectance values showing the hydrocarbon-generative type and level of maturation. Stippled pattern represents the range of values that are mature for each hydrocarbon-generative type. Most samples plot on the field of gas-prone and thermally immature, but 12 samples plot on the mature fields of oil-prone, gas- and oil-prone, and/or gas-prone only. These twelve samples are listed in Table 2.

(Fig. 16). Most analyzed samples are thermally immature, (i.e., below the stippled areas on Fig. 16), including samples with the highest HI (Table 1), such as coals which, although organic-rich, have not been buried or heated sufficiently to generate either oil or gas. Only twelve samples are mature and within the generation window for each type of organic matter (Type I, II, and III) to generate oil, oil and gas, and/or dry gas only. Thermally mature samples are from the Hubbard Creek Member (3 samples), Remote Member (1 sample), Tenmile Formation (5 samples), Bushnell Rock Formation (2 samples), and Umpqua Group (1 sample). Some are associated with thrusts or basaltic sills. However, the source rock generative potential of these thermally mature samples is generally poor to fair (i.e., too lean to produce much hydrocarbon) (Table 2).

In summary, source rock analyses indicate that the best generative potential is found in coals and carbonaceous mudstones in the deltaic units of the upper Umpqua Group (e.g., Coquille River and Remote members) and the overlying forearc basin units, such as the Baughman Member of the Tyee Formation, and the Bateman and Spencer formations (Fig. 16). Rocks that have sufficiently high levels of thermal maturation to produce oil and thermogenic gas are generally organically lean deep-marine and shelf/slope mudstones of the underlying lower Umpqua subduction zone units (e.g., Bushnell Rock Formation, Slater Creek Member, Tenmile Formation, and Berry Creek Member) (Fig. 16). Cretaceous pelagic limestone and coals and carbonaceous mudstones of the deltaic Remote Member represent the most effective source rocks in the southern Oregon Cost Range and northern margin of the Klamath Mountains in terms of source rock generative potential and thermal maturity (Fig. 16).

Conclusions

An Eocene forearc basin sequence and underlying subduction zone complex form the southern Oregon Coast Range. Owing to syndepositional intrabasin tectonism and earlier oceanic volcanism, thickness and lateral facies variations of sedi-

Table 2. Source rocks that have the best maturity in southern Oregon Cost Range

No. in Fig. 16	UNIT	SAMPLE NO.	ROCK TYPE	TOC	HI (S_2/TOC)	T_{max}	R_o
5	Hubbard Creek	RN-91-112	Shale	Fair	Gas	*Mature (?)	N/A
6	Hubbard Creek	Subsurface	Mudstone	Fair	Gas	*Mature (?)	N/A
10	Hubbard Creek	RN-91-348	Mudstone	Fair	Gas	*Mature (?)	N/A
1	Remote	RN-91-270	Coal	Very Good	Gas & Oil	Mature	Immature
3	Tenmile	Subsurface	Mudstone	Fair	Gas	Mature	N/A
7	Tenmile	RN-91-070	Mudstone	Fair	Gas	Mature	N/A
8	Tenmile	RN-91-354	Mudstone	Fair	Gas	Mature	N/A
9	Tenmile	Subsurface	Mudstone	Fair	Gas	Mature	N/A
11	Tenmile	Subsurface	Mudstone	Fair	Gas	Mature	Immature
2	Bushnell Rock	Subsurface	Siltstone	Fair	Gas	Mature	Immature
4	Bushnell Rock	Subsurface	Siltstone	Fair	Gas	Mature	N/A
12	L. Umpqua	RN-90-322	Mudstone	Poor	Gas	Mature	Mature

*T_{max} values are likely to be too high because of adsorption of pyrolytic organic compounds onto the smectitic clay-rich matrix

mentary units are pronounced. This has led to difficulties in creating a coherent stratigraphic framework for the basin by previous investigators (e.g., Baldwin, 1974; Molenaar, 1985). The stratigraphic problem, in turn, has resulted in erroneous prediction of hydrocarbon potential.

Organic geochemical analyses (e.g., Rock-Eval, TOC, R_o) of the southern Oregon Coast Range strata indicate that the most organic-rich source rocks with the highest generative potential are the subbituminous coals and carbonaceous overbank mudstones in the deltaic White Tail Ridge Formation (e.g., Coquille River and Remote members) and the overlying forearc basin units, such as the Baughman Member of the Tyee Formation, and the Bateman and Spencer formations. The organic matter is predominantly Type III (gas-prone terrestrial matter). These organic-rich forearc and marginal basin units, however, are thermally immature and have produced non-commercial quantities of biogenic methane in some water wells. However, higher levels of thermal maturation necessary to produce oil and thermogenic gas (i.e., in the oil and gas window) are locally present in deep-marine and outer shelf/slope mudstones of the underlying more deeply buried lower Umpqua subduction zone complex units (e.g., Bushnell Rock Formation, Slater Creek Member, Tenmile Formation, and Berry Creek Member). Unfortunately, most of these marine mudstones are organically lean and are non-source to marginal source rocks.

Although the best source rock and highest thermal maturity are not generally coincident in any southern Oregon Coast Range units, a few organically rich source beds (e.g., coals and carbonaceous mudstones of the White Tail Ridge Formation) are sufficiently thermally mature to produce thermogenic gas or possibly oil in the previously more deeply buried southern part of the basin before uplift. Some usually immature source beds in the Umpqua and younger units have also been thermally matured by flash heating by thick basalt sills and/or by thermal friction or migration of hydrothermal fluids along thrust faults. Cretaceous Whitsett pelagic limestone and shale and Remote Member coals and carbonaceous overbank mudstone represent the most effective source rocks in the southern Oregon Coast Range and adjacent northern margin of the Klamath Mountains in terms of source rock generative potential and thermal maturity.

Thermogenic dry gas (mainly methane) detected by carbon and deuterium isotopic analysis (Kvenvolden *et al.*, 1995) in some water wells and natural seeps, could have been generated from subducted Mesozoic Klamath Mountains pelagic limestones and from lower Eocene Umpqua deep-marine slope to basinal mudstones which contain both oil- and gas-prone Type II and III organic matter. This dry gas could have migrated up into the overlying thermally immature to submature upper Umpqua reservoir sandstone (e.g., deltaic White Tail Ridge Formation) and possibly into potentially fractured and jointed lithic sandstone and conglomerate reservoirs in the Bushnell Rock and Tenmile formations and in lower Umpqua turbidite strata which were folded and thrusted in the late-early Eocene. The Camas Valley mudstone and diagenetically tight turbidite and deltaic sandstone and mudstone of the Tyee Formation of the overlying forearc basin sequence could act as a seal for natural gas accumulations.

Natural gas could migrate up along faults and joints to charge small accumulations in potential reservoir sandstones in the lower Tyee Mountain turbidites in which some secondary porosity and permeability has been recognized in thin section. Overlying hemipelagic mudstone beds and less permeable turbidite sandstones in the Tyee Mountain Member could act as seals although a seal and structural or stratigraphic traps are not necessary in tight-gas sandstone reservoirs (Law and Dickinson, 1985; Law *et al.*, 1994; Law and Spencer, 1993). These accumulations may also occur in untested anticlines which were formed in the Tyee Mountain Member in the late-middle Miocene in the northeastern part of the study area.

The higher regional geothermal gradient of the Western Cascades arc, hydrothermal fluids (derived from Miocene granodiorite plutons), and/or heat from thick upper Eocene basaltic andesitic sills have locally thermally matured Eocene source rocks along the eastern margin of the Oregon Coast Range. Thermogenic methane in seeps as well as hydrothermal fluids, could have migrated along older thrust faults and possibly into fault propagation folds on the eastern flank of the southern Oregon Coast Range.

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