Chapter 2

Geologic Assessment of Undiscovered Oil and Gas in the Paleozoic–Tertiary Composite Total Petroleum System of the Eastern Great Basin, Nevada and Utah

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Chapter 2 of
Geologic Assessment of Undiscovered Oil and Gas Resources of the Eastern Great Basin Province, Nevada, Utah, Idaho, and Arizona

By U.S. Geological Survey Eastern Great Basin Assessment Team

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Geologic Assessment of Undiscovered Oil and Gas in the Paleozoic–Tertiary Composite Total Petroleum System of the Eastern Great Basin, Nevada and Utah

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Abstract

The U.S. Geological Survey (USGS) completed an assessment of the undiscovered oil and gas potential of the Eastern Great Basin Province (EGB) in 2004. USGS assessments of undiscovered oil and gas use the total petroleum system (TPS), which includes mapping the distribution of potential source rocks and known petroleum accumulations and determining the timing of petroleum generation and migration. The assessment is geologically based and includes source and reservoir rock stratigraphy, timing of tectonic events and the configuration of resulting structures, formation of traps and seals, and burial history modeling. The TPS is subdivided into assessment units (AU) based on similar geologic characteristics and accumulation and petroleum type. For the EGB, we defined the Paleozoic-Tertiary Composite Petroleum System and three AUs and quantitatively estimated the undiscovered oil and gas resources within each. The three AUs are (1) Neogene Basins AU, formed during Basin and Range extensional tectonics; (2) Neogene Ranges and Other Structures AU, which includes mountain ranges related to the same tectonic event; and (3) the Sevier Thrust System AU of western Utah and southeastern Nevada. The oil and gas potential of each AU was based in part on burial and thermal history modeling. The results also show several potential scenarios for petroleum generation and migration in the TPS based on varying depositional thickness, erosion amount, and heat flow. Model results showed that the Mississippian Chainman Formation entered the oil generation window during the Permian, but oil generation ceased in late Mesozoic. Part of the Chainman began to generate oil again after additional burial in Neogene basins.

Introduction

The U.S. Geological Survey (USGS) completed a quantitative estimate of the undiscovered oil and gas potential of the Eastern Great Basin (EGB) Province of eastern Nevada and western Utah in 2004 (fig. 1). The assessment of the EGB Province was based on geologic principles and uses the total petroleum system (TPS) concept.

A TPS includes all genetically related petroleum within a limited mappable geologic space and other essential mappable geologic elements (reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum (Magoon and Dow, 1994). A TPS consists of one or more assessment units (AU), which are the basic geologic units for assessing resources. An AU is a mappable part of a TPS in which discovered and undiscovered fields constitute a single, relatively homogeneous population. The chosen methodology of resource assessment is based on the simulation of the number and sizes of undiscovered fields. Using these criteria, the USGS defined one composite TPS for the EGB and three AUs within the TPS (fig. 1) and quantitatively estimated the undiscovered oil and gas resources within each.

Province boundaries were determined, in part, from boundaries established for other assessment provinces. The west, south, and north boundaries were established from the 1995 assessment of the EGB. Most of the east boundary is common to the Wyoming thrust belt and the Uinta-Piceance Basin Province boundaries. The southeastern boundary was determined to be near the Wasatch fault and along parts of the Hurricane fault in southwestern Utah.

Exploration History

Natural gas was first discovered in the EGB in the late 1800s at depths of about a thousand feet on the east shore of the Great Salt Lake during the drilling of water wells. The gas was collected and stored in wooden pipes and shipped to Salt Lake City.

Oil was first discovered near Rozel Point in the late 1800s, also on the east side of the Great Salt Lake, after numerous oil seeps were discovered in the area. Several attempts were made to drill the seeps but wells could not

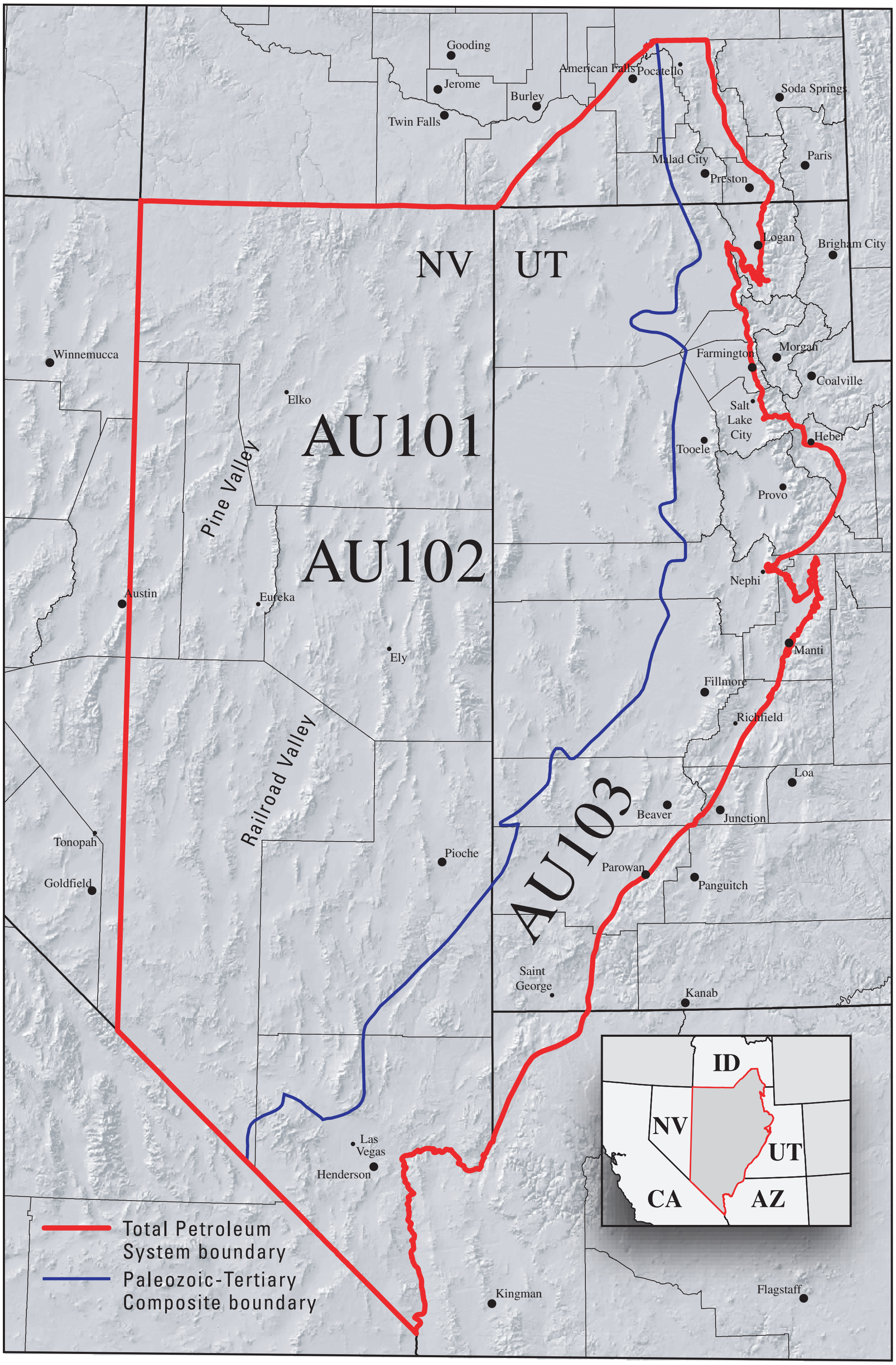


Figure 1. Boundaries of Eastern Great Basin Province and the three assessment units in the Paleozoic-Tertiary Composite Total Petroleum System. Numbers 101, 102, 103 refer to the number system for the Neogene Basins AU (50190101), Neogene Ranges and Other Structures AU (50190102), and Sevier Thrust System AU (50190103).

sustain production. The first commercial oil production was from West Rozel field drilled from a floating platform in the Great Salt Lake. Three wells completed in fractured Pliocene basalt produced about 28,000 barrels of low-gravity oil before being shut in because of low production rates and unfavorable economic conditions (Bortz, 1983).

The first commercial oil production in Nevada began in 1954 with the completion of Shell Oil #1–35 Eagle Springs, the discovery well for the Eagle Springs field in Nye County, Nevada. In all, about 90 exploration wells were drilled in the EGB from the early 1900s until the first commercial production in 1954. Many of the early wells were drilled on or downdip from the numerous oil seeps throughout the basin (Bortz, 1983; Brady, 1984). As the exploration industry became more established, popular exploration targets were large, surface exposed anticline structures. Some of these structures had oil shows in prospective reservoirs, but no accumulations were found.

The 1954 discovery in Nevada led to a sharp increase in drilling for about 3 years, but later drilling decreased due to low oil prices. Four more spikes in drilling activity occurred 1961, 1965 to 1970, 1977 to 1981, and 1984 to 1988 — inspired by new field discoveries. The correlation between the number of new oilfield discoveries and the number of wells or total footage drilled, however, is poor.

Numerous complications plagued early exploration efforts in the province, many of which persist today: (1) Multiple tectonic compressional events created numerous and diversified structural configurations, followed by an extension event that dissected and rearranged many of the previously formed structures; (2) several stacked and structurally segregated carbonate sequences were difficult to identify without biostratigraphy; (3) multiple deposition and differential erosion events resulted in a complex burial and thermal history and led to difficulties identifying vertical stratigraphy; (4) seismic acquisition in Neogene basins was difficult because thick, unconsolidated basin fill sediments are interspersed with thick, but commonly discontinuous, volcanic beds; (5) the area is remote so there are long distances to service industries; and (6) absence of pipelines.

Production History

All commercial production in the EGB (except for the recent Navajo Sandstone discovery near Richfield, Utah, in the Sevier thrust belt) has been in two Neogene basins or valleys, Railroad Valley and Pine Valley (fig. 1). This low rate of discovery exists even though many of the basins within the Basin and Range Province appear to have the components necessary to generate, migrate, trap, and accumulate oil (gas production is rare). Railroad Valley has produced about 44 million barrels of oil (MMBO) from nine fields, but only five fields have oil accumulations large enough (more than 0.5 MMBO) to be included in the assessment (fig. 2). Producing reservoirs in the area include Paleozoic platform carbonate rocks, Tertiary volcanic rocks, and Tertiary lacustrine siltstones. Most of the trap types are classified as structural, although the volcanic and lacustrine reservoirs have a stratigraphic component.

Pine Valley has four fields (15 producing wells) and has produced about 5 MMBO (fig. 2), but only Blackburn field has produced enough oil to be included in the assessment. Other fields have produced only a few hundred to a few thousand barrels of oil and were not considered as part of the assessment.

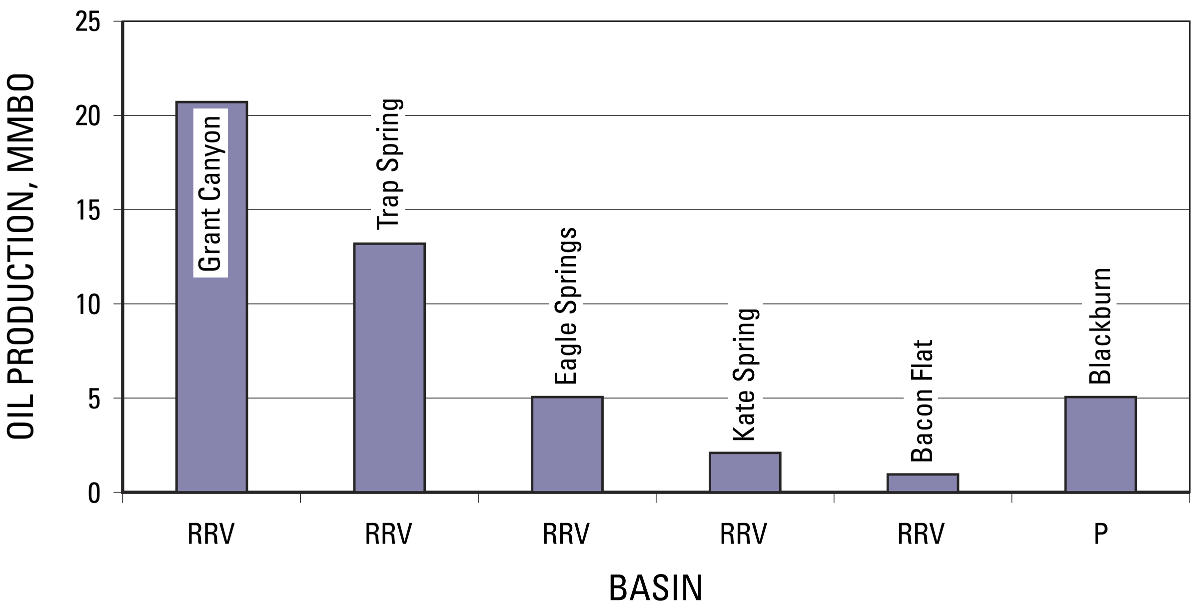


Figure 2. Cumulative oil production plots for major producing fields in Railroad and Pine Valleys, Nevada (data current to 2004). MMBO, million barrels of oil.

Province Geology

Stratigraphy

The EGB Province has a wide variety of rock types including passive margin platform carbonates and marine and nonmarine clastic rocks that reflect a wide range of depositional environments, and volcanic intrusives and extrusives. All depositional environments and subsequent rock types are a response to a combination of orogenic events, structural styles, sea level fluctuation, or climate cycles. Most of the stratigraphic sequences that were used in this study could be classified as second and third order depositional cycles as defined by Vail and others (1977), and Cook and Corboy (2004) classified the Paleozoic carbonates as third-order cycles.

A generalized sedimentary section and depositional profile of Phanerozoic rocks in the EGB (fig. 3) document an evolution from a mostly passive carbonate platform in the lower to mid Paleozoic to a dominance of marine and nonmarine clastic facies in the upper Paleozoic and lower Mesozoic, respectively, and then to continental lacustrine and volcanic rocks in the upper Mesozoic and Cenozoic. A more detailed description of the stratigraphic section is given in sections on source rocks and reservoir rocks.

Tectonics and Related Structure

Several major tectonic events combined to produce the complex structural and stratigraphic patterns that characterize the geologic framework of the EGB Province (fig. 4). These events include the Antler orogeny, the Sonoma orogeny, late Paleozoic and Mesozoic thrusting, the Sevier thrust system, and Neogene extension (or Basin and Range extension), as discussed herein.

Antler Orogeny and Roberts Mountain Thrust

The EGB Province was part of a passive carbonate platform margin environment throughout most of the early to middle Paleozoic. However, as the Late Devonian Antler orogeny began in the western Cordillera, the passive carbonate platform environment was replaced by clastic sedimentation in a thrust related foredeep basin. The Roberts Mountain allochthon formed a north-south-trending upland area in central Nevada in Early Mississippian time, with the Roberts Mountain thrust as the leading thrust (Ketner and Smith, 1982). The allochthon consisted of an assemblage of lower Paleozoic, deep-basin graptolitic, cherty, and organic shales thrust over an autochthonous assemblage of fine grained clastics of Mississippian and Devonian carbonates. East-vergent thrusting created an eastward-migrating foredeep trough in front of the thrusting, followed by a forebulge or bathymetric high, and finally an easternmost back basin (fig. 5; Poole and Claypool, 1984, Cook and Corboy, 2004).

Sonoma Orogeny and Golconda Thrust

The Sonoma orogeny occurred in Permian and Triassic time, resulting in the eastward transport of the Golconda allochthon that consists of deepwater clastics of the Havallah sequence. The allochthon was thrust over the beveled Antler allochthon highland, although the east-verging Golconda thrust is west of and roughly parallel to the Roberts Mountain thrust. Little deformation or metamorphism accompanied the emplacement of the Golconda allochthon and only a modest amount of sediment was shed off of the uplifted fault sheet. As a result, the Sonoma orogeny, although having some effect on the burial history of Mississippian source rocks from Permian and Early Triassic deposition, did not play a major role in the petroleum potential of the EGB Province.

Central Nevada Thrust Belt

The central Nevada thrust belt (CNTB) is a narrow north-south-trending zone (at approximately 116.5º long) of compressional structures located in the hinterland of the Sevier orogenic belt. The thrust system was probably continuous for tens to hundreds of miles in the north-south direction (Taylor, 2001), but Neogene extension segregates the province into basins and ranges, and exposures of the CNTB are now observable only in the ranges. In addition, little evidence exists as to the thrust system's subsurface configuration, including how Neogene extension segmented the compressional structures. Although poorly constrained, evidence appears to support an Early Triassic to mid-Cretaceous age for the thrusting (Ketner, 1984), but the rates and timing of compression probably varied. Taylor (2001) mapped parts of the thrust belt as three stacked thrust sheets with the hanging walls consisting of Precambrian through Permian strata. Chamberlain and Gillespie (1993) mapped thrust sheets in southeastern Nevada, which they identified as part of the CNTB; in their opinion, structures within the thrust system may hold large accumulations of oil and gas and represent the best chance for a significant oil discovery in Nevada.

Sevier Thrust System

Willis (1999) defined the Cordilleran thrust system as an east-verging thrust system that extended from Alaska to Mexico and was tectonically active from Late Jurassic to early Tertiary time. It is part of the Cordilleran thrust system, but the name Sevier is limited to the EGB of Utah and adjacent areas. The main or frontal part of thrusting is approximately 60 mi wide and extends from southeastern Nevada to the Utah part

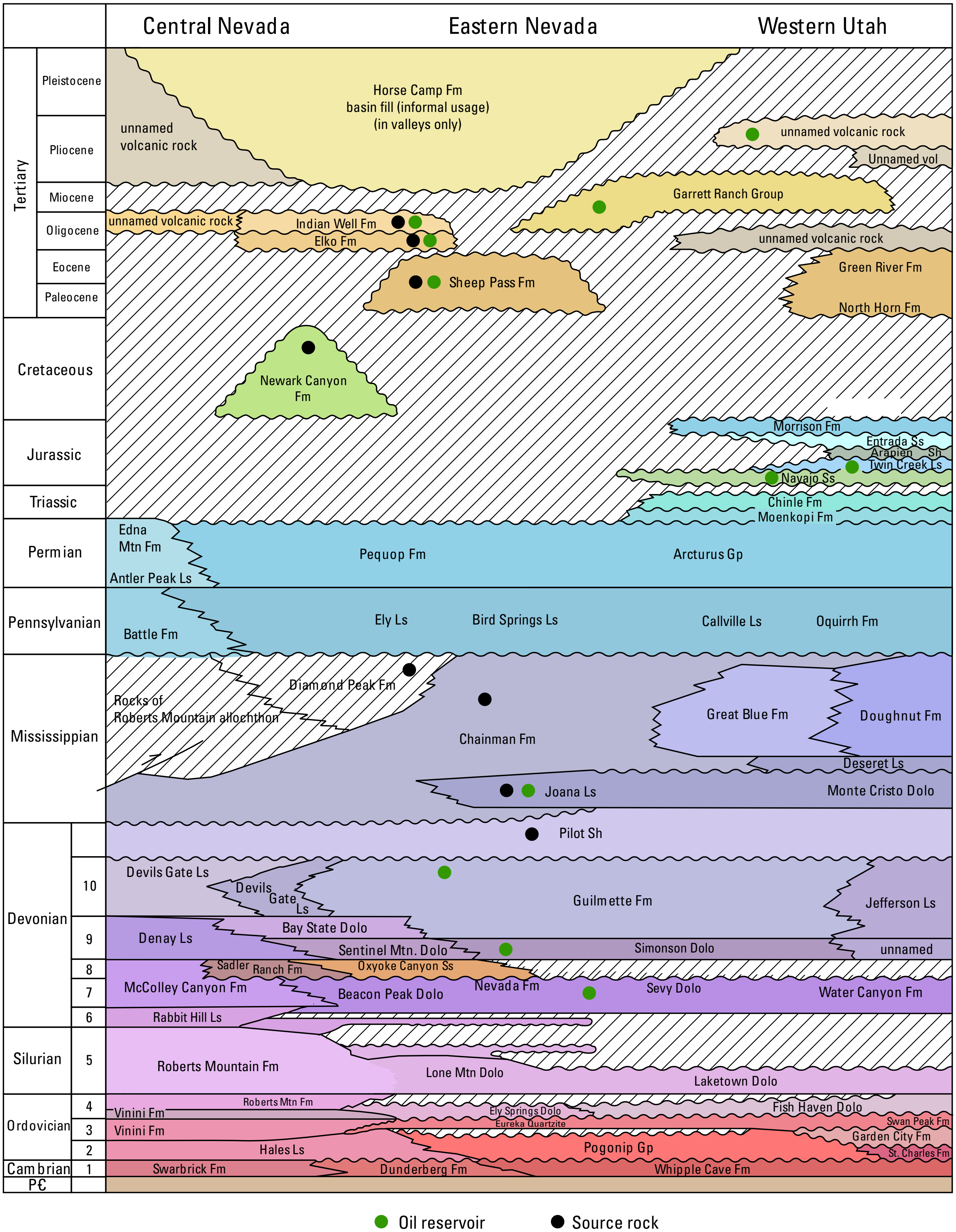


Figure 3. Generalized stratigraphic column of Phanerozoic strata in the eastern Great Basin showing intervals of petroleum production, source rocks, major sequence boundaries, hiatus intervals (hachured), and unconformities. Paleozoic section modified from Cook and Corboy, 2004. Ls, limestone; Dolo, dolomite; Fm, formation; Vol, volcanic; Ss, sandstone.

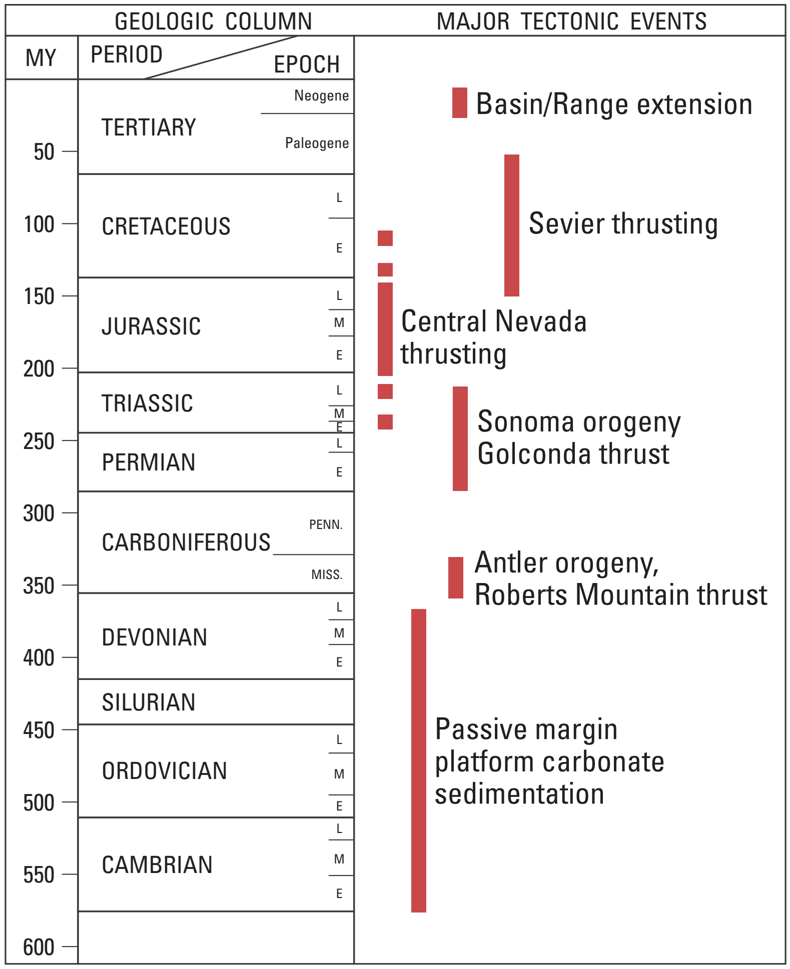


Figure 4. Time sequence of major tectonic events of the eastern Great Basin. E, Early; M, Middle; L, Late; Miss., Mississippian; Penn., Pennsylvanian.

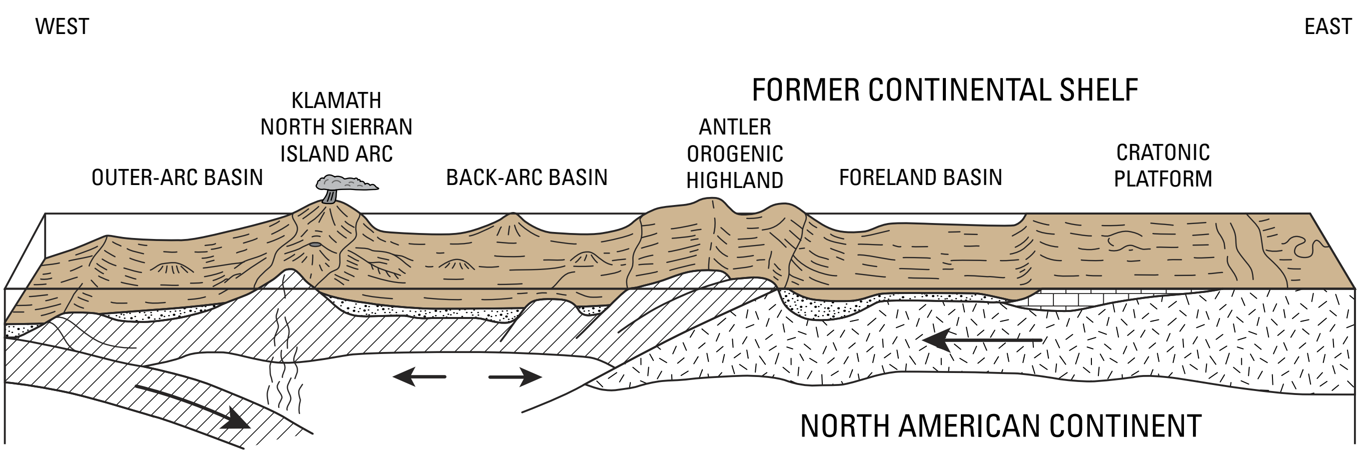


Figure 5. Generalized diagram for Late Devonian and Mississippian time showing geomorphic effects of the Antler orogeny. Modified after Cook (1988).

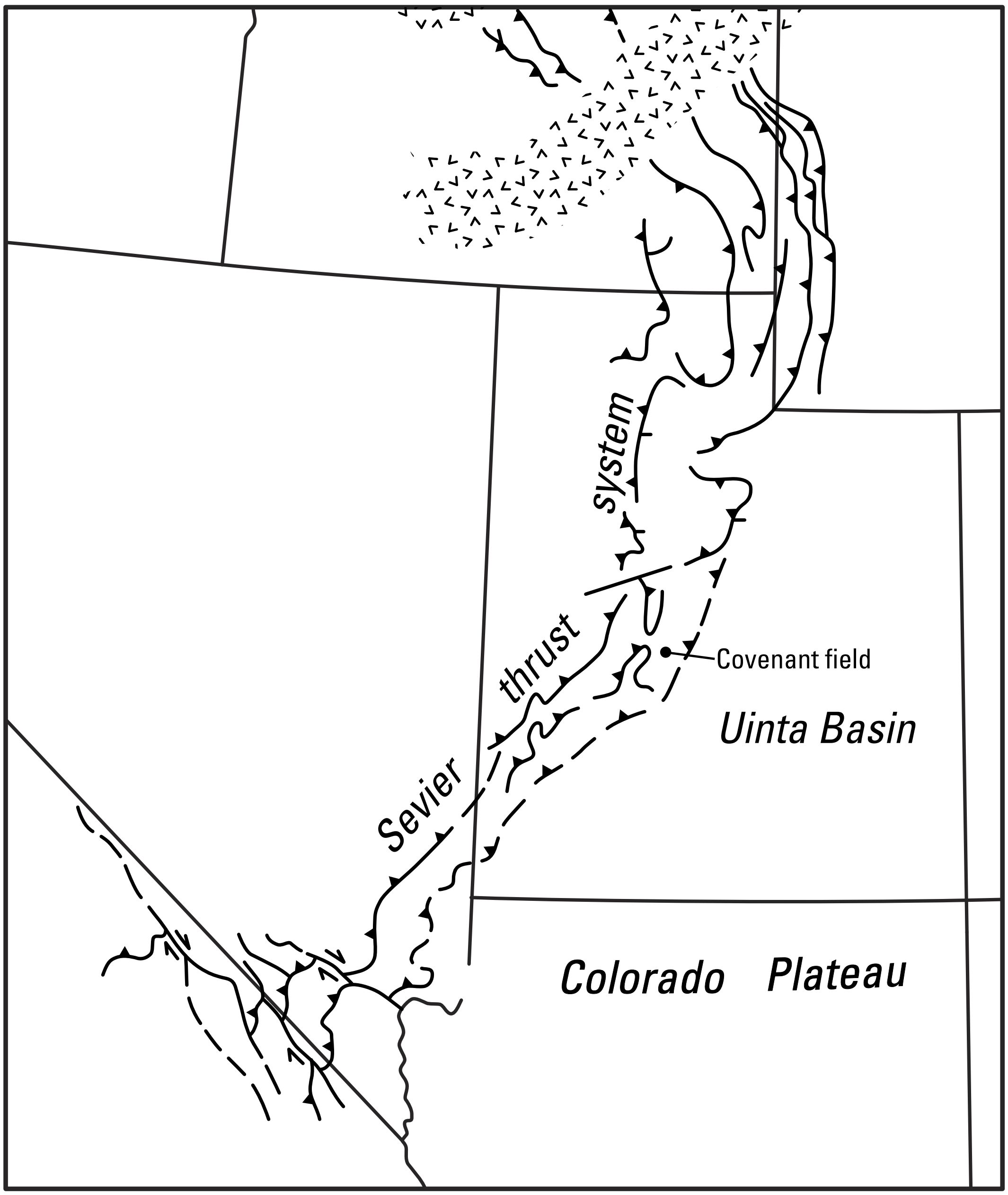


Figure 6. Generalized map of major fault traces and location of Covenant field of the Sevier thrust system.

of the Wyoming thrust belt (fig. 6). Deformation in the eastern part of the thrust zone was thin skinned and susceptible to fault imbrication (thrust repetition of sedimentary sequences above the basement) and folding (Miller and others, 1992; Cowan and Bruhn, 1992).

The Sevier system is distinguished from the Laramide system in both time and style. Although the systems overlap in time, Laramide structures developed from the end of the Cretaceous through the Eocene, a sequence of shorter duration than the Sevier system, and involve thick-skinned deformation characterized by uplift and thrusting of Precambrian basement.

The effects of the Sevier emplacement of thrust sheets on autochthonous terrane are typical of thrust systems with a foredeep basin in front of the leading thrust and a forebulge high and a backbulge basin. The system prograded from west to east, depositing as much as several thousand feet of sediment, including potential source rocks of the Cretaceous Mowry and Hilliard Shales in the foredeep east of the province boundary. By the Late Cretaceous, most of the thrusting had ceased; then, either in the early Tertiary or as part of Neogene extension, compressional stresses relaxed enough to produce backsliding on thrust planes (Wernicke and Axen, 1988). As a result, the load of the hanging wall was removed from the footwall and may have promoted isostatic rebound in the footwall, which resulted in the formation of extensive fold belts, such as the Sevier Valley and Virgin River folds (Wernicke and Axen, 1988). However, Carpenter and others (1989) argued that the folds are from Sevier compression and not from isostatic rebound.

Neogene Extension and Related Structures

The EGB Province underwent extensional deformation in the Neogene, resulting in the formation of the present-day Basin and Range Province. Basin and Range extension began about 25 Ma when the west-moving North American plate started to override the Pacific plate (before overriding the Farallon plate [Wernicke, 1992]). As the North American plate continued migrating westward, a deep seated, relatively stationary, north trending upwelling of the mantle caused extension in the east-northeast direction. Thin and structurally weak Phanerozoic rocks broke into horst and graben (basin and range) blocks. As in many extensional terranes, individual basins differ in their structural configurations—some basins are bound by steep to vertical normal faults, some by gently dipping normal faults, and some by steep faults at the surface that become listric at depth— which complicates exploration strategies.

Magmatism and metamorphic core complexes are associated with basin and range extensional tectonics (Miller and others, 1998). The Columbia Plateau basalts flooded southern Idaho and adjacent areas, and there was uplift of metamorphic core complexes in northeastern Nevada. The emplacement of core complexes enhanced the effects of extension by pushing strata away from the uplift.

Episodic Tectonics and Structural Zones

The EGB has had numerous orogenic events, but evidence indicates that the more recent events were spatially episodic. For example, Potter and others (1995) suggested that extensional deformation of Eocene strata in west-central Utah occurred in late Eocene and that these rocks lie in a domain that underwent little extensional deformation in Neogene time. Axen and others (1993) described two zones of late Paleogene to early Miocene extension; they trend north-south at approximately the same longitude as Railroad Valley and Pine Valley, in east-central Nevada, and contribute to the complexity of the regional structural framework.

Basin Development

Railroad Valley

Railroad Valley (fig. 1) has produced most of the oil in the EGB Province and has been extensively studied to determine relations between structure and oil production. Several interpretations of basin configuration have evolved, based on improved seismic acquisition and processing and better understanding of deformation styles and kinetics. Lund and others (1993) and Potter and others (1992) for example, reported that a low-angle attenuation fault that underlies Railroad Valley, exposed in the adjacent range, was a result of asymmetric arching rather than a series of down-to-the-west high-angle normal faults. According to them (Lund and others, 1993; Potter and others, 1992), (1) some high-angle normal faults exist as part of the deformation process, but they are not the dominant style, and (2) a transfer of heat from the lower plate of the low-angle fault to the otherwise cool upper plate could occur by either convection or discrete pathways through the high-angle normal faults or fracture zones, possibly allowing source rocks in the upper plate to reach oil generating temperature.

Pine Valley

Pine Valley (fig. 1) has four new field discoveries, but only the Blackburn field has commercial production. The distribution of fields and seeps indicates that oil could have multiple migration routes throughout the valley, but the lack of traps or seals may limit the volumes of accumulation.

The area has had two major periods of deformation: the emplacement of the Mississippian Roberts Mountain allochthon and Neogene extension. The Roberts Mountain allochthon was emplaced between mid-Osagean and Meramecian time that encompassed the Diamond Peak and Chainman Formations (fig. 3). The allochthon moved deep-basin cherty, graptolitic, organic shales (termed the Western Assemblage, WA) about 65 mi eastward, overriding parts of the Chainman Formation. According to Carpenter and others (1993), the emplacement of the allochthon was relatively passive; however, postallochthon Mesozoic deformation faulted and folded sections above and below the Roberts Mountain thrust. Although the organic material in the WA has not been typed to oil produced in the valley, the combination of the WA and the Chainman Formation could represent substantial source rock potential for the area.

Pine Valley was formed by Neogene extension starting in late Oligocene time and by fault offsets in Holocene alluvium, which indicates extension is ongoing (Carpenter and others, 1993). The basin floor dips east into the high-angle Pine Valley fault, which defines the east edge of the basin. Folds and faults in the area formed during both preextensional and extensional deformation. Force folds, normal faults, and reverse faults are typical features creating multiple structural configurations and potential traps in the basin.

Other Valleys

Numerous basins in the EGB are similar to Railroad and Pine Valleys. Many have had geophysical surveys and some have been tested by drilling, but only Railroad Valley has been extensively drilled. Regional gravity data converted to depth indicate that many valleys are deep enough to generate Mississippian oil yet have had few, if any, tested wells. To date, traps involving Paleozoic carbonate reservoirs are small but prolific, as shown in the Grant Canyon and Blackburn field production charts (fig. 7). Volcanic rocks are extensive and could be important oil reservoirs; however, at Trap Spring and Eagle Springs fields they are less productive than nearby carbonate reservoirs. Tertiary clastic reservoirs have limited production, limited connection to source rocks in the oil generation window, limited areal extent, and unproven but potentially good reservoir quality.

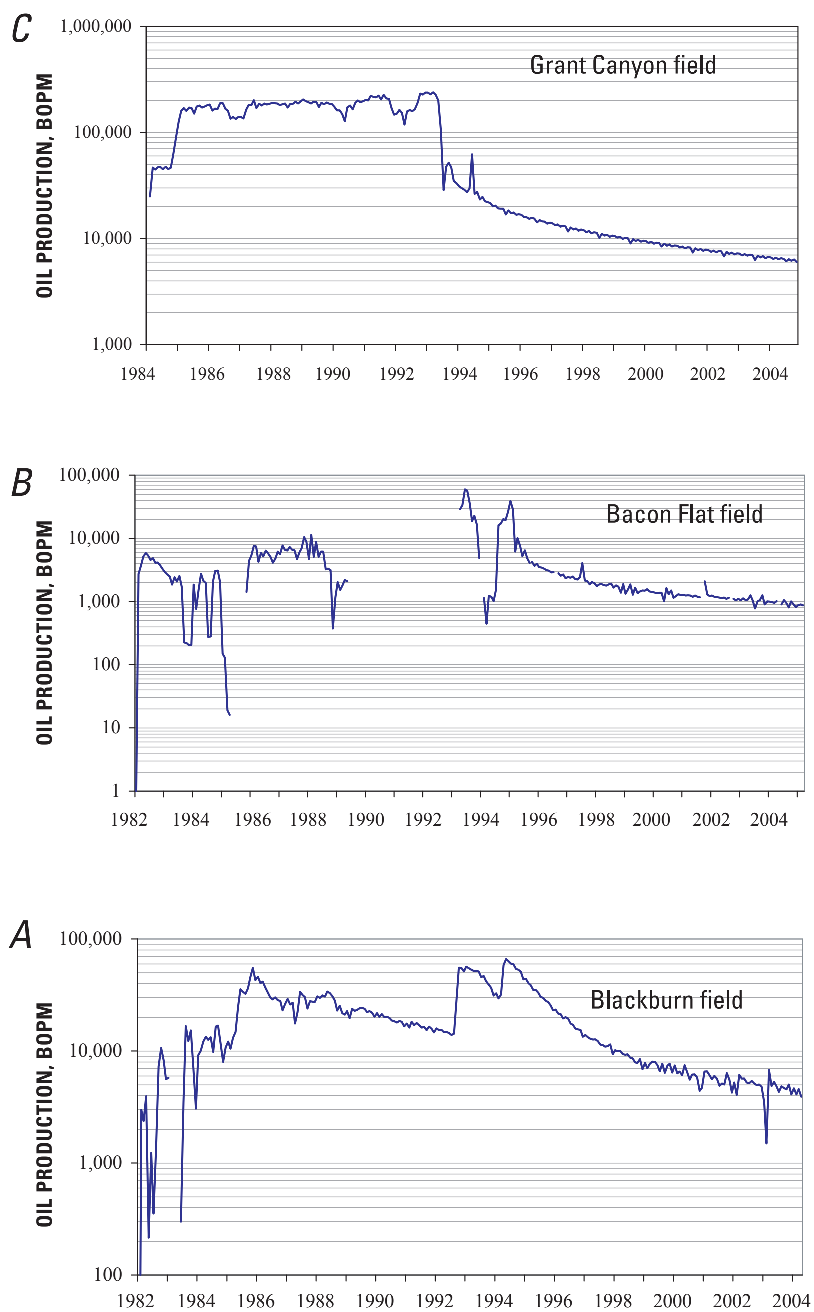


Figure 7. Oil production chart of major carbonate producing fields in the eastern Great Basin. A, Blackburn field; B, Bacon Flat field; C, Grant Canyon field. Data from IHS Energy Group (2004). BOPM, barrels oil per month.

Paleozoic-Tertiary Composite Total Petroleum System

We recognize that there could be more than one petroleum system in the EGB Province because there are multiple potential source and reservoir rocks of various ages and rock types. For assessment purposes, however, fluids from all source rocks were combined into a single Paleozoic-Tertiary Composite TPS as few correlations of source to reservoir hydrocarbons were available at the time of the assessment to identify separate TPSs. In addition, because different source rocks (described in the next section) are commonly juxtaposed, oil and gas from each one could possibly accumulate in the same reservoir.

Source Rocks

Several published geochemical databases of source rocks in the Paleozoic-Tertiary Composite TPS were evaluated, and each analysis was ranked and sorted by total organic carbon (TOC). Formations or groups (described in the next section) that have an average TOC greater than 0.5 percent were included as potential source rock (table 1). The number of samples to calculate a mean TOC for each formation may vary; therefore, direct comparison of formations as to quality of source rock should be done with caution. We did not normalize or perform a robust statistical analysis of the reported data.

Western Assemblage (Rocks of the Antler Allochthon)

Western Assemblage (WA) source rocks were part of the Antler allochthon—a group of Cambrian through Devonian base-of-slope to deep-basin strata that are time equivalents to continental margin carbonates to the east. The assemblage was thrust eastward some 50 to 100 mi in Early Mississippian time as older over younger stacked nappes—the north-south-trending Roberts Mountain thrust (RMT) was the youngest and easternmost thrust (Johnson and Pendergast, 1981; Roberts and others, 1958; Speed and Sleep, 1982). Exposed rocks of the WA are between the RMT and the Golconda thrust to the west (Poole and others, 1992, their plates 3–5), a span of approximately 60 mi.

The WA consists of several formations including (in ascending order) the Preble, Vinini, Comus, Valmy, and Woodruff Formations and the Slaven Chert, collectively called rocks of Roberts Mountain allochthon in figure 3 (Poole and Claypool, 1984). Lithologies include chert, graptolitic shale, sandstone, siltstone, and minor limestone, and bedded tuff, presumably deposited in a rift or ocean basin and on the adjacent continental slope. The chert, shale, and limestone are mostly in exposures in southern Nevada; quartz content increases to the north (Poole and Claypool, 1984).

The maximum original thickness of the Antler allochthon was about 16,000 ft, but Pennsylvanian erosion thinned the unit considerably, especially to the east and possibly to the west. In Pine Valley (fig. 1), the average present day thickness is only about 3,000 ft, which could be the combined result of post-Pennsylvanian erosion and Neogene extensional deformation.

The WA has the highest TOC of any potential source rock in the EGB Province. Analysis of outcrop samples indicates a mean TOC content of 4.35 ± 3.13 percent (table 1). At some locations, WA shales are classified as oil shale (Moore and others, 1983; Garside and others, 1988).

Data from Poole and Claypool (1984) indicated WA source rocks consist mostly of Type III kerogen (fig. 8). Vitrinite reflectance (R_o) and TMAX values indicate a maturity range from immature to overmature, with R_o values ranging from 0.4 to 4 percent or more and a mean of 1.55 ± 0.88 percent. TMAX values range from 416º to 576ºC, with a mean of 459 ± 42ºC (table 1). Poole and others (1983) mapped maximum surface thermal maturity for Paleozoic rocks in most of the EGB using thermal and color alteration indices from Paleozoic conodonts. Their map shows an area where source rocks are overmature, which trends north-south several kilometers west of the Roberts Mountain thrust, and an area where source rocks range from immaturity to average maturity eastward to the RMT. Poole and Claypool (1984) reported that in northern Nevada, low hydrogen indices indicate that the organic matter is overmature and that a significant amount of hydrocarbons has been generated. However, in parts of southern Nevada (west of the RMT), hydrogen indices indicate moderate levels of maturity. In any event, hydrocarbons generated from WA source rocks have not been typed to any produced oil in the province.

Pilot Shale

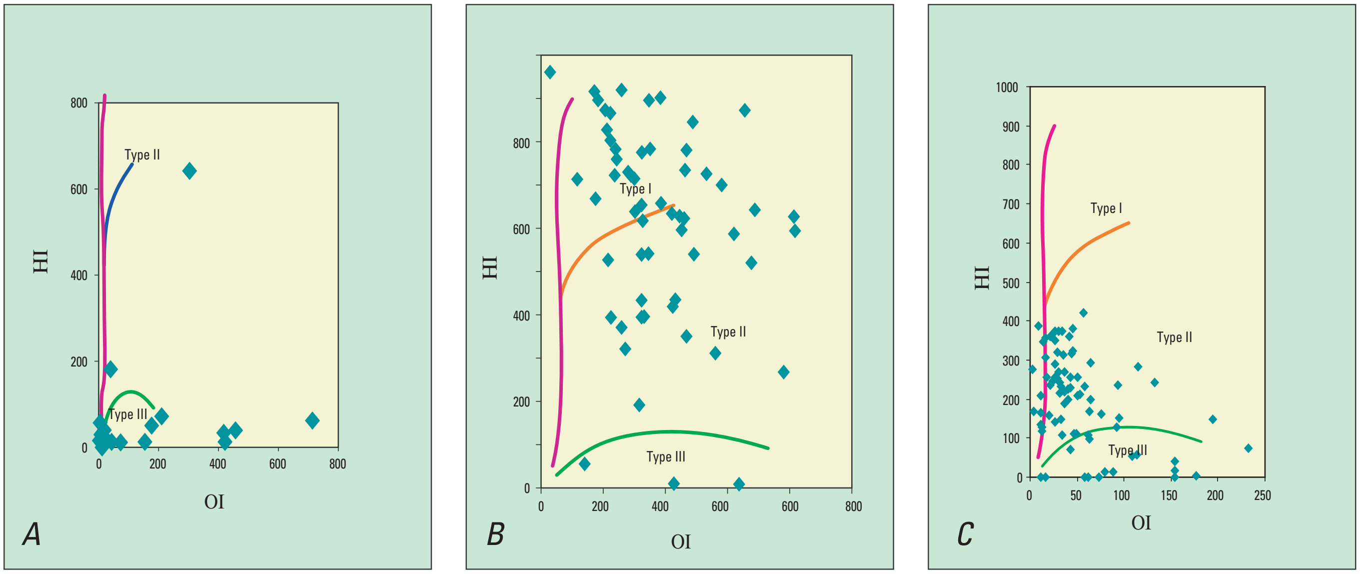
The Pilot Shale (fig. 3) represents the first sustained period of clastic sedimentation after long persistent deposition of thick platform carbonates in the lower Paleozoic. The formation has not received much consideration as a source rock because the overlying Chainman Formation is considered to be the most important source rock in the EGB. Sandberg and Poole (1975) were the first to describe the potential of the Pilot as a viable source rock. It was deposited in the Antler foreland basin, which developed in latest Devonian time and continued into Kinderhookian time. Clastic debris was shed from the Roberts Mountain highland eastward into the basin and onto the stable platform east of the basin, although Sandberg and others (1980) claimed that some of the clastic debris came from the east. The Pilot Shale consists mostly of shale, mudstone, and siltstone with minor amounts of thin limestone beds, which were deposited in a variety of environments including debris flows, turbidites, and fallout

Table 1. Analysis of Eastern Great Basin source rocks.

[Data are mean values per formation for maturation, organic types, and kerogen types. Formations are ranked by total organic carbon (TOC) values in ascending order. Data are tabulated from Nevada Bureau of Mines and Geology (2004), Barker and Peterson (1991), Maughan (1984), Inan and Davis (1994), Palmer (1984), Poole and Claypool (1984), and Poole and Sandberg (1977). Fm, formation; Sh, shale; Mbr, member; Ls, limestone; S1, S2, S3, types of organic matter from Rock-Eval pyrolysis; R_o, vitrinite reflectance; TAI, thermal alteration index; TMAX, temperature of maximum HC generation; HC, hydrocarbon; C_{15}+, total organic extracts; HC/TOC, ratio hydrocarbons to total organic carbon; HI, hydrogen index; OI, oxygen index; SD, standard deviation; g, gram; mg, milligram]

Formation	Age	TOC (percent)		S1 (mg HC/g rock)		S2 (mg HC/g rock)		S3 (mg HC/g rock)		S1/S1+S2 (mg HC/g rock)		S1+S2 (mg HC/g rock)		S2/S3 (mg HC/g rock)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Western Assemblage	Paleozoic	4.35	3.13												
Manning Canyon Fm	Permian	3.06	3.28							0.11		0.41	0.53		
Sheep Pass Fm	Paleogene	2.51	1.87	0.66	0.52	7.54	11.39	2.26	3.15	0.09	0.05	14.26	11.31	2.82	1.55
Phosphoria Fm	Permian	1.66													
Ochre Mtn. Ls	Mississippian	1.60								1.00		0.46			
Elko Fm	Oligocene	1.58	1.25	0.28	0.11	3.08	3.27	0.92	0.69	0.14	0.16			3.75	3.26
Chainman Fm	Mississippian	1.53	1.30	0.29	0.43	3.33	6.48	0.68	0.48	1.08	7.34	5.82	8.87	5.94	10.20
Joana Ls	Mississippian	1.21	1.30	0.44	0.59	2.96	3.14	0.51	0.14	0.08	0.04	0.40		6.39	6.51
Dell Phosphatic Mbr	Mississippian	1.15	1.22												
Pilot Sh	Mississippian	1.09	0.67	0.16	0.09	1.70	3.08	0.52	0.26	0.15	0.09	0.24		2.21	3.11
Mississippian	Mississippian	1.08	0.97	0.20	0.18	0.49	1.28	0.28	0.14	0.34	0.22	0.63		1.40	2.93
Webb Fm	Mississippian	1.02	1.01							0.04	0.06	2.63	4.34		
Indian Well Fm	Oligocene	0.91		0.19		4.69		1.53		0.03				3.06	
Diamond Pk Fm	Mississippian	0.83	0.51	0.19	0.31	1.01	1.99	1.32	1.21	0.06	0.05	0.14	0.03	0.65	0.89

Formation	Age	TMAX (°C)		$C\ 15^+$ (ppm)		HC/TOC		HI		OI		R_o (percent)		TAI	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Western Assemblage	Paleozoic	459	42			2.5		82.8	13.8	22.4	16.20	1.55	0.88		
Manning Canyon Fm	Permian	506								119					
Sheep Pass Fm	Paleogene	472	25	3294	2914	4.03		0.20 360		73.8		0.86	0.17	2.13	0.25
Phosphoria Fm	Permian														
Ochre Mtn. Ls	Mississippian					0.2		0.0		87.5		1.70			
Elko Fm	Oligocene	446	6	2189	1787									2.00	0.00
Chainman Fm	Mississippian	444	30	1691	3095	2	2	111	118	111	89	1.18	0.92	3.37	0.94
Joana Ls	Mississippian	440				0.97	0.80					2.80		3.35	1.20
Dell Phosphatic Mbr	Mississippian														
Pilot Sh	Mississippian	461	60	1392	93							1.37		2.60	0.22
Mississippian	Mississippian	464	25	686	868							1.60	0.88	2.79	0.34
Webb Fm	Mississippian	482	63			0.89		110	94	30	30	4.32			
Indian Well Fm	Oligocene	448													
Diamond Pk Fm	Mississippian	420	26	466	225							1.72	0.08	2.50	0.00



Western Assemblage | Chainman Formation | Elko Formation

Figure 8. Organic matter types based on Hydrogen Index (HI) and Oxygen Index (OI). A, Western Assemblage rocks (from Poole and Claypool, 1984); B, Chainman Formation from Aminoil #1-23 Land Co., Pine Valley, Nevada (from Poole and Claypool, 1984); C, Oligocene Elko Formation (from R.C. Johnson, U.S. Geological Survey, written commun., 2004).

sedimentation. There is an increase in grain size toward the highland, and the formation becomes more carbonate rich to the east into Utah on the stable platform.

The Pilot Shale is divided into three informal units based on fossils, depositional history, and areal distribution. The lower part of the Pilot was deposited unconformably over the Guilmette Formation (fig. 3) in a rapidly subsiding foreland basin. The unit contains organic rich carbonate mudstones, thin limestones, shales, and carbonate debris from underlying carbonate erosion. The middle unit is considered to be Late Devonian (Sandberg and Poole, 1975) and consists of a thin basal sandstone overlain by thin, organic-rich shales and tan siltstones. The upper unit, of Kinderhookian age, consists of a few thin, organic-rich shales interbedded with deepwater limestones, siltstones, and cherts; it is unconformably overlain by the Joana Limestone.

The Pilot Shale ranges in thickness from a zero edge to more than 1,000 ft. The lower unit is laterally extensive and is about 1,000 ft thick in the deepest part of the foreland basin but decreases from there to a zero edge to the east and west. The two overlying units are relatively thin and discontinuous.

Total organic carbon (TOC) in the Pilot Shale is relatively lean compared to other known source rocks in the United States. In table 1, the listed mean TOC content is 1.09 ± 0.67 weight percent, although data from Sandberg and Poole (1975, their figure 6) showed a few TOC values from a single location to be over 2.0 percent and one value over 3.0 percent in the lower unit. However, they (Sandberg and Poole, 1975) reported most TOC values to range from 0.2 to 1.7 percent. In addition, they speculated that the Pilot (at their sample locality) was in the early to middle stage of maturation and that some TOC values were reduced because of hydrocarbon expulsion. Table 1 lists the mean R_o as 1.37 percent, indicating overmaturity with respect to oil generation; TAI and S1/S1+S2 indicate undermature, and TMAX indicates overmature conditions. Although maturity level data are apparently conflicting, all values indicate the Pilot Shale is or was in the oil generation window.

Joana Limestone

The Mississippian Joana Limestone (fig. 3) is similar to the Pilot Shale in being a potential source rock but is also commonly considered as a potential reservoir as well. The formation is subdivided into two third-order stratigraphic sequences that are internally composed of seven parasequences (Giles, 1996). The upper part of the Pilot and the basal part of the Joana record a shoaling upward, westward-prograding sequence from basin to slope during a sea level fall, then retrograding eastward into platform margin carbonates during a relative sea level rise (Cook and Corboy, 2004; Giles, 1996). The contact with the overlying Chainman Formation varies from a conformable surface (Sandberg and others, 1980) to unconformable where the Chainman is in direct contact with the underlying Pilot (Cook and Corboy, 2004). The Joana was probably deposited in a shallowing-upward environment with thin, interbedded siliciclastics and carbonates at the base; but near the top, oolitic grainstones and packstones and crinoid grainstones are prevalent. As the foreland basin began to subside, carbonate production waned and clastic sedimentation again began to dominate, as recorded by the overlying Chainman Formation.

The Joana Limestone is interpreted to be an elongated north-south-trending carbonate bank deposit (Gutschick and others, 1980). In places its contact with the Chainman Formation is unconformable as its original thickness and distribution are speculative. Several measured composite sections in central Nevada show a thickness range from 80 to 440 ft (Giles, 1996), and the American Hunter #1 Black Jack Springs Federal well (White Pine Valley) penetrated an apparently unfaulted interval of about 500 ft.

Part of the Joana Limestone should be classified as source rock, although any expelled oil has not been typed to known produced oil in the EGB. Table 1 shows the following mean values: TOC, 1.21 percent (standard deviation, 1.30 percent; R_o, 2.8 percent; and thermal alteration index (TAI), 3.35, indicating overmature; TMAX and S1/(S2 + S3) indicate undermature. Gilmore (1990) reported conodont alteration indices (CAI) in the Joana near Ely, Nevada, of 1.5 to 2, which indicate a temperature in the oil generation window. Although maturity-level data are apparently conflicting, the Joana is probably similar to the Pilot Shale and Chainman Formation as to maturity and generation levels. Therefore, all or parts of the Joana are considered as having been in the oil generation window, although clear evidence is lacking.

Chainman Formation and Equivalents

The Mississippian Chainman Formation is considered the main source rock for the EGB because (1) it is a thick, regionally extensive, organic-rich shale, and (2) its expelled oil has been typed to several producing fields in Nevada (Meissner and others, 1994). Similar to the Pilot Shale, the Chainman was deposited in a north-south-trending Antler foreland basin and craton platform system. The basin consists of a deep flysch trough in front of the Roberts Mountain allochthon, where coarse clastic material of the Diamond Peak Formation was deposited in proximal areas and clastic mudstone and siltstone of the Chainman farther to the west (Poole and Claypool, 1984). The rocks grade eastward into a starved basin in which carbonate and organic-rich phosphatic beds of the Deseret Limestone were deposited. Strata on the cratonic platform in western Utah and farther to the east consist mostly of carbonates, including the Great Blue Formation and equivalents. Following a period of erosion, most of the EGB became a stable carbonate platform with the deposition of the overlying Pennsylvanian Ely Limestone.

Thickness of the Chainman Formation and equivalents ranges from more than 6,000 ft in the foreland basin trough and Oquirrh basin of northwestern Utah to a few hundred feet in southeastern Nevada and southwestern Utah. However, true thicknesses are difficult to predict because structural deformation commonly has repeated or removed section. At some surface localities more than 5,000 ft is exposed; some well logs show 3,000 ft or more of section, but thicknesses are commonly less than 3,000 ft.

Because the Chainman Formation is an important petroleum source rock, it has been widely sampled for geochemical analysis; analytical data are listed in table 1. In some cases, the analyses are listed as Mississippian instead of Chainman. Because well log inspection could not always identify the specific Mississippian formation that was sampled and analyzed, such data are listed separately. Table 1 indicates that data listed for the Chainman show a mean TOC content of 1.53 ± 1.30 percent, and the data listed for Mississippian show a mean TOC content of 0.77 ± 0.84 percent. The difference in TOC values is probably because the sampled formations listed as Mississippian, although time equivalent to the Chainman, were not deposited in an environment conducive to the preservation of organic matter, such as slope deposits (turbidites) or thin carbonates. Table 1 lists a summary of Chainman Formation source rock parameters. A hydrogen index/oxygen index plot (fig. 8) of a well in Pine Valley indicates that organic matter in the Chainman consists of Type II kerogen.

Newark Canyon Formation

The Lower Cretaceous Newark Canyon Formation has limited exposure in Nevada. The formation unconformably overlies Permian rocks and is unconformably overlain by Tertiary sedimentary and volcanic rocks (fig. 3). It consists of limestones, conglomerates, sandstones, siltstones, and shales (Nolan and others, 1956) deposited in freshwater lakes, as indicated by assemblages of gastropod and plant fragments. Typically, the upper part is composed of conglomerates as much as 50 ft thick (Haworth, 1979), although in some exposures there are only shale and thin bedded mudstone, carbonaceous limestone, and medium-grained sandstone (Smith and Ketner, 1976).

The Newark Canyon Formation ranges in thickness from 1,500 to 4,000 ft in some surface exposures (Smith and Ketner, 1976; Nolan and others, 1956) but is rarely that thick in the subsurface because of attenuation faulting during Neogene extension and subsequent erosion. Mullarkey and others (1991) performed source rock evaluations of the Newark Canyon Formation in north-central Nevada on samples from 3 wells and 66 outcrop sites. In the Cortez Range, 115 ft of limestone and calcareous shale had an average TOC of 2.5 percent, with a mixture of Type II and Type III kerogen (hydrogen indices 7–424 mg hydrocarbon/g TOC). The correlative section in the Pinon Range averaged 8 percent TOC (ranging to as much as 23.5 percent) of Type I and Type II kerogen (hydrogen indices 457–912 mg hydrocarbon/g TOC). Subsurface samples are similar to the Cortez Range samples for organic content and kerogen type. The Newark Canyon Formation is undermature to mature with respect to petroleum generation with an average TMAX value of 440ºC, although other maturity data did not match maturity levels inferred from TMAX in some cases. The combined TOC data indicate that the formation is potentially an excellent petroleum source rock, and saturated hydrocarbon distributions confirm that it was deposited in a lacustrine environment.

Sheep Pass Formation

The Sheep Pass Formation is Late Cretaceous to Eocene in age (Winfrey, 1960; Brokaw and Shawe, 1965; Fouch and others, 1979; Good, 1987). In places, it unconformably overlies the Pennsylvanian Ely Limestone, Permian rocks, and (or) the Newark Canyon Formation. The formation is unconformably overlain by Oligocene Garrett Ranch Group volcanics (Murray and Bortz, 1967), the Elko Formation, and (or) younger valley-fill sediments (fig. 3). The formation is regionally extensive, covering about 1,800 mi^2.

Winfrey (1960) divided the Sheep Pass Formation into six members, which consist of Pennsylvanian and Permian limestone and sandstone clasts and fragments, black shales, massive to bedded sandstones, ostracode and pelecypod-rich shale and siltstones, and thin, freshwater limestone. Individual beds can be traced for long distances, which indicate a stable lacustrine environment with consistent water depths.

Thickness of the Sheep Pass Formation ranges from a zero edge to more than 3,300 ft; average is less than 3,000 ft in Railroad Valley. Wells used in the burial history analysis have thicknesses ranging from 500 to 900 ft, and in the Grant Range, east of Railroad Valley, 400 to 700 ft of section was measured (Winfrey, 1960; Brokaw and Shawe, 1965).

Data show a mean TOC of 2.51 ± 1.87 percent (table 1), which indicates a good to excellent source rock. Claypool and others (1979) reported that Sheep Pass Formation extractable organic matter compares favorably with oil produced from the Eagle Springs field in Railroad Valley (fig. 9). However, Poole and Claypool (1984) showed that some of the oil produced from the Trap Spring field falls between Sheep Pass extract and Chainman Formation extract, indicating a possible mixing of the two oils. Burial history modeling (see section "Burial History Modeling Results") indicates that the Sheep Pass in the deepest part of Railroad Valley is currently in the early stages of oil generation and has expelled only 3 percent of its oil. Source rock data (table 1) indicate inconsistent maturity results for the Sheep Pass with mean TAI, R_o, and TMAX values of 2.13 (early maturity), 0.86 percent (mature), and 472ºC (overmature), respectively; S1/S1+S2 data indicate an immature generation stage. Data (table 1) also show that the source rock contains Type III kerogen, although Claypool and others (1979) reported that the oil is a sapropelic Type II kerogen.

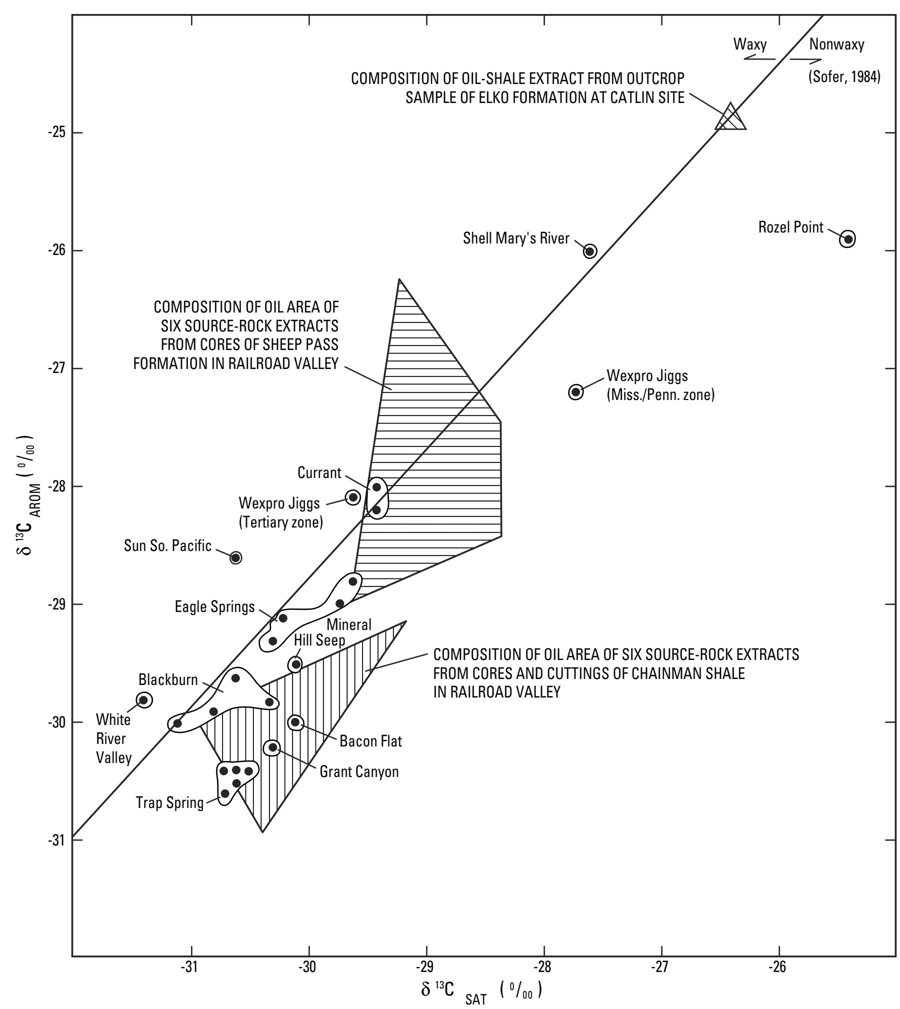


Figure 9. Carbon isotopic composition of C13 saturated (SAT) and aromatic (AROM) hydrocarbon fractions of crude oils and source rock extracts in the eastern Great Basin (from Poole and Claypool, 1984).

Elko Formation

The Elko Formation, late Eocene or early Oligocene in age (Smith and Ketner, 1976), is unconformably overlain by Oligocene volcanics and the Indian Well Formation (fig. 3). It is possibly equivalent to the upper part of the Sheep Pass Formation (Fouch and others, 1979), but correlation is uncertain. The formation consists of lacustrine strata, minor amounts of tuffaceous material, thin bedded limestone, chert, conglomerate, and black shales, some of which are oil shale grade (Smith and Ketner, 1976; Smith and Howard, 1977; Solomon and Moore, 1982a, 1982b). Areal distribution of the Elko extends across a radius of tens of miles surrounding Elko, Nevada (Smith and Ketner, 1976).

A 1,200 ft section near Elko described by R.C. Johnson (U.S. Geological Survey, unpub. data, 2004) shows a tripartite division: a lower part of high-energy sand and conglomerate beds; a middle section of interbedded oil shale, coal, and mudstone; and an upper section of dolomitic mudstone. Other measured sections range in thickness from a few hundred feet to more than 2,500 ft (Smith and Ketner, 1976). Solomon and others (1979) suggested that the strata represent a vertical succession from lake margin carbonate mudflats, to an intradeltaic and deltaic system, and to organic-rich shales deposited in an open, deepwater lacustrine environment.

The Elko Formation is composed of two distinctly different organic rich lithologies: a lignitic, gas-prone siltstone and an oil shale. Both are thermally immature (Palmer, 1984), although the Wexpro Co., # 1 Jiggs well, Huntington Valley, east of Pine Valley (fig. 1), produced minor amounts of gas. The siltstones have vitrinitic kerogen and pristane/phytane ratios slightly greater than 1.0 and similar ratios in shales less than 0.5. Hydrous pyrolysis of solvent-extracted oil shale produced waxy oil-like bitumen whose mature biomarkers and stable carbon isotopic composition resemble the unreacted oil shale. Table 1 shows a mean TOC of 1.58 ± 1.25 percent, although individual mean values are higher in the Elko area with TOCs of about 3.4 percent. The data indicate that the formation is a good to excellent source rock with Type I and Type II kerogen (fig. 8) capable of generating large amounts of oil and gas where thermally mature. Other data (table 1) indicate conflicting ranges of maturity, with TAI data indicating immaturity, TMAX data indicating peak maturity, and S1/S1+S2 data indicating an early stage of generation.

Indian Well Formation

The Oligocene Indian Well Formation (Smith and Ketner, 1976) unconformably overlies the Elko Formation in most localities and is overlain by Oligocene and Miocene ignimbrites and Neogene valley fill (fig. 3). The formation is a lacustrine deposit with some interbedded fluvial and flood plain deposits (Solomon and others, 1979). Strata include water-laid tuff, conglomerate, flat to crossbedded sandstone and siltstone, and minor limestone and calcareous mudstone. Clasts of Devonian Oxyoke Canyon Sandstone and Mississippian Chainman and Diamond Peak Formations are present both in sandstone and in conglomerate beds (Smith and Ketner, 1976). The formation thicknesses range from a few hundred feet to more than 3,500 ft (Smith and Ketner, 1976; Solomon and Moore, 1982a, 1982b). The Indian Well Formation appears to have limited value as a source rock in the EGB, although data are sparse. The formation has a mean TOC of 0.91 percent (table 1), but published data are also too limited to determine generation and maturation status.

Source Rocks in the Sevier Thrust Belt

The newly discovered Covenant field in the Sevier thrust belt near Richfield, Utah, produces from the Jurassic Navajo Sandstone (fig. 3), although there may also be production from overlying units (Moulton and Pinnell, 2005). Source of the produced oil is speculative. Moulton and Pinnell (2005) reported a Paleozoic source, on the basis of two marine biomarkers indicating the oil to be Mississippian in age, which is possibly mixed with an overmature condensate that may have originated from Lower Cretaceous rocks in the footwall of a deep-seated thrust. If the source for Covenant field oil is Mississippian, it could have migrated from eastern Nevada, but it is possible that local Mississippian rocks have sufficient TOC to generate oil (fig. 10). The Jurassic Arapien Shale, which overlies the Navajo Sandstone, is also a possible source, although lithologic descriptions from Sprinkel (1982) of the Arapien in central Utah did not identify it as a source rock but indicated it to be an excellent seal to oil leaking from underlying reservoirs.

Reservoir Rocks

Paleozoic Carbonates

An extensive stable platform developed over the EGB from Cambrian through Devonian time, which included a broad continental shelf to the east and slope and oceanic basin to the west. More than 15,000 ft of platform carbonates were deposited across a rifted North American continent until the Antler orogeny altered the shape of this megaplatform into a foreland basin for clastic deposition (Cook, 1988).

The depositional model for the carbonates in the EGB Province includes several environmental settings, from east to west: (1) supratidal, resulting in interbedded clastics, carbonate, and evaporates; (2) shelf or platform resulting in shallow to moderate water depth, grainstones, packstones, and mudstones; (3) platform margin, resulting in high-energy reefs and bioclastic buildup deposits; (4) slope, resulting in turbidites, debris flows, and mudstone; and (5) deepwater basin, resulting in calcareous mudstones, cherts, shales, and pelagic chalks. Shelf and shelf margin deposits have

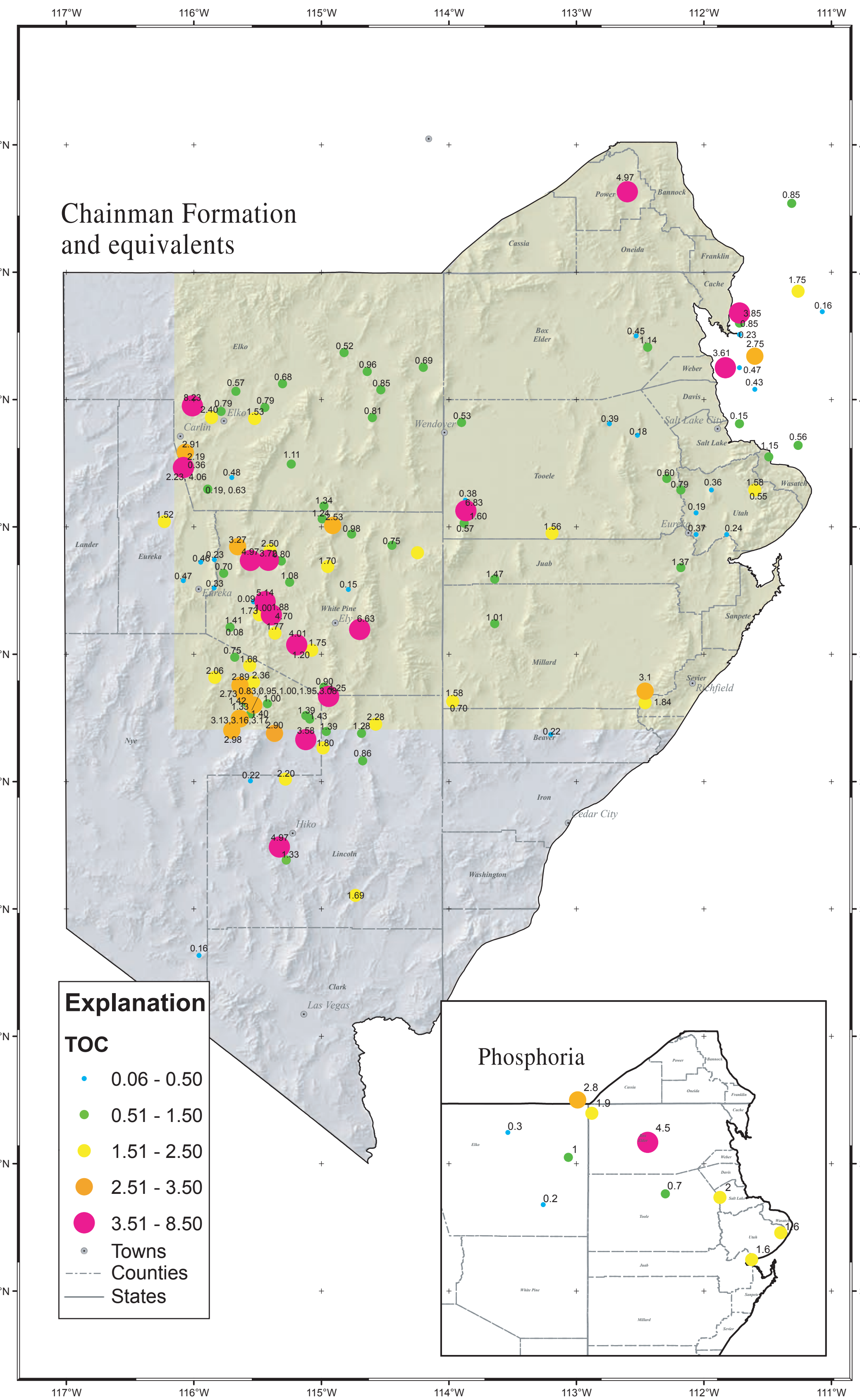


Figure 10. Mean total organic carbon (TOC) content of samples from wells and outcrop for the Mississippian Chainman Formation and equivalent rocks and the Phosphoria Formation.

the best potential as reservoir-quality rocks because they contain abundant grains and bioclastic material that can be diagenetically altered to increase porosity and permeability. Carbonate apron and slope deposits are potential reservoirs, but most turbidites and debris flows in the western part of the province are too thin to be viable reservoirs.

Cambrian-Ordovician-Silurian

Cook and Corboy (2004) described 10 shoaling-upward third-order depositional sequences as part of the Paleozoic platform carbonate system in western North America (fig. 3). The first five sequences represent third-order aggrading and prograding cycles—the first four are prograding westward and the fifth is retrograding eastward. From Cambrian through Silurian time the platform/slope interface trended north-northeast just west of the present-day RMT and just east of the western boundary of the EGB Province (fig. 1). Sequences 1–5 include the Whipple Cave Formation, Pogonip Group, Eureka Quartzite, Ely Springs Dolomite, Laketown Dolomite, and Lone Mountain Dolomite, respectively (fig. 3).

Each of the first five sequences is consistent with being a typical carbonate depositional system that includes supratidal facies in western Utah, shelf or platform bioclastic shallow-water carbonates in eastern Nevada, and platform margin and slope deposits in central Nevada. Some of the sequences are fully to partly eroded in southwestern Utah.

The reconstructed composite thickness of the five sequences ranges from a zero edge in southwestern Utah to more than 16,000 ft in either eastern Nevada or in the Oquirrh basin in western Utah (Poole and Sandberg, 1977; Poole and others, 1977; Ross, 1977; Stewart and Suczek, 1977). The thickness of each sequence averaged about 3,000 ft.

Because most of the platform carbonates are shoaling-upward, third-order sequences, the tops are prone to diagenetic alteration including karsting, dissolution, dolomitization, and brecciation, all of which can increase porosity and permeability. Handford and Loucks (1993) showed that even tops of fourth-order cycles can have diagenetic alteration, although at a smaller scale than third-order cycles. Geophysical log analysis from several wells in Nevada show that most of the carbonate sequences have a sonic log measured porosity of less than 8 percent, but the tops of sequences commonly have porosities that range from 10 to 40 percent (fig. 11). Cook and Corboy (2004) reported that the upper part of the Laketown Dolomite (Silurian) near the Utah-Nevada border is karsted, with subaerial leaching of reef and stromatoporoid bioclastics. Read and Zogg (1988) described 15 ft of core from the Guilmette Formation (depositional sequence 10) in the Apache Corporation, #1–21 Grant Canyon discovery well and reported little matrix porosity but large secondary porosity, which could also indicate large secondary permeability.

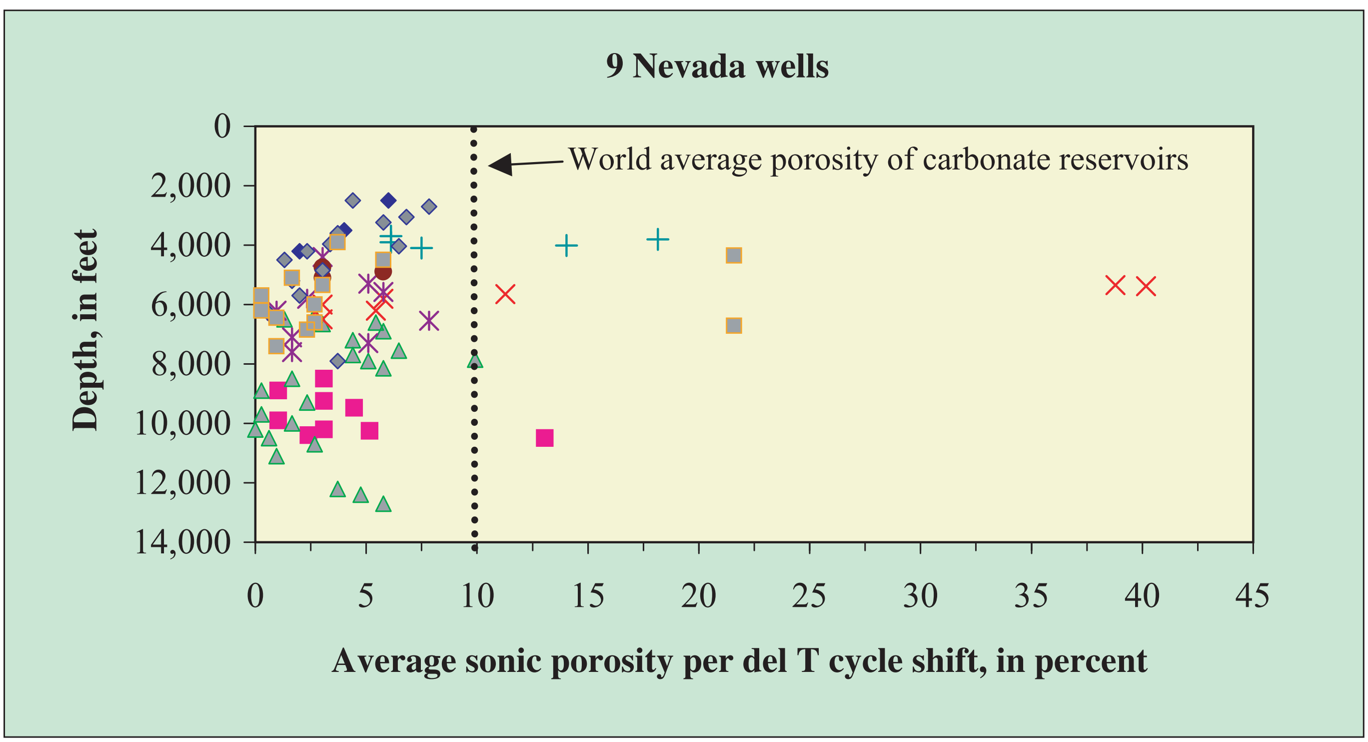


Figure 11. Well depth and sonic-derived porosity for Paleozoic carbonate rocks. Most values plot less than 6 percent porosity. Higher values indicate secondary porosity near the tops of carbonate sequence boundaries. Each set of symbols refer to one individual well. All wells are located in eastern Nevada.

Devonian

Five depositional sequences, 6 through 10 (fig. 3), represent several Devonian environments similar to the Cambrian, Ordovician, and Silurian Systems (Cook and Corboy, 2004). All sequences are shoaling upward, with the upper part of the sequence aerially or subaerially exposed to karsting and diagenetic alteration. Most, if not all, oil production from carbonates in the EGB Province is from the upper parts of Devonian sequences. Sequence 6 consists of platform carbonates of the lower parts of the Sevy Dolomite and Water Canyon Formation, and the platform margin includes the Beacon Peak Dolomite (Cook and Corboy, 2004). Sequence 7 consists of the upper parts of the Sevy Dolomite and Water Canyon Formation, and the platform margin includes the Beacon Peak Dolomite.

Sequence 8 includes the Oxyoke Canyon Sandstone, a thick, siliciclastic and dolomitic sandstone deposited unconformably on the Beacon Peak Dolomite and Sevy Dolomite in a marginal marine environment. The formation averages about 300 ft thick but was reported to be over 1,000 ft thick in the Pinon Range, Nevada (Kendall, 1975). Dead oil in the Oxyoke Canyon was reported in the Mobil Oil Petan Trust F–12–19–P well, at the north end of Pine Valley (fig. 1). Seaward to the Oxyoke Canyon, the Sadler Ranch Formation was deposited as a thin continental margin reef and biostrome buildup.

Sequence 9 includes the Simonson Dolomite and the lower part of the Guilmette Formation as shelf carbonates, and the Sentinel Mountain Dolomite and the Bay State Dolomite as platform margin deposits (fig. 3). Within the Guilmette Formation, there may be 3 fourth-order shoaling upward cycles all of which have an increase in bioclastic material at the top with possible diagenetic alteration. In the Confusion Range of western Utah, however, there is no evidence of dissolution or karsting of the Guilmette (Cook and Corboy, 2004). At Grant Canyon field, Read and Zogg (1988) reported that a thick section of vuggy and fractured dolomite of the Simonson Dolomite was penetrated in the Apache Corp. #1–21 Grant Canyon well and showed the producing interval was part of a west verging rotated block with internal contacts dipping steeply to the east. As a result, the interpreted oil/water contact cuts formation boundaries, implying that secondary porosity could have formed after Neogene rotation. At the same field, Hulen and others (1994) showed flat-lying carbonates in a horst block of undifferentiated Guilmette Formation and Simonson Dolomite with an oil/water contact parallel to formation boundaries, implying that secondary porosity could have developed after deposition but before Neogene rotation. Timing of porosity development relative to structural deformation and timing of oil generation and migration are important considerations when developing a strategy for field development. Read and Zogg (1988) described 15 ft of Guilmette core from the #1–21 Grant Canyon discovery well and reported the diagenetic sequence as early dolomitization, then early dissolution followed by later stages of dolomitization, fracturing, and brecciation, and still later by quartz cementation.

Sequence 10 includes the middle and upper parts of the Guilmette Formation, consisting of shelf carbonate deposits, and the Devils Gate Limestone consisting of platform-margin deposits. All diagenetic effects that were described in Sequence 9 may be applied to Sequence 10. The Pilot Shale unconformably overlies the Guilmette and Devils Gate (fig. 3).

Tertiary Lacustrine Rocks

Tertiary lacustrine formations can include both reservoir and source rocks. The Elko Formation, for example, can be divided into three units. The lower unit consists of sandstone and conglomerate deposited in a high-energy environment, with good porosity and permeability; this unit can be laterally discontinuous, possibly creating a stratigraphic trap. The overlying middle unit is a good source rock including oil shale and can also act as a seal to an underlying reservoir. The upper unit is a dolomitic mudstone, which can also act as a seal to hydrocarbon migration.

All lacustrine formations including the Newark Canyon, Sheep Pass, Elko, and Indian Well Formations (fig. 3) that were described in some detail in the section on source rocks, have common characteristics reflecting similar depositional environments, but with varying proportions of fresh-water carbonate, shale, sandstone, and volcanic debris.

To date, production from Tertiary lacustrine reservoirs is limited, but there is production from the Sheep Pass Formation in the Eagle Springs field, and formerly there was production from Currant field; both fields are in Railroad Valley (fig. 1). There was limited production from the Indian Well Formation in Pine Valley (Tomera Ranch and Three Bar fields) and from the Elko Formation in Huntington Valley to the east (Wexpro Corp., #1 Jiggs). Future undiscovered resources from Tertiary lacustrine reservoirs maybe limited because (1) Tertiary source rocks in Neogene valleys are generally isolated from external heat sources and are too shallow to be in the oil generation window, (2) migration of oil from Mississippian source rocks into Tertiary lacustrine reservoirs may be limited because of permeability barriers and unconnected pathways (unlike volcanic reservoirs), and (3) Tertiary source rocks and reservoirs are limited to basins (valleys) and are not part of the deeper subthrust geometry (unlike Mississippian source rocks).

Tertiary Volcanic Rocks

Volcanic rocks form a large part of the Neogene rock sequence: ash-flow tuffs and basalt flows from major calderas in eastern and central Nevada. A single tuff flow is generally divided into three zones: (1) a lower layer with low grain density (less than 2.0 g/cc, grams per cubic centimeter), commonly poorly indurated and low fracture intensity; (2) a middle layer with high grain density (2.5 g/cc), well indurated and with high fracture intensity; and (3) an upper layer that is similar to the lower layer (Riehle and others, 1995). Commonly there are two or more stacked flows, although parts of the underlying flow may be eroded by the emplacement of the overlying flow, which can create a complex zonal distribution of porosity and permeability, both vertically and laterally.

Thickness of the volcanic section can vary greatly because of Neogene erosion and faulting. The variability creates erosional and stratigraphic traps such as Trap Spring and Eagle Springs fields in Railroad Valley (fig. 1). In the EGB, the thickness of ash flow tuffs in Railroad Valley can be more than 9,000 ft (French, 1994b), but maps from Cook (1960) show restored thicknesses of volcanic rocks that range from less than 1,000 ft to more than 3,000 ft.

Some parts of ash-flow tuffs are good petroleum reservoirs, as demonstrated by production data from the Trap Spring field (fig. 12), because their hydraulic and petrophysical properties can be similar to those of siliciclastic rocks (Nelson and Anderson, 1992; Schlumberger Limited, 1987). However, there are some differences—for example, individual grains are usually angular; therefore, pore throats may be slotted and tend not to be as connected as pore throats in siliciclastics containing more rounded grains. In addition, the tuffs commonly have abundant authigenic clays and zeolites that can decrease pore connectivity and matrix permeability.

Tertiary basalt reservoirs produced minor amounts of oil from the Rozel Point and West Rozel fields in north-central Utah. The reservoir is shallow (less than 2,500 ft depth) and averages about 100 ft in thickness (Bortz, 1983). Reservoir storage and delivery are almost entirely from fractures with low matrix porosity, but basalts commonly have well-connected fractures with a good petroleum delivery system. Poorly developed traps, low reservoir storage, and inefficient seals (top and lateral) are probably the main reasons for the low volumes of trapped oil.

Pennsylvanian and Permian

The Pennsylvanian and Permian Systems are important to the generation and accumulation of petroleum in the EGB Province. Most workers agree, for example, that these rocks provided significant overburden for the burial of Mississippian source rocks deep enough for generation at the end of the Permian and (or) into the Triassic (Poole and Claypool, 1984; Barrett, 1987; Barker and Peterson, 1991; and Inan and Davis, 1994). Oil expelled from Mississippian source rocks in the Late Permian and the Early Triassic may have been stored in Pennsylvanian and Permian reservoirs and later released as the reservoirs began to be eroded during the Mesozoic. Pennsylvanian and Permian erosion may have also reduced the thermal stress on Mississippian source rocks, temporarily stopping the oil generation process.

In Early Pennsylvanian time, a passive platform carbonate shelf developed over most of the EGB. Some minor volumes of clastics were shed eastward from the eroding Antler highland in central Nevada but the area would eventually be onlapped by rising sea levels. Clastics were also shed from the northeast-trending Piute uplift in southwestern Utah, but most of the area was covered by carbonates of Ely Limestone, Bird Spring Formation, and the Callville Limestone in Nevada and the Oquirrh Formation in Utah (Peterson, 2001).

In Middle to Late Pennsylvanian time, several areas started to be uplifted including the expansion of the Piute highland northward into west-central Utah, the Tintic highland

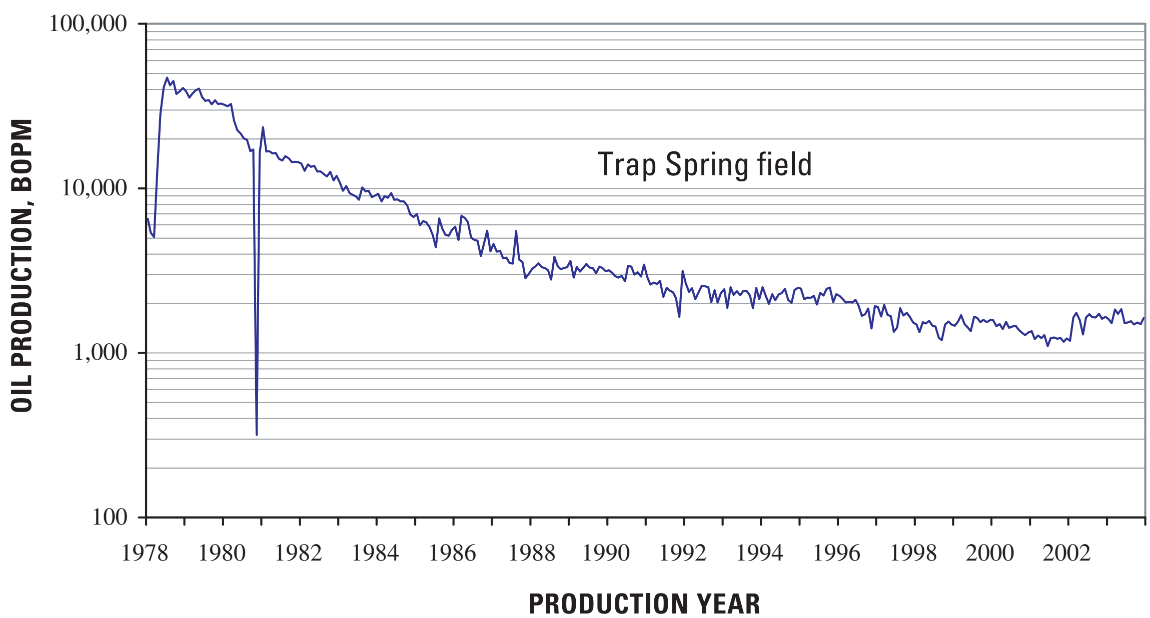


Figure 12. Oil production plot for volcanic reservoirs in the Trap Spring field, Railroad Valley, Nevada. BOPM, barrels oil per month.

in east-central Nevada, and the Oquirrh-Uinta highland in northeastern Nevada and northwestern Utah. These highland areas shed limited siliciclastics into adjacent lowlands, but not enough to starve carbonate sedimentation over most of the EGB.

In Early to mid-Permian time, highland areas were eroded, and deposition in the EGB consisted mostly of shelf carbonates to the west and siliciclastics to the east, which now compose the Pequop Formation and the Arcturus Group, respectively (fig. 3). In Late Permian time, two narrow bands of sediment accumulated, one consisting of carbonates and siliciclastics that rimmed a northeast-trending highland in southwestern Utah and extended into the Uinta highland, and the other consisting of siliciclastics trending north-south through Eureka, Nevada. Most of the carbonate strata in southern Nevada are called the Park City Group or the Spring Mountain Formation, and in northwestern Utah they form the Phosphoria Formation or the Park City Group, which includes the Kaibab and Toroweap Formations. The phosphatic and organic-rich Meade Peak Member of the Phosphoria Formation is an excellent source rock (Maughan, 1984; Peterson, 2001, his figure 27) generating oil that could have migrated (through Permian or Triassic rocks) to the southern part of the Sevier thrust system (fig. 6), although migration routes may be limited.

The original thickness of the combined Pennsylvanian and Permian section extended from over 30,000 ft in the Oquirrh basin to more than 15,000 ft in the foreland basin east of the RMT, and totaled less than 1,000 ft in southwestern Utah (Peterson, 2001). Currently, parts of the Upper Pennsylvanian section are missing, although the Permian section is thickest in northern Nevada and northwestern Utah, but the section was later eroded in southern Nevada and in the Sevier thrust area.

Mesozoic

The following descriptions of Mesozoic strata provide a generalized view of complex stratigraphic relations and the erosional events that occurred during that depositional period. Mesozoic units could be an important part of the EGB TPS, but it is unknown whether oil generated from Mississippian source rocks migrated into or through Mesozoic beds. The recent oil discovery in the Jurassic Navajo Sandstone in south-central Utah, in the Sevier thrust system, invokes numerous questions about timing of oil generation and migration paths in that part of the TPS.

In Early Triassic time, a narrow northeast-trending shallow seaway centered near Ely, Nevada; in it were deposited carbonates and clastic rocks of the Moenkopi Formation (fig. 3): the clastic material was shed from the Sonoma orogenic highland to the west and northwest and from highlands to the east and southeast. A Late Triassic sea level drop created widespread exposure of the continent, with the development of numerous fluvial systems (Chinle Formation) that drained to the north-northwest (Dubiel, 1994).

The Early and Middle Jurassic, dominated by arid environments, accumulated thick eolian deposits including Wingate, Kayenta, and Navajo Formations of the Glen Canyon Group (Peterson, F., 1994) and the overlying Carmel Formation. Most Jurassic formations appear to have uniform thickness over most of the southern EGB (Blakey, 1988), although true thicknesses are difficult to reconstruct (Peterson, F., 1994). The Navajo Sandstone thickens considerably in southwestern Utah and southeastern Nevada, even though there is an unconformity at the top of the Navajo (Peterson, F., 1994). Although the Carmel Sandstone is a thick Jurassic unit, parts were truncated in the Early Cretaceous, resulting in a regional unconformity.

During Late Jurassic time, increased uplift in western and central Nevada reversed stream direction from northwest to east and northeast, resulting in the deposition of the Morrison Formation (Peterson, F., 1994). The Morrison consists of thick fluvial sandstones, variegated shales and mudstones, and lacustrine beds; the fine-grained strata could form a seal or barrier to fluid flow in the deeper stratigraphic sections, although the present-day extent of the Morrison is limited to the eastern edge of the Sevier thrust belt.

Cretaceous

The Cretaceous in the EGB was characterized by the presence of a large, mostly flat continental landmass adjacent to the epicontinental seaway to the east. As described earlier in the section, one of the Lower Cretaceous Newark Canyon Formation source rocks, land-surface depressions, which produced large lacustrine lake deposits, formed intermittently from the extension and collapse of highland areas of the Sevier hinterland (Vandervort and Schmitt, 1990). Other than areally restricted lake deposits, the Cretaceous provided little overburden that affected the Paleozoic-Tertiary TPS.

Traps

Petroleum traps in the EGB are dominated by structural types in the form of numerous folds, thrusts, and thrust-related structures that resulted from largely compressional deformation throughout the upper Paleozoic and Mesozoic and from Neogene basin and range extension. Indeed, most of the producing fields in the province are from horsts, half horsts, hanging-wall blocks, and folds associated with differential fault movement—features detected by seismic, gravity, and magnetic surveys that provide the principal means of exploration in the region. Volcanic reservoirs, however, may have a stratigraphic component associated with trapping. Different fracture characteristics within a volcanic flow unit could control reservoir quality; unfractured rock, for example, could be a top or lateral seal that is a barrier to flow. In addition, top or lateral truncation of a reservoir could form a stratigraphic trap. Tertiary lacustrine reservoirs, such as in the

Elko Formation, have the potential to trap oil in highly porous and permeable reservoirs that are lateral to, or beneath, low permeability rocks.

Seals

Seals to oil and gas reservoirs are a matter of considerable uncertainty in the EGB. In the Neogene Basins AU, low-permeability valley fill sandstones, mudstones, and siltstones form seals to underlying carbonate reservoirs and to volcanic reservoirs. The effectiveness of these types of seals is questionable due to considerable vertical and lateral variation in valley fill sediments. Commonly, there is oil stain in the valley fill section above or near a producing reservoir, which could imply leakage through the seal. For example, the Cenex Oil, #8–15 Federal well near San Spring field in Railroad Valley (fig. 1; Gabb, 1994) had oil shows in valley fill near the reservoir/valley fill contact; and Montgomery and others (1999) described free oil recovery in carbonate slide blocks encased in valley fill in the Ghost Ranch field, also in Railroad Valley. In Pine Valley only one of four new field discoveries has produced economic volumes of oil to date (2006), possibly because some of the seals leak and are not preserving economic quantities of oil. However, the sealing capacity of the valley fill at Grant Canyon field must be efficient, considering the large volume of oil in place, the large oil column, and the strong water drive. The distribution of an effective seal from valley fill strata could be approached using probabilistic methods—that is, the chance that a reservoir has a particular type of lithology to form an effective seal can be mathematically defined.

In the Neogene Ranges and Other Structures AU, thrust faults, normal faults, slide blocks, and extensional deformation created stratigraphic disorder among source rocks, reservoir rocks, and seals. As a result, predicting the stratigraphic position of seals is difficult but may be aided probabilistically by geophysical means. Timing of oil generation and migration is also problematic because there is large uncertainty in the burial history of source rocks at any one location.

Thermal History

In the EGB, several potential sources may have contributed to the heating of source rocks, including heat flow from mantle and crustal sources and hydrothermal fluids associated with gold deposits, geothermal systems, and volcanic activity.

Heat flow is a function of the heat generated in Earth's interior from radioactive decay and is measured by the product of the geothermal gradient and the thermal conductivity of the rock. Heat flow in the EGB is a complex system arising from regional effects of Neogene extension and volcanism (Blackwell, 1983). The province has an average heat flow of 85 ± 10 mW/m^2 (milliwatts per square meter) but contains subprovinces of both higher and lower heat flow (Blackwell, 1983). The northern part of the province is characterized by high heat flow (>104 mW/m^2), called the Battle Mountain High (BMH), along with several hot spots along the western and northeast province margins (fig. 13). There is also a large area of low heat flow (<60 mW/m^2), called the Eureka Low (EL), in the central part of the province. There is speculation that the EL is a shallow (depth less than 10,000 ft), hydrologically controlled heat sink associated with interbasin ground water flow in Paleozoic carbonates (Sass and others, 1971; Garside and Davis, 1994). However, in the EL area, the lateral distribution of carbonate sedimentation and the effective lateral hydraulic connection (flow velocity) of the carbonate units should be heterogeneous, similar to other parts of the Basin and Range, especially in Nevada. If true, that would contradict the theory of a hydrologically controlled heat sink. Therefore, it is possible that the heat flow of the EL is a normal condition and the BMH is the anomaly. Temperatures may be too high in the deep parts of many basins in the BMH area to preserve generated petroleum, although we did not construct burial history diagrams to model petroleum generation potential.

Geothermal

Numerous reports describe geothermal systems in the EGB, although few are known with fluid temperatures greater than 100ºC (the approximate minimum temperature to start oil generation). Geothermal systems in the EGB that affect petroleum maturation and generation systems were most prominently recognized in Railroad Valley, where Hulen and others (1994) postulated that a localized, moderate temperature geothermal system influenced oil generation and accumulation at the Grant Canyon and Bacon Flat fields. Their conceptual model showed that pre-Holocene water infiltrated exposed bedrock from nearby mountain ranges, penetrated deep into the subsurface through faults and fractures, and was then heated. As the ground water heated, its density decreased, causing it then to ascend through nearby faults and fractures and to raise the temperature of adjacent source rocks enough to generate oil. The process dissolved calcium carbonate, which enhanced the porosity and permeability of the reservoir and deposited mineral matter above the reservoir, which created a seal. The sealing capacity of the precipitated mineral matter may explain the apparent effective seal at the Grant Canyon field.

Hulen and others (1994) reported drillstem test temperatures from wells at Grant Canyon and Bacon Flat fields as high as 255ºF (124ºC), a 5.0ºF/100 ft (90ºC/km) gradient and showed that the temperature profile fit a typical convective geothermal system. They compared temperatures from two Railroad Valley wells, located some distance away from the Grant Canyon field, that plotted between gradients of 1.06º to 1.7º/100 ft (19º to 30ºC/km), which Hulen and others (1994) described as a normal geothermal gradient for

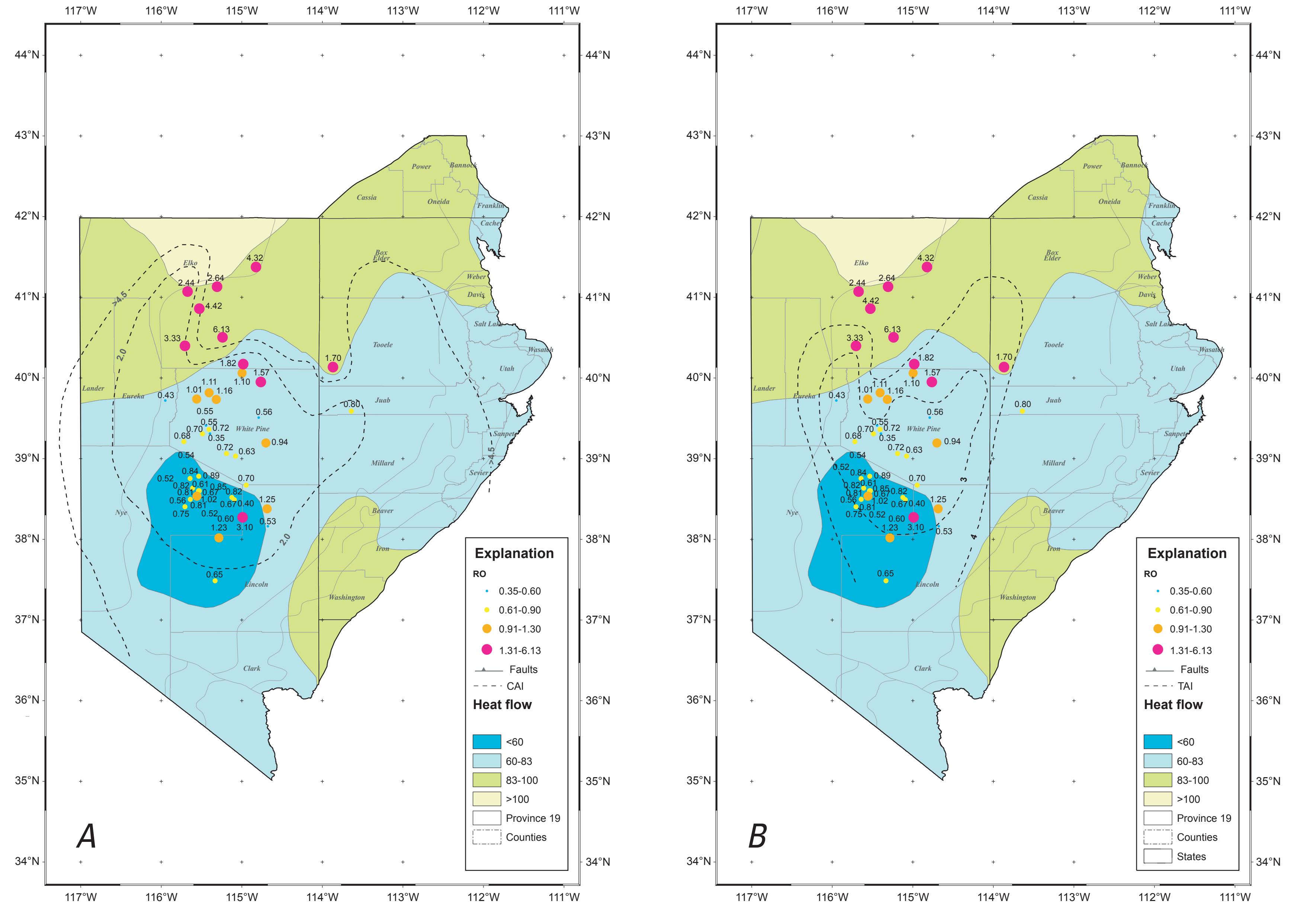


Figure 13. Source rock maturation characteristics of the Mississippian Chainman Formation in the eastern Great Basin. Includes mean values for heat flow and vitrinite reflectance (R_o) derived from wells or outcrop. A, conodont alteration index (CAI); B, thermal alteration (TAI). Note that CAI and TAI patterns are similar and generally tract heat flow and Ro. Maps show areas of heat flow anomalies including the Battle Mountain high (northeastern Nevada) and the Eureka low (southeastern Nevada). Heat flow data from Blackwell (1983), R_o and TAI data from Nevada Bureau of Mines and Geology (2004), CAI data from Harris and others (1980).

Railroad Valley.

Goff and others (1994) reported that geothermometer data from Grant Canyon, Bacon Flat, and Blackburn fields showed that reservoir equilibration temperatures reached 120ºC, which put the Chainman Formation source rock into the oil generation window. Our burial history model of the Grant Canyon area corroborates Goff's interpretation, although our model showed that little oil was generated locally but had migrated from deeper in the basin. Geothermal systems in the EGB could generate enough heat to raise the temperature of source rocks into the oil generation window, but there are only few reported systems and they are probably localized; therefore, geothermal heat is probably not a significant contributor to the expulsion and accumulation of hydrocarbons yet to be discovered in the province.

Hydrothermal Systems Associated with Carbonate-Hosted Gold Deposits

Linear trends of sediment-hosted gold deposits are present in northern Nevada, and the gold emplacement process may have locally produced temperatures that could help mature petroleum source rocks. The hydrothermal systems were thought to be active in the Eocene and were largely controlled by deep-seated, Precambrian crystalline basement structures possibly related to accreted terrane boundaries (Grauch, 1998). Recent research indicated emplacement temperatures of 150 to 250ºC, low pH, and low-to moderately saline fluids of mixed meteoric and magmatic or metamorphic origin (Woitsekhowskaya and Peters, 1998). The uncertainties associated with the effectiveness of this type of heat source are (1) whether or not hydrothermal fluids would reach potential source rocks, inasmuch as they are stratigraphically above the hosted carbonates; and (2) whether or not heat would dissipate at a slow rate away from fluid pathways to elevate temperatures to oil generation levels. Some situations may exist for the right mix of fluid temperature and stratigraphic position to produce sufficient heat in potential source rocks to generate oil, but probably only on a local scale.

Burial History Model

Several burial history models are published concerning oil generation and accumulation in Railroad Valley and Pine Valley, including Barrett (1987), Barker and Peterson (1991), French (1994b), and Inan and Davis (1994). Our goal was to integrate the results of previous work with our study to provide a better understanding of the burial and thermal history of the region, and to estimate timing of petroleum generation and expulsion, and to help in the assessment of undiscovered oil and gas resources.

The purposes of our burial history modeling were to estimate the timing of petroleum generation, estimate expulsion amounts from source rocks in Railroad Valley, and help develop a conceptual model of maturation and generation history that can serve as an analogue for source rocks in other valleys in the EGB. Our approach was to calibrate or match measured R_o to simulated R_o for each burial history site or well (fig. 14). Even though measured R_o matched simulated R_o, the resulting generation and expulsion outputs were not unique but represent one possible outcome of the modeling process. However, all input values were consistent with geologic conditions, which lent confidence that model results were reasonable. Model results are summarized in table 2.

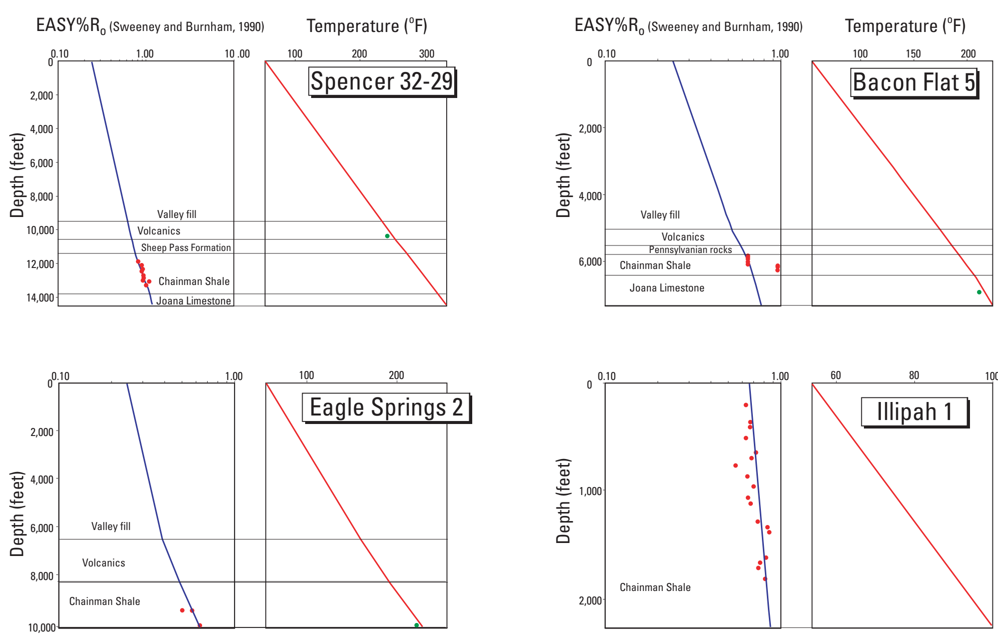


Figure 14. PetroMod1D templates showing model calibration data from burial history sites (named wells) in the eastern Great Basin. ºF, degrees Fahrenheit.

Table 2. Timing of oil generation for base of Type II Chainman source rock, except where designated.

[Start and peak of oil generation are represented by transformation ratios of 0.01 and 0.50, respectively. Values are in Ma (millions of years ago). Values in brackets are transformation ratios at the present time. Fm, formation; R_o, vitrinite reflectance; ºF, degrees Fahrenheit; ft, feet; %, percent; <, less than]

Burial history location	Oil generation Start	($\%R_o$)	Peak	($\%R_o$)	Depth at start of oil generation, ft	Temperature at start of oil generation (°F)
Spencer Federal #32–29, Chainman Fm	6	0.69	2 [0.99]	0.92	9,750	253
Spencer Federal #32–29, Sheep Pass Fm	2	0.69	0 [0.03]	0.75	10,100	
Eagle Springs Unit 2	no oil					
Bacon Flat #5	<1	0.68	0 [0.013]	0.69	6,250	251
Illipah #1	267	0.69	0 [0.33]	0.87	9,710	233

Methods

One-dimensional burial history modeling was completed as part of the assessment process to understand timing and conditions of oil generation, migration, and accumulation. The commercial code PetroMod1D, version 8.0, of Integrated Exploration Systems (IES), Germany, was used to model three wells in Railroad Valley (fig. 15) and one well in the White Pine Range, about 30 miles north of Railroad Valley (table 3). We used a standard method for all wells, including hydrous pyrolysis derived kinetics for Type II kerogen (WD–S of Lewan and Ruble, 2002), and all models were calibrated to R_o and present-day temperature data. There was uncertainty in reconstructing stratigraphic thicknesses because of the complex depositional and erosional history of the region. Initial estimated thicknesses and erosional intervals were based on published data and then were adjusted during model calibration; final input parameters are listed in table 4. Some sensitivity analysis was done to determine what input parameters had the greatest influence on modeling outcomes. In all cases Pennsylvanian and Permian thickness and paleo-heat flow were the most sensitive.

Illipah #1

The Northwest Exploration Company #1 Illipah well located about 30 miles north of Railroad Valley was completed as a dry hole in 1980. The well penetrated Chainman Formation from the surface to about 2,265 ft. Thicknesses of eroded intervals of Pennsylvanian and Permian strata and Tertiary volcanic rocks were estimated based on data from Peterson (1994). Data for the burial history model included (1) 2,265 ft of Chainman Formation, plus 9,000 ft of Pennsylvanian and Permian rocks that were subsequently eroded during Paleozoic time; and (2) assumed thicknesses of 500 ft of the Sheep Pass Formation and 800 ft of Tertiary volcanic rock, both of which were eroded by the end of Oligocene time. No valley fill was deposited in this area.

Table 3. Well Information used for burial history modeling.

[ft, feet; GL, ground level, KB, kelly bushing; T., township; R., range; sec., section; N., north; E., east; NV, Nevada]

Well name	Operator	Location	Elevation (ft)	Total depth (ft)	County, State
Spencer-Federal #32–29	Milestone Petroleum Inc.	T. 9 N., R. 57 E., sec. 29	4,757 GL	14,505	Nye, NV
Eagle Springs Unit #2	Shell Oil Co.	T. 7 N., R.56 E., sec. 2	4,721 KB	10,182	Nye, NV
Bacon Flat #5	Northwest Exploration Co.	T. 7 N., R. 56 E., sec. 17	4,726 GL	7,300	Nye, NV
Illipah #1	Northwest Exploration Co.	T17N, R58E, sec. 11	6,851 GL	7,154	White Pine, NV

Table 4. Data used to generate burial history curves. Well information is in table 3.

[Thermal gradient used to calibrate model is given for each location. Fm., Formation; ft, feet; PermPenn, Permian/Pennsylvanian; ºF, Fahrenheit; %, percent; ss, sandstone; sh, shale; ls, limestone; slst, siltstone; dolo, dolomite; Ma, millions of years ago]

System/Series, Unit or Event	Present thickness (ft)	Age range (Ma)	Deposited, later eroded (ft)	Amount of erosion (ft)	Generalized lithology					
					%ss	%sh	%ls	%slst	%tuff	%dolo
Illipah No. 1 (thermal gradient 20°F/1,000 feet)										
Erosion		23 - 0		1,300						
Volcanics	0	34 - 23	800					70	30	
Sheep Pass	0	65 - 34	500		50			50		
Erosion		251 - 65		9,000						
Permian	0	299 - 251	5,500		50		50			
Pennsylvanian	0	318 - 299	3,500		50		50			
Chainman	2,265	348 - 318				100				
Spencer No. 32–29 (thermal gradient 19°F/1,000 feet)										
Valley fill	9,510	13 - 0			50			50		
Erosion		23 - 13		2,200						
Volcanics	1,058	34 - 23	2,200					70	30	
Sheep Pass Fm.	828	65 - 34				50		50		
Erosion		248 - 65		4,000						
PermPenn	0	318 - 248	4,000		50		50			
Chainman Fm.	2,454	348 - 318				100				
Joana Ls.	655	360 - 348					70			30
Eagle Springs Unit No. 2 (thermal gradient 17°F/1,000 feet)										
Valley fill	6,510	13 - 0			70			30		
Erosion		23 - 13		1,200						
Volcanics	1,800	34 - 23	1,200					70	30	
Erosion		40 - 34		200						
Sheep Pass	0	65 - 40	200			50		50		
Erosion		248 - 65		3,400						
PermPenn	0	318 - 248	3,400		50		50			
Chainman Fm.	1,867	348 - 318				100				
Joana Ls.	6	349 - 348					100			
Bacon Flat No. 5 (thermal gradient 23°F/1,000 feet)										
Valley fill	5,030	13 - 0			50			50		
Erosion		23 - 13		2,314						
Volcanics	486	34 - 23	2,314					70	30	
Erosion		40 - 34		500						
Sheep Pass	0	65 - 40	500			50		50		
Erosion		251 - 65		4,000						
Permian	0	299 - 251	4,000		50		50			
Pennsylvanian	283	318 - 299					100			
Chainman Fm.	636	348 - 318				100				
Joana Ls.	865	360 - 348					70			30

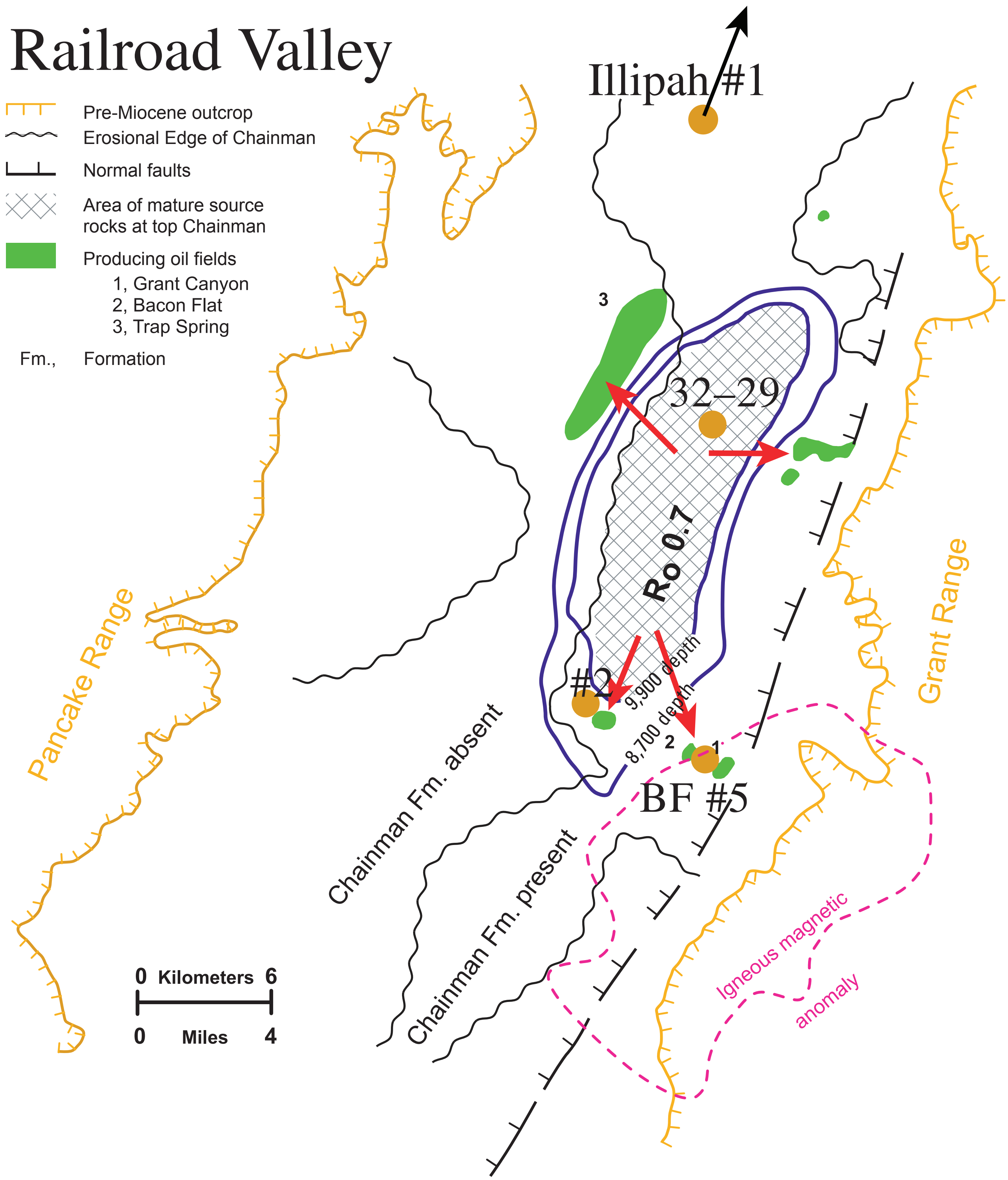


Figure 15. Oil generation region (crosshatch) for the Mississippian Chainman Formation in Railroad Valley, Nevada. Wells on map (orange dots were used in burial history modeling. Red arrows show generalized oil migration direction from oil generation window.

Measured R_o data used in calibration ranged from 0.56 to 0.87 percent. Initial heat flow values were estimated based on Barrett (1987); final values ranged from 46 to 67 mW/m^2.

Spencer #32–29

The Milestone Petroleum Inc. #32–29 Spencer Federal well, completed in1985, is located in an area containing one of the thickest Tertiary valley fill sections in Railroad Valley. The well was completed as a dry hole, but a production test recovered 86 ft of free oil, most of which was typed to the Chainman Formation, but a small amount possibly came from the Sheep Pass Formation (French, 1994b). Meissner (1995) considered the Chainman Formation at this location to have been in the middle of the oil generation window. Input thicknesses and erosion amounts were estimated using formation tops listed in French (1994b). Data used for the burial history included (1) 2,454 ft of Chainman Formation; (2) 4,000 ft of Pennsylvanian and Permian rocks, which were eroded after Permian time; (3) 828 ft of Sheep Pass Formation; (4) 3,258 ft of Tertiary volcanics, of which 2,200 ft were then eroded by the end of middle Miocene time; and (5) 9,510 ft of Neogene valley fill. Initial heat flow values were estimated from Barker and Peterson (1991), Barrett (1987), and Blackwell (1983); final values ranged from 50 to 67 mW/m^2.

#2 Eagle Springs Unit

The Shell Oil Co. # 2 Eagle Springs Unit well was completed as a dry hole in 1954; it is located about 3 mi northwest of Grant Canyon and Bacon Flat fields and about 1.5 mi north of the San Spring field in Railroad Valley. The well is just south of Meissner's (1995) projected oil generation window for the Chainman Formation. Well data indicate minor core and mud log hydrocarbon shows in Tertiary volcanics and the Chainman Formation, and petroliferous odors were detected in Paleozoic carbonate rocks. Drill-stem testing recovered only mud and water. Present-day thickness and erosion data were estimated from formation tops listed in the well report and from Peterson's (1994) reconstruction of depositional and erosional events of the Phanerozoic. Burial history included (1) 1,867 ft of Chainman Formation; (2) 3,400 ft of Pennsylvanian and Permian strata, all of which was eroded after Permian time; (3) 200 ft of Sheep Pass Formation, which was subsequently eroded prior to Tertiary volcanic deposition; (4) 3,000 ft of Tertiary volcanics of which 1,200 ft was subsequently eroded by the end of middle Miocene time; and (5) 6,510 ft of Neogene valley fill. Initial heat flow values were estimated from Barker and Peterson (1991), Barrett (1987), and the regional heat flow map of Blackwell (1983); final values ranged from 46 to 63 mW/m^2.

Bacon Flat #5

The Northwest Exploration Co. #5 Bacon Flat well, completed as a dry hole in 1981, is located between Grant Canyon and Bacon Flat fields on the east side of Railroad Valley. Well records indicate significant oil shows, but amount and type are unknown. Thickness and erosion data were estimated from formation tops listed in well reports and from Peterson's (1994) reconstruction of deposition and erosion events of the Phanerozoic. Data for the burial history model included (1) 636 ft of Chainman Formation; (2) 283 ft of Pennsylvanian; (3) 4,000 ft of Permian, all of which was eroded after Permian time; (4) 500 ft of Sheep Pass Formation, which was eroded prior to Tertiary volcanic deposition; (5) 2,800 ft of Tertiary volcanics, of which 2,314 ft was eroded by the end of middle Miocene time; and (6) 5,030 ft of Neogene valley fill. Initial heat flow values were estimated from Barker and Peterson (1991), Barrett (1987), a regional heat flow map of Blackwell (1983), and Hulen and others (1994); final values ranged from 46 to 105 mW/m2. Heat flow for this well was modeled similarly to other wells pre-2.5 Ma but was increased to 105 mW/m^2 at 2.5 Ma. The sharp heat increase in heat flow was used in the model because of a reported rising granite diapir (Francis and Walker, 2001) in the Pliocene preceded by a thermal event in Miocene time that reset the K/Ar age of the original Late Cretaceous intrusion (Fryxell, 1988; Francis and Walker, 2001), or from hydrothermal circulation described in Hulen and others (1994).

Burial History Model Results

Illipah #1

Model results indicate that oil generation started at 267 Ma (middle Permian) with an R_o of 0.69 percent, a depth of 9,710 ft, and a temperature of 233ºF (112ºC) (converted to a thermal gradient of 2.04ºF/100 ft, 36.7ºC/km) for the base of the Chainman Formation (fig. 16). Model results indicate that at peak oil generation only 33 percent of the oil had been expelled, which occurred at 188 Ma (Early Jurassic) at a depth of 8,600 ft, with an R_o of 0.87 percent and a temperature of 206ºF (97ºC). Oil generation decreased and eventually stopped because of erosion of the Pennsylvanian and Permian section, in middle Mesozoic time, when temperatures dropped below the critical oil generation temperature of 100ºC. The Chainman Formation, at this location, was probably not buried deep enough to reenter the oil generation window at a later time.

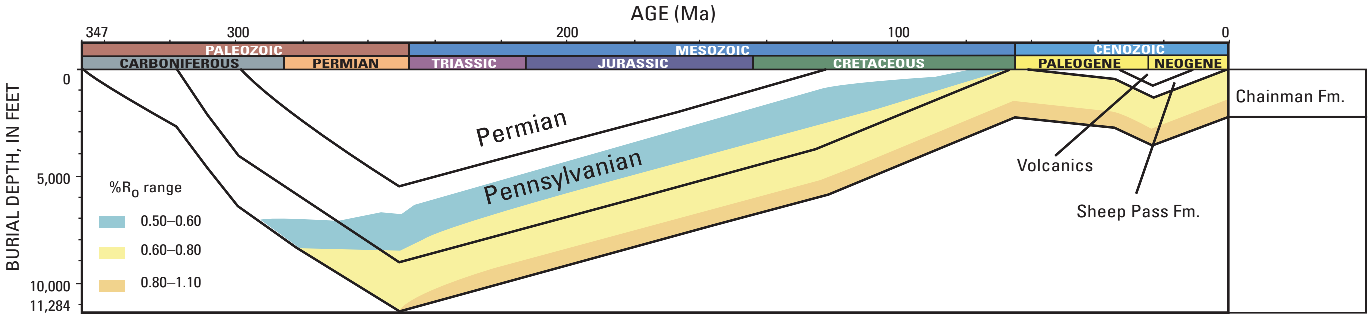


Figure 16. Burial history plot for Illipah #1 well. Data used as model input are presented in table 4. Location shown in figure 14 and listed in table 3.

Spencer Federal #32–29

The simulation calculated the petroleum expulsion threshold at 6 Ma (upper Miocene) but reached peak generation at 2 Ma from the base of the Chainman Formation (fig. 17) at a depth of 9,750 ft, with an R_o of 0.69 percent and a temperature of 253ºF (118ºC). At peak oil generation, the R_o was 0.92 percent, at a depth of 12,540 ft and a temperature of 300ºF (149ºC). Currently, the model indicates that the Chainman Formation, at this location, is at a transformation ratio of 0.99, meaning that the formation has expelled virtually all available oil. The simulation calculated an R_o of 0.6 percent for the Chainman Formation in Early Triassic time but reached temperatures needed to expel oil at 6 Ma, after Railroad Valley was formed.

The simulation calculated the petroleum expulsion threshold at 2 Ma at an R_o of 0.69 percent and at a depth of 10,100 ft for the Sheep Pass Formation (fig. 17). Model results indicate that currently the Sheep Pass has expelled about 3 percent of its oil, with an R_o of 0.75 percent. Of the four simulated wells in this assessment, the #32–29 Spencer is the only well where the Sheep Pass was in the oil generation window.

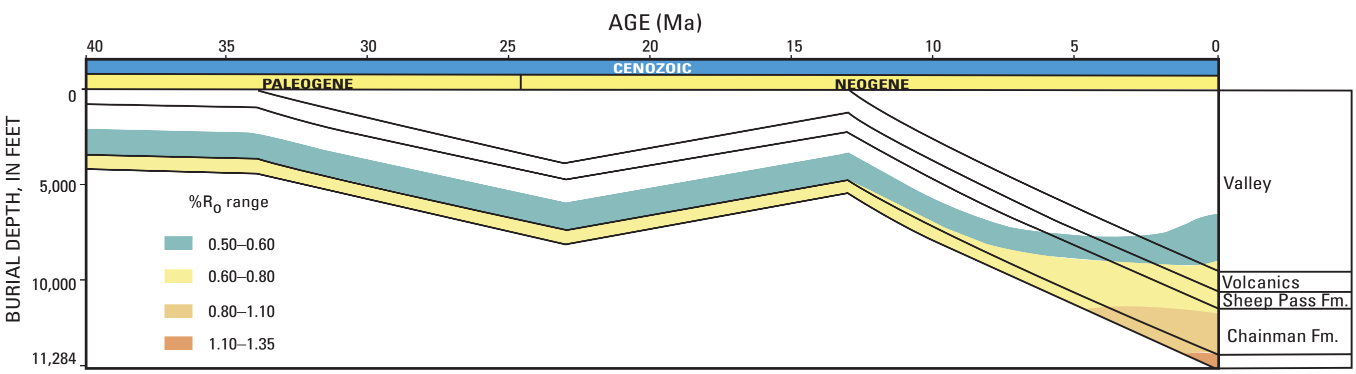


Figure 17. Burial history plot for Spencer Federal #32–29 well. Data used as model input are presented in table 4. Location shown in figure 14 and listed in table 3.

Eagle Springs Unit 2

Simulation results showed that the base of the Chainman Formation did not reach the oil expulsion window (fig. 18). The model calculated a maximum R_o of 0.56 percent (same as the measured value) but did not reach the expulsion threshold, which is consistent with well data and measured R_o data from the Chainman Formation at this location.

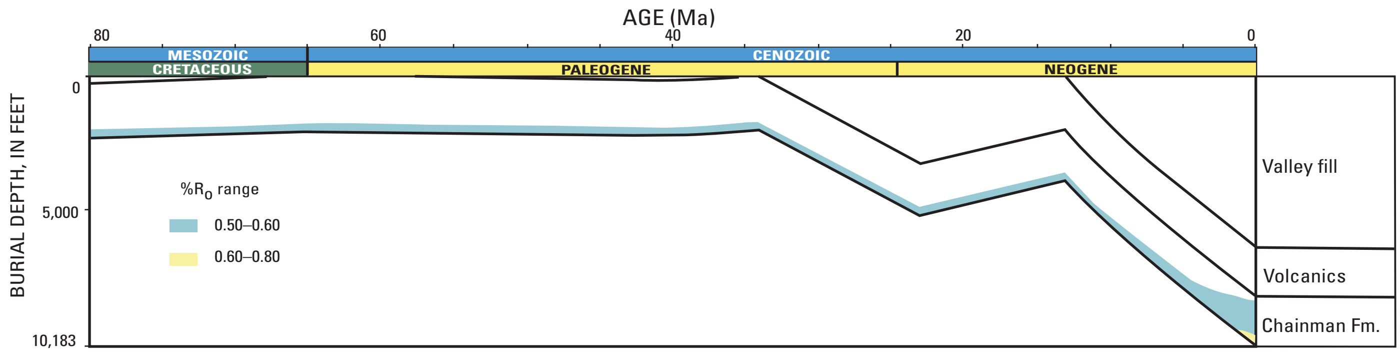


Figure 18. Burial history plot for Eagle Springs #2 Unit well. Data used as model input are presented in table 4. Location shown in figure 14 and listed in table 3.

Bacon Flat #5

The simulation calculated the oil expulsion threshold at less than 1 Ma for the base of the Chainman Formation (fig. 19). At initial expulsion, the R_o was 0.68 percent and the temperature was 251ºF (124ºC) at a depth of 6,250 ft. Model results indicate that currently the Chainman Formation has expelled about 1.3 percent of its oil and has an R_o of 0.69 percent. The R_o values for this well are inconsistent with the normal burial and thermal increase from valley fill overburden, assuming a constant valley fill thickness. Therefore, an external heat source was needed to increase temperatures to place the Chainman into the oil generation window. If the model is correct and only 1.3 percent of its oil has been expelled from source rocks at that site, most of the Chainman oil at Grand Canyon field must have migrated from deeper in the basin.

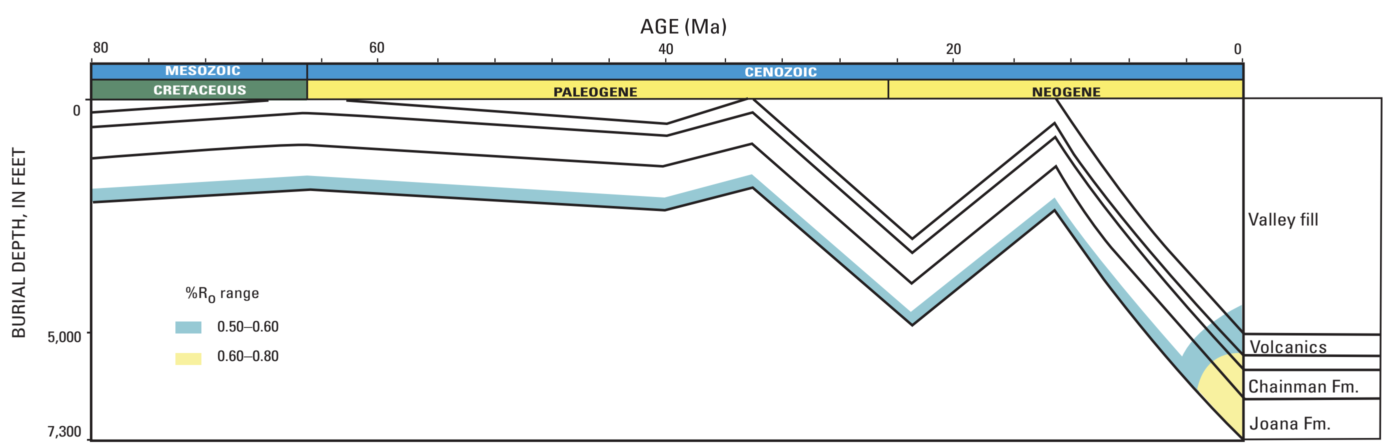


Figure 19. Burial history plot for Bacon Flat #5 well. Data used as model input are presented in table 4. Location shown in figure 14 and listed in table 3.

Summary of Burial History

Burial history reconstructions generated several possible scenarios for petroleum generation and migration in the Paleozoic-Tertiary Composite TPS because of uncertainty in assigning original depositional thicknesses, stratigraphic intervals removed by erosion, and heat flow values. Model outcomes showed that the Mississippian Chainman Formation first entered the oil generation window during the Permian but that generation stopped in late Mesozoic time and that generation was renewed where the formation was later buried deep enough in Neogene basins. The Chainman at or near the surface today may have first entered the oil window as a result of external heat sources. However, as previously explained, that method does not appear to be a significant part to the overall heat equation. The most plausible heat source was that resulting from deep burial by Pennsylvanian and Permian rocks. Generation of Chainman oil during Permian time is consistent with evidence from outcrop studies. For example, Poole and Claypool (1984), on the basis of geologic mapping several areas in eastern Nevada, reported oil shows in Chainman exposures and also that the strata were mature relative to oil generation. In addition, mud log and sample data from American Hunter Exploration #1 Blackjack Springs Federal well (in the southern White Pine Range, north of Railroad Valley) recorded up to C4 gas from the Chainman Formation and numerous oil shows at depths of 1,900 to 2,900 ft. Under normal burial conditions, overburden thickness of those shallow depths could not produce enough heat to generate oil. Therefore, the Chainman at that location must have previously been buried much deeper. From burial history simulation of the #1 Illipah well (fig. 16), the Chainman there may have reached an R_o of 0.6 to 0.85 percent and expelled about 33 percent of its oil during the Permian.

Late Mesozoic erosion caused oil generation to stagnate from Jurassic through Paleogene time, but the Chainman started to regenerate oil at 6 Ma when buried to depths of about 8,700 ft beneath Neogene valley fill sediments. Chainman source rocks that are currently at or near the surface have not reentered the generation window, but these rocks still show remnants of Permian generation. Mississippian oil generated in the Permian may have migrated to (1) lower Paleozoic carbonates or Pennsylvanian and Permian reservoirs; (2) central Utah through regional conduits formed by Paleozoic carbonates, Pennsylvanian and Permian formations, or if generation started in Mesozoic time, through Triassic or Jurassic rocks; (3) the surface; or (4) any combination of the above. In addition, the Chainman Formation may have been buried in the footwall of central Nevada thrusts during the Mesozoic, which could have placed it in the oil generation window; however, that possibility has not been proven.

Oil shows in the Sheep Pass Formation at or near the surface in Neogene ranges have not been reported. Sheep Pass oil has been expelled in Neogene basins at about 2 Ma, although localized external heat sources could have increased expulsion rates and amounts. There is no published evidence, however, that there are more than minor accumulations of Sheep Pass derived oil.

Petroleum Occurrence

Basin Depth

Gravity data collected in the EGB were converted to depth to help determine oil generation potential of Neogene valleys. Depths were calculated to the top of major carbonate units, the first large density contrast between them and overlying Mesozoic and Cenozoic clastic rocks. The data were filtered to generate 8,200 ft and 8,700 ft depth contours (fig. 20), which reflect the approximate depths needed to place the Chainman Formation into the oil generation window as calculated from the burial history modeling. Gravity data and gravity modeling and depth conversion are from Richard Saltus (U.S. Geological Survey, written commun., 2004) and modeled after Chuchel and others (1989). The resulting map (fig. 20) showed numerous basins with depth to carbonates of more than 8,700 ft and a few additional basins with depth to carbonates between 8,200 and 8,700 ft. Most of the basins greater than 8,200 ft deep were in Nevada, although several large areas were in the Sevier Thrust System AU. The large area outlined in the southwestern part of the province, southeast of Goldfield, Nevada (fig. 1), is the Timber Mountain caldera, which is not prospective for petroleum generation because of the thick Tertiary section composed almost entirely of volcanic rocks. The location and surface area of the 8,700 ft depth contour in Railroad Valley (see fig. 1) is approximately the same as the oil generation window area outlined by Meissner (1995; his fig. 14). Although the accuracy of the depth contours as drawn on the top of the Paleozoic carbonates (fig. 20) may be questionable in places, a few well log inspections showed good correlation between log depths and gravity converted depths. Selection of valleys with the potential to generate oil and gas was reported in the assessment of undiscovered oil and gas resources in the Neogene Basins AU.

Events Chart

An events chart (fig. 21) was developed as a summary of the critical events and components of the Paleozoic-Tertiary Composite TPS that were described in detail in the preceding sections. These include ages of source, reservoir, and seal rocks and the timing of oil generation, migration, trap formation, and accumulation.

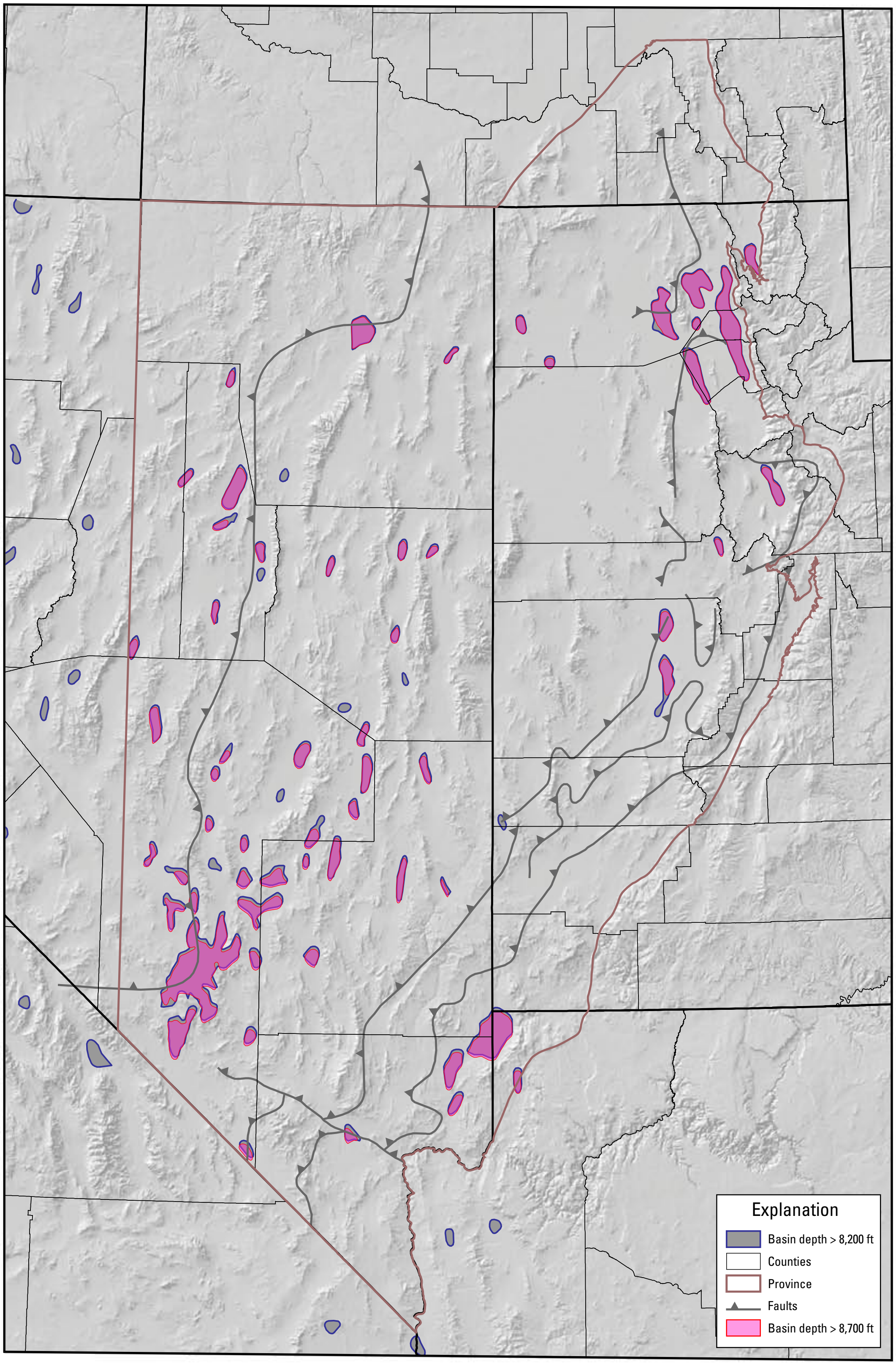


Figure 20. Valleys in the eastern Great Basin in which depths from the surface to the top of the Paleozoic carbonates are 8,200 feet and 8,700 feet. Depths were converted from regional gravity data from Richard Saltus, U.S. Geological Survey, written commun., 2004). The 8,200-foot and 8,700-foot depths roughly correspond to depths needed to place the Chainman Formation into the oil generation window.

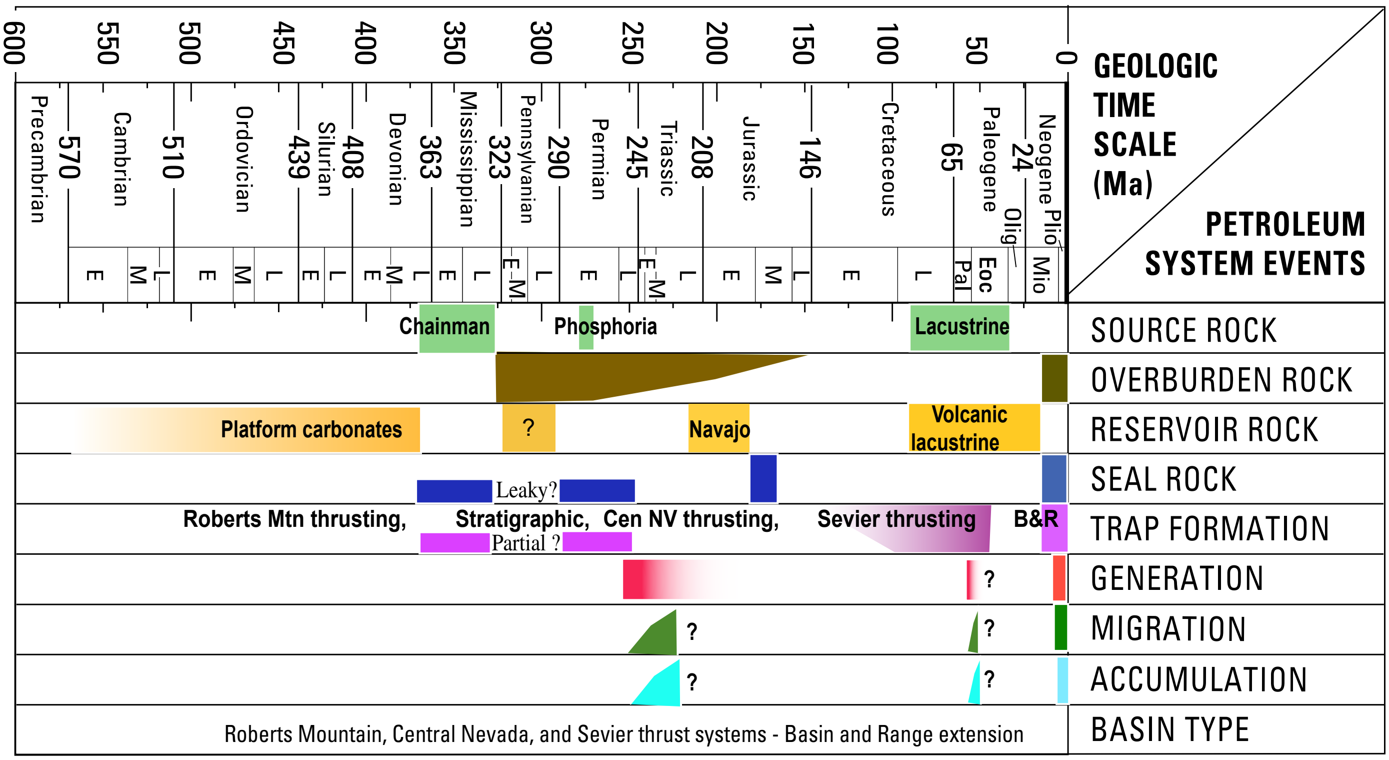


Figure 21. Events chart for the Paleozoic-Tertiary Total Petroleum System in the Eastern Great Basin. Ma, mega-annum; L, late; M, middle; E, early; Eoc, Eocene; Mio, Miocene; Plio, Pliocene; Olig, Oligocene; Pal, Paleocene; B&R, Basin and Range; Mtn, Mountain; Cen NV, Central Nevada.

Assessment of Undiscovered Petroleum by Assessment Unit

Petroleum exploration in the EGB in recent years has not met anticipated results. At present, the province is informally classified as a frontier and high risk province because of the small number of drilled and producing wells compared to its total geographic area. The range of undiscovered oil and gas resources estimated in this assessment (table 5) reflects the general uncertainty of assessing new field discoveries in the province.

Our assessment of the Paleozoic-Tertiary Composite TPS was divided into (1) the Neogene Basins AU, (2) the Neogene Ranges and Other Structures AU, and (3) the Sevier Thrust System AU. (Note: Coal-bed gas and oil shale were not assessed). Each AU is defined on the basis of geologic characteristics and conditions favorable for hydrocarbon generation and accumulation that combine to distinguish it from other assessment units, such as (1) source, reservoir, and seal rocks; (2) burial, thermal, and migration histories; and (3) trapping mechanisms.

Following a numbering system established by the USGS to facilitate petroleum resource assessment (U.S. Geological Survey, 2000), the unique number assigned to the Paleozoic-Tertiary Composite TPS is 501901, of which “5” denotes the region (North America), “019” denotes the province (EGB), and “01” denotes the TPS. The AUs, in turn, are numbered as shown below (also see Klett and Le, this CD–ROM).

501901	Paleozoic-Tertiary TPS
50190101	Neogene Basins AU
50190102	Neogene Ranges and Other Structures AU
50190103	Sevier Thrust System AU

A thorough analysis of all the available geologic data within the TPS, as well as performance and development information, was presented to a review panel for a final determination of the criteria and boundaries to be used for each of the AUs. In addition, estimates of the sizes and numbers of undiscovered oil and gas accumulations, based on a tabulation of existing field and well records provided by Klett and Le (this CD–ROM), were presented on input-data forms to the review panel. These input-data forms, included in this report as Appendices A–C, constitute the basis for estimating undiscovered hydrocarbon resources in three AUs in the Paleozoic-Tertiary Composite TPS. The default minimum accumulation size that has potential for

Table 5. Eastern Great Basin Province assessment results.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. TPS is Total Petroleum System. AU is Assessment Unit. Gray shade indicates not applicable]

Conventional Oil and Gas Resources

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field Type	Total Undiscovered Resources											
		Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Paleozoic-Tertiary Composite TPS													
Neogene Basins AU	Oil	160	740	1,780	827	20	93	244	108	1	5	15	6
	Gas					0	0	0	0	0	0	0	0
Neogene Ranges and other Structures AU	Oil	47	375	1,216	470	6	48	162	61	0	3	10	4
	Gas					114	898	2,981	1,133	5	38	135	50
Sevier Thrust System AU	Oil	33	231	809	301	10	75	279	100	1	4	17	6
	Gas					42	295	1,317	434	2	13	58	19
Total Conventional Resources		**240**	**1,346**	**3,805**	**1,598**	**192**	**1,409**	**4,983**	**1,836**	**9**	**63**	**235**	**85**

additions to reserves is 0.5 million barrels of oil equivalent (MMBOE). Other data compiled or calculated for each AU to aid in the final estimate of undiscovered resources include gas to oil ratios, natural gas liquids to gas ratios, API gravity, sulfur content, and drilling depth. Additionally, allocations of undiscovered resources were calculated for Federal, State, and private lands and for various ecosystem regions. The assessment process includes a statistical analysis of existing fields including plots of cumulative and individual field size and number with discovery date and number of well penetrations of the AU (NRG Associates, 2004). However, because the EGB has few fields and new field wildcats, meaningful statistical analysis added little value to the assessment.

Neogene Basins AU

The Neogene Basin AU covers all of the Neogene basins in the EGB west of the Sevier thrust system in central Utah (fig. 1), but only the structural basin part was assessed. In Nevada, the Neogene basins are long, narrow valleys, but in Utah they are generally wider and shallower. The combined surface area of the basins is about 60 million acres, but basin widths narrow with depth. They are filled with Neogene clastic sediments deposited as fans, alluvium, and colluvial debris, collectively called valley fill. The valley fill unconformably overlies Tertiary volcanic rocks and lacustrine strata and Paleozoic carbonate rocks. Valley fill depths range from a few thousand feet to nearly 10,000 ft as determined from well logs and by gravity modeling.

The west boundary of the AU coincides with the province boundary. The AU also includes the area west of the Roberts Mountain thrust because extension tectonics that formed the basins was as prevalent west of the thrust as it was to the east.

Only two basins (or valleys) in the AU have established production, Railroad Valley and Pine Valley, both in Nevada (fig. 1). Railroad Valley has several oil fields ranging from one well to some 50 wells per field. Of the six wells at Grant Canyon field, one well had the highest sustained production rate (greater than 4,000 BOPD for more than 3 years) in the conterminous 48 United States.

Reservoirs that produce in the two productive basins consist primarily of Paleozoic carbonates and Tertiary volcanic rocks, with minor production from a Tertiary lacustrine unit. The largest fields produce from volcanic rock reservoirs; one of which contains about 50 wells and covers some 5,000 acres (Trap Spring field), while another has 33 wells and covers about 2,500 acres (Eagle Springs field). Lacustrine and carbonate fields are small and range from two to seven wells, although production from the carbonate Guilmette Formation at the Grant Canyon field is prolific.

Limited geochemical analyses (fig. 9) indicate that the Chainman Formation is the primary source rock for oil accumulation in the two producing basins in the Neogene Basins AU. Analyses also show Tertiary lacustrine beds to be a minor source of oil; Western Assemblage source rocks contain substantial amounts of TOC, but their oil has not been typed to production.

Although several fields located in Railroad Valley and Pine Valley indicate generation, migration, and trapping of Chainman oil, all other valleys have either limited or no well penetrations. Therefore, the gravity-depth conversion was critical to assess the petroleum potential of the Neogene Basins AU. As previously discussed, conversion of gravity data to determine depth to the top of the major carbonate/source rock interface shows some 50 areas (fig. 20) in which Chainman Formation source rock could be buried to depths that place the Chainman in the oil generation window.

Estimated Resources

We estimated the number of undiscovered oil accumulations in this AU to be a minimum of 2, a maximum of 150, and a mode of 25, as shown on the data form in Appendix A. Only eight new oilfields have been discovered since the first economic discovery in 1954, and although there have been no new field discoveries (above the minimum size of 0.5 MMBO) since 1996, we believe it likely that at least two new oilfields above that minimum will be discovered. This low number (as well as the mode of 25) is not a lack of good reservoir or source rock but reflects large uncertainty in trap size and the competency of lateral and vertical seals. As for the maximum estimate of 150 undiscovered fields, this is a reflection of the large geographic size of the assessment unit, the variety of possible traps, and the number of basins that have few or no well penetrations in basins with possible Chainman oil generation.

We estimated the sizes of undiscovered oil accumulations to be a minimum of 0.5 MMBO, a median of 5 MMBO, and a maximum of 500 MMBO. The default minimum size of 0.5 MMBO reflects that there will be one field found greater than the minimum size but that most discovered fields are small. We used a median size of 5 MMBO to reflect the probability that most of the fields will be relatively small, although the size of the largest existing oil field (Grant Canyon) is about 20 MMBO and there has been only one additional field greater than 10 MMBO. A maximum size of 500 MMBO reflects the large uncertainty in mostly unexplored parts of the assessment unit.

This assessment gave no potential for undiscovered gas fields above the minimum size. The Chainman Formation was probably not buried deep enough to generate significant amounts of gas. Only if Type III lacustrine source rocks are buried to generation depths is there the probability of significant amounts of generated gas. Associated gas, however, was assessed a mean of 108 BCFG (table 5).

Mean estimates of undiscovered resources for the Neogene Basins AU are 827 MMBO (from oil both in oil and in gas fields), no gas accumulations, and 6 MMBNGL (table 5). Table 5 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future oil discoveries is considered to be uncertain on the basis of the sparsely drilled area, although there is good potential because these basins have all the assessed components to produce oil.

Neogene Ranges and Other Structures AU

The Neogene Ranges and Other Structures AU covers the same geographic area as the Neogene Basins AU (fig. 1), but the assessment was only for the ranges, which are the uplifted areas adjacent to the basins, and they are long and narrow and contain lithologic units similar to those buried beneath the valley fill sediments in Neogene valleys, which are mostly Paleozoic carbonates like those in Railroad and Pine Valleys. In the early drilling history of the EGB, especially in Nevada, exposed structural closures were tested to various depths, but in many cases there were either no oil shows or only dead oil shows. We feel the dead oil shows were probably a result of oil that was generated by the Chainman Formation in Permian time and passed through these large structures in the late Paleozoic. Potential for new discoveries in this AU is from the Chainman generating oil in Mesozoic or Cenozoic time, after burial to sufficient depths either in the footwall or hanging wall of thrust systems. If this occurred, potential oil traps could have formed by (1) thrust and subthrust structural closures beneath the ranges, possibly related in part to the central Nevada thrust belt, (2) other structures and traps that predate Neogene extension but were preserved following Neogene extension, and (3) structures and traps that were created as a result of Neogene extension. However, this AU is classified hypothetical because there is no production, and few wells penetrate target structures. There is also great uncertainty as to timing of oil generation, migration, size and timing of traps, and sealing capacity.

Estimated Resources

The minimum, median, and maximum estimates of the sizes and numbers of undiscovered oil and gas accumulations in the Neogene Ranges and Other Structures AU are given on the data form in Appendix B. As previously indicated, all our estimates are necessarily speculative, owing to the lack of drilling and discovery of economic accumulations of hydrocarbons. However, suitable source and reservoir rocks are present in the AU, so there is a reasonable expectation that some future discoveries will be made, although large uncertainties exist in hydrocarbon generation, timing, and migration, as well as trap size and competency of lateral and vertical seals.

Our estimates of the minimum, median, and maximum numbers for undiscovered oil accumulations greater than 0.5 MMBO are 1, 5, and 50, respectively, and 1, 3, and 30, respectively for gas accumulations greater than 3 BCFG (Appendix B). Respective values for accumulation sizes are 0.5, 8, and 1,000 MMBO for oil and 3, 40, and 3,000 BCFG for gas. Both the minimum and median values reflect our best estimates as to the numbers and sizes of accumulations to be discovered, based on what is known or can reasonably be inferred from the existing geologic conditions. The maximum values reflect a high potential that may exist, considering the large geographic extent of the AU, the variety of possible traps, and the many ranges that are yet to be explored.

Mean estimates of undiscovered resources for the Neogene Ranges and Other Structures Assessment Unit are 470 MMBO, 1,194 BCFG of associated and nonassociated gas, and 54 MMBNGL (table 5). Table 5 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future oil discoveries is considered to be uncertain on the basis of the sparsely drilled area; currently no fields are producing in the AU.

Sevier Thrust System AU

The Sevier Thrust System AU is a 60-mi-wide, north-south-trending structural zone in the eastern part of the EGB (fig. 1); it is part of the Sevier orogenic belt that extends from Mexico to Canada and within which deformation occurred from Late Jurassic and into Eocene time. This east-verging system is characterized by relatively thin skinned, younger over older thrust sheets and fold belts. Folds include those formed from either Sevier compression (Carpenter and others, 1989) or from isostatic rebound in the footwall of thrust sheets after the hanging wall detached during Neogene extension (Wernicke and Axen, 1988). A recent oil discovery in folded strata of the Jurassic Navajo Sandstone (Covenant field near Richfield, Utah; fig. 1) has created renewed interest in this area, although there is still great uncertainty as to the possibility of there being fields with characteristics similar to the Navajo discovery. Oil generation and migration routes to structural closures or stratigraphic traps in fold-thrust systems can be limited. However, the Covenant field provides an excellent example to assess future undiscovered oil and gas resources in this AU. In addition, the Anderson Junction field (Harris, 1994) in southwestern Utah, although just east of the Sevier thrust system, produced minor amounts of oil in the Pennsylvanian Callville Formation, with oil shows in Devonian rocks and dead oil shows in Mississippian rocks. Although production is along the trend to the Covenant field, the Anderson Junction structure has a different structural style, timing of oil generation, and fluid flow history (Jim Coogan, Western State College, Gunnison, Colo., written commun., 2004).

Estimated Resources

The minimum, median, and maximum estimates of the sizes and numbers of undiscovered oil and gas accumulations in the Sevier Thrust System AU are given on the data form in Appendix C. As previously indicated, all our estimates are necessarily speculative, owing to the lack of drilling and discovery of economic accumulations of hydrocarbons. However, suitable source and reservoir rocks are present in the AU, so there is a reasonable expectation that some future discoveries will be made although large uncertainties exist as to hydrocarbon generation, timing, and migration, as well as trap size and competency of lateral and vertical seals.

Our estimates for the minimum, median, and maximum numbers for undiscovered oil accumulations greater than 0.5 MMBO are 1, 5, and 30 respectively, and for gas accumulations greater than 3 BCFG 1, 2, and 10, respectively (Appendix C). Respective values for accumulation sizes are 0.5, 8, and 1,000 MMBO for oil and 3, 40, and 3,000 BCFG for gas. Both the minimum and median values reflect our best estimates as to the numbers and sizes of accumulations to be discovered, based on what is known or can reasonably be inferred from the existing geologic conditions. The maximum values reflect a high potential considering (1) the large geographic extent of unexplored areas in the AU, (2) the new Covenant field discovery, (3) the variety of possible traps, and (4) the possibility of oil that has been generated locally.

Mean estimates of undiscovered resources for the Sevier Thrust System Assessment Unit are 301 MMBO, 534 BCFG of associated and nonassociated gas, and 25 MMBNGL (table 5). Table 5 also shows a resource breakdown into the F95, F50, and F5 fractiles. The potential for future oil discoveries is considered to be optimistic based on the recent new field discovery and favorable geologic conditions for future discovery.

Assessment Summary

The EGB province is a difficult province to assess because it is structurally complex and sparsely drilled and has small, partly segregated oil generation systems. However, the province contains thick and extensive source rocks and thick, extensive, and numerous but diverse reservoir rocks. Although not readily apparent, its thermal history also seems favorable for oil generation in most areas. High heat flow in the northern part may have, in places, overmature Chainman Formation, but Tertiary source rocks may be in a favorable oil generating window. Although structural traps are the most common type of trap in the province, there is uncertainty whether their size is large enough to accumulate significant amounts of hydrocarbons. Large uncertainties also exist as to the integrity of lateral and top seals to reservoirs.

Mean estimates of undiscovered resources for the EGB Province are 1,598 MMBO, 1,836 BCFG of associated and nonassociated gas, and 85 MMBNGL (table 5). Table 5 also shows a resource breakdown into the F95, F50, and F5 fractiles.

Comparison of Results of 1995 and 2005 Assessments

A comparison between a 1995 USGS resources estimate (Peterson and Grow, 1995) and this assessment for the EGB Province show an appreciable change in the estimated size of undiscovered resources. In 1995, Peterson and Grow (1995) estimated a total mean undiscovered oil and gas resource of 383 MMBO and 242 BCFG for six conventional plays in the EGB Province. In 2005, a mean resource of 1,598 MMBO and 1,836 BCFG was estimated for the three assessment units in the Paleozoic-Tertiary Composite TPS; all these are the estimates used in table 5 of this report. All plays from the 1995 assessment were incorporated into the three AUs.

Even considering differences in methodology, the 2005 estimates reflect a notable increase in resource estimates even though there were only two new field discoveries in the

10 years since the 1995 assessment. The Covenant field in central Utah was discovered in 2004, but little information was released by the time this assessment was made. We interpret that discovery, however, to indicate good potential for future discoveries in the Sevier Thrust System AU. In addition, the overall increased estimates reflect the general conclusions that (1) exploration and drilling activity, to date, throughout the Paleozoic-Tertiary Composite TPS has been inadequate to fully evaluate its hydrocarbon potential, and (2) good source and reservoir rocks, as well as other essential elements that form a TPS, exist in many of the unexplored areas, thus indicating strong possibilities for future discoveries in all the AUs.

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Appendix A. Input data for the Neogene Basins Conventional Oil and Gas Assessment Unit (AU 50190101). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03).

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	L.O. Anna	Date:	14-Dec-04
Region:	North America	Number:	5
Province:	Eastern Great Basin	Number:	5019
Total Petroleum System:	Paleozoic-Tertiary Composite	Number:	501901
Assessment Unit:	Neogene Basins	Number:	50190101
Based on Data as of:	NRG (2003) data current through 2001, IHS Energy Q2 2004		
Notes from Assessor:	NRG reservoir montonic reserve growth model		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall): Oil

What is the minimum accumulation size? 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 7 Gas: 0
Established (>13 accums.) ____ Frontier (1-13 accums.) X Hypothetical (no accums.) ____

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd 6.5 2nd 3rd 3.1 3rd 3rd ____
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ____ 2nd 3rd ____ 3rd 3rd ____

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size:	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum siz	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0) 2	mode 25	maximum 150
Gas Accumulations:	minimum (>0) 0	mode 0	maximum 0

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (mmbo):	minimum 0.5	median 5	maximum 500
Gas in Gas Accumulations (bcfg):	minimum	median	maximum

Appendix A. Input data for the Neogene Ranges and Other Structures Conventional Oil and Gas Assessment Unit (AU 50190102). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03).—Continued

Assessment Unit (name, no.)
Neogene Basins, 50190101

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	65	130	195
NGL/gas ratio (bngl/mmcfg)	30	60	90

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)			
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	10	23	48
Sulfur content of oil (%)	0.1	1.3	4.7
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	500		1,500		4,600

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)			
CO_2 content (%)			
Hydrogen-sulfide content (%)			
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)					

Appendix B. Input data for the Neogene Ranges and Other Structures Conventional Oil and Gas Assessment Unit (AU 50190102). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03).

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	L.O. Anna	Date:	14-Dec-04
Region:	North America	Number:	5
Province:	Eastern Great Basin	Number:	5019
Total Petroleum System:	Paleozoic-Tertiary Composite	Number:	501901
Assessment Unit:	Ranges and Other Structures	Number:	50190102
Based on Data as of:			
Notes from Assessor:			

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall): Oil

What is the minimum accumulation size? 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 0 Gas: 0
Established (>13 accums.) ______ Frontier (1-13 accums.) ______ Hypothetical (no accums X

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size:	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum siz	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0)	1	mode	5	maximum	50
Gas Accumulations:	minimum (>0)	1	mode	3	maximum	30

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (mmbo):	minimum	0.5	median	8	maximum	1,000
Gas in Gas Accumulations (bcfg):	minimum	3	median	40	maximum	3,000

Appendix B. Input data for the Neogene Ranges and Other Structures Conventional Oil and Gas Assessment Unit (AU 50190102). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03)—Continued

Assessment Unit (name, no.)
Ranges and Other Structures, 50190102

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	65	130	195
NGL/gas ratio (bngl/mmcfg)	30	60	90

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)	22	44	66
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	10	23	48
Sulfur content of oil (%)	0.1	1.3	4.7
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	1,000		2,500		4,600

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)			
CO_2 content (%)			
Hydrogen-sulfide content (%)			
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	1,000		3,500		6,000

Appendix C. Input data for the Sevier Thrust System Conventional Oil and Gas Assessment Unit (AU 50190103). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03).

SEVENTH APPROXIMATION
DATA FORM FOR CONVENTIONAL ASSESSMENT UNITS (Version 6, 9 April 2003)

IDENTIFICATION INFORMATION

Assessment Geologist:	L.O. Anna	Date:	15-Dec-04
Region:	North America	Number:	5
Province:	Eastern Great Basin	Number:	5019
Total Petroleum System:	Paleozoic-Tertiary Composite	Number:	501901
Assessment Unit:	Sevier Thrust System	Number:	50190103
Based on Data as of:			
Notes from Assessor:	Recent Navajo Sandstone discovery		

CHARACTERISTICS OF ASSESSMENT UNIT

Oil (<20,000 cfg/bo overall) **or** Gas (≥20,000 cfg/bo overall): Oil

What is the minimum accumulation size? 0.5 mmboe grown
(the smallest accumulation that has potential to be added to reserves)

No. of discovered accumulations exceeding minimum size: Oil: 0 Gas: 0
Established (>13 accums.) ______ Frontier (1-13 accums.) ______ Hypothetical (no accums X

Median size (grown) of discovered oil accumulations (mmbo):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______
Median size (grown) of discovered gas accumulations (bcfg):
1st 3rd ______ 2nd 3rd ______ 3rd 3rd ______

Assessment-Unit Probabilities:

Attribute	Probability of occurrence (0-1.0)
1. **CHARGE:** Adequate petroleum charge for an undiscovered accum. ≥ minimum size:	1.0
2. **ROCKS:** Adequate reservoirs, traps, and seals for an undiscovered accum. ≥ minimum size:	1.0
3. **TIMING OF GEOLOGIC EVENTS:** Favorable timing for an undiscovered accum. ≥ minimum siz	1.0

Assessment-Unit GEOLOGIC Probability (Product of 1, 2, and 3): 1.0

UNDISCOVERED ACCUMULATIONS

No. of Undiscovered Accumulations: How many undiscovered accums. exist that are ≥ min. size?:
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum (>0)	1	mode	5	maximum	30
Gas Accumulations:	minimum (>0)	1	mode	2	maximum	10

Sizes of Undiscovered Accumulations: What are the sizes (**grown**) of the above accums?:
(variations in the sizes of undiscovered accumulations)

Oil in Oil Accumulations (mmbo):	minimum	0.5	median	8	maximum	1,000
Gas in Gas Accumulations (bcfg):	minimum	3	median	40	maximum	3,000

Appendix C. Input data for the Sevier Thrust System Conventional Oil and Gas Assessment Unit (AU 50190103). Seventh Approximation Data Form for Conventional Assessment Units (NOGA, version 6, 05-06-03).—Continued

Assessment Unit (name, no.)
Sevier Thrust System, 50190103

AVERAGE RATIOS FOR UNDISCOVERED ACCUMS., TO ASSESS COPRODUCTS
(uncertainty of fixed but unknown values)

Oil Accumulations:	minimum	mode	maximum
Gas/oil ratio (cfg/bo)	200	300	500
NGL/gas ratio (bngl/mmcfg)	30	60	90

Gas Accumulations:	minimum	mode	maximum
Liquids/gas ratio (bliq/mmcfg)	22	44	66
Oil/gas ratio (bo/mmcfg)			

SELECTED ANCILLARY DATA FOR UNDISCOVERED ACCUMULATIONS
(variations in the properties of undiscovered accumulations)

Oil Accumulations:	minimum	mode	maximum
API gravity (degrees)	20	37	50
Sulfur content of oil (%)	0.1	1.3	4.7
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	1,000		3,000		5,000

Gas Accumulations:	minimum	mode	maximum
Inert gas content (%)			
CO_2 content (%)			
Hydrogen-sulfide content (%)			
Depth (m) of water (if applicable)			

	minimum	F75	mode	F25	maximum
Drilling Depth (m)	1,000		3,000		6,000

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