Investigation of High-Temperature, Igneous-Related Hydraulic Fracturing as a Reservoir Control in the Blackburn and Grant Canyon/Bacon Flat Oil Fields, Nevada

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TABLE OF CONTENTS

	PAGE
ABSTRACT	1
INTRODUCTION	2
GEOLOGIC SETTING OF THE EAST-CENTRAL BASIN-AND-RANGE OIL FIELDS	4
BLACKBURN AND GRANT CANYON/BACON FLAT OIL FIELDS	9
RESEARCH PROGRESS TO DATE	18
Blackburn Results	18
Grant Canyon/Bacon Flat Results	25
Publications	30
HYPOTHESIS: THE ROLE OF ACTIVE AND PALEO-HYDROTHERMAL SYSTEMS IN EVOLUTION OF THE BASIN-AND-RANGE OIL FIELDS	30
REFERENCES	35

FIGURES

	PAGE
Fig. 1. Producing oil fields of Nevada	3
Fig. 2. Regional geologic map of the Blackburn oil field and vicinity	8
Fig. 3. Geologic map of the Blackburn oil field and vicinity	10
Fig. 4. Interpretive geologic sections through the Blackburn oil field	11
Fig. 5. Generalized geologic map of the Grant Canyon/Bacon Flat oil field, Nye County, Nevada	12
Fig. 6. Geologic section through the Grant Canyon/Bacon Flat oil field	13
Fig. 7. Paragenesis of vein mineralization and petroleum entrapment, Blackburn oil field	21
Fig. 8. Homogenization temperatures of fluid inclusions in vein- and vug-filling minerals, Blackburn oil field	23
Fig. 9. Homogenization temperatures of primary and secondary fluid inclusions in vein- and vug- filling quartz and dolomite from the Grant Canyon oil field	28
Fig. 10. Homogenization temperatures of primary fluid inclusions in vein- and vug- filling quartz and dolomite from the Grant Canyon oil field	29
Fig. 11. Schematic east-west geologic section through the Grant Canyon/Bacon Flat oil field, illustrating the possible role of a moderate- to high-temperature, meteoric-hydrothermal system in oil migration and entrapment as well as sealing of the reservoir trap.	31

TABLE

Table 1. Producing oil fields of Nevada, with cumulative production through April 1988	5
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ABSTRACT

Research in progress to evaluate natural, igneous-related hydrothermal fracturing as a reservoir control in two eastern Nevada oil fields has revealed evidence of a far more comprehensive role for moderate- to high-temperature hydrothermal systems in Basin-and-Range oil-reservoir evolution. Fluid-inclusion and petrographic studies have shown that (now) oil-bearing dolomite breccias of the Blackburn field (Pine Valley, Eureka County) were formed when overpressured, magmatically-heated, high-temperature ($>350^{\circ}\text{C}$) hydrothermal brines explosively ruptured their host rocks; similar studies of texturally identical breccias of the Grant Canyon/Bacon Flat field (Railroad Valley, Nye County) so far do not support such an explosive origin. At Grant Canyon, however, hydrothermal, breccia-cementing quartz hosts primary oil, aqueous/oil, and aqueous fluid inclusions (homogenization temperature = 120°C) which document a direct geothermal connection for oil migration and entrapment. Moreover, at both Blackburn and Grant Canyon/Bacon Flat, the oil reservoirs are top- and side-sealed by hydrothermally altered Tertiary ignimbrites and epiclastic rocks. Contemporary geothermal activity is also apparent at Grant Canyon/Bacon Flat, where subsurface water temperatures reach 171°C , and at Blackburn, above which a petroleum-producing hot spring issues at a temperature of 90°C . We suggest that in the Basin and Range province, hydrothermal systems may have: (1) matured oil from otherwise submature source rocks; (2) transported oil to ultimate entrapment sites by convection in moderate- to high-temperature fluids; and (3) sealed reservoir traps through hydrothermal alteration of overlying Tertiary caprocks.

INTRODUCTION

Beginning in June 1990, a research project sponsored by the Office of Basic Energy Sciences (OBES) and initiated by the University of Utah Research Institute (UURI) was undertaken to investigate the role of high-temperature hydrothermal (natural hydraulic) fractures and breccias as reservoir controls in the unusual oil fields of the Basin and Range province of eastern Nevada (Fig. 1; Appendices 1 and 2). Textures of oil-filled fractures and breccias at two of these fields, Blackburn and Grant Canyon/Bacon Flat (Fig. 1), curiously but strongly suggested formation of these features in overpressured, high-temperature hydrothermal systems (Appendix 1). Preliminary fluid-inclusion data suggested that, at least at Blackburn, the very high fluid temperatures required for such disruption at one time prevailed in the reservoir rocks. Moreover, both fields are underlain by granitic stocks, once the potent magmatic heat sources required for such explosive rock rupture.

Results of the OBES-sponsored research to date have strongly supported a high-temperature paleohydrothermal origin for the Blackburn oilfield breccias but to date are inconclusive for the corresponding Grant Canyon rocks. At both sites, however, further fluid-inclusion and alteration studies have unexpectedly suggested numerous other ways in which moderate- to high-temperature hydrothermal systems may have been (and may continue to be) critical in the formation of the Basin-and-Range petroleum reservoirs. Not only have these systems created essential secondary porosity, they may also have (1) matured oil from otherwise submature source rocks; (2) transported oil to entrapment sites as either solute or globules dispersed in convecting hydrothermal fluids; (3) sealed the traps through argillic alteration of overlying glassy volcanic and volcanoclastic rocks. (Some of these processes may even be currently active at Blackburn, above which a hydrocarbon-rich hot spring issues at a temperature of about 90°C, and at Grant Canyon/Bacon Flat, where reservoir temperatures at a little over 1600 m depth approach 171°C.

The two producing oil wells of the Grant Canyon field have consistently been among the most prolific in the United States --in tandem yielding a little over 6000 barrels per day

Figure 1. Producing oil fields of Nevada.

(Montgomery, 1988b). Bortz (1989), moreover, believes that 100,000,000-barrel "giant" fields of the Grant Canyon type await discovery in the Basin and Range. The work summarized in this progress report has been aimed at increasing our basic knowledge of these vital resources and facilitating their effective exploration and development.

GEOLOGIC SETTING OF THE EAST-CENTRAL BASIN AND RANGE OILFIELDS

Productive oil reservoirs discovered to date in eastern Nevada (Table 1; Fig. 1) are confined to two typical, deeply alluviated, northerly-trending fault-block valleys of the Basin-and-Range province. (Regional geology of the province is detailed in Appendix 1). The Eagle Springs, Trap Springs, Bacon Flat, Grant Canyon, and Kate Springs fields are situated in northern Nye County's Railroad Valley (Fig. 1). The Blackburn, North Willow Creek, and Tomera Ranch fields, all discovered since 1982 (Montgomery, 1988a), produce from the eastern flank of Pine Valley, roughly 160 km to the north-northwest.

Geology and reservoir characteristics of the Railroad Valley oil fields are summarized in Duey (1983), Flanigan (1988), Veal et al. (1988), Read and Zogg (1988), and Ehni and Evans (1989). Drilling and seismic studies show that Railroad Valley is an asymmetric, down-to-the-east graben, bordered by horsts forming the Pancake Range to the west and the Grant Range to the east. Exposures in the Pancake Range are dominated by Oligocene ignimbrites, through which isolated windows of gently folded Paleozoic siliciclastic and carbonate strata project; these rocks are locally disrupted by low-angle faults, probably of multiple origins. Paleozoic rocks predominate in the Grant Range, where they are intruded by widely scattered felsic stocks of Tertiary to Cretaceous age (Kleinhampl and Ziony, 1985; Fryxell, 1988). Both high-angle and low-angle faults are common in the Grant Range, and the latter may represent both overthrusting and gravity sliding (Quinlivan et al., 1974; Fryxell, 1988; Cameron and Chamberlain, 1987).

Beneath Railroad Valley itself, the Paleozoic sequence is deeply and extensively blanketed by block-faulted Eocene lacustrine sedimentary rocks and overlying Oligocene ignimbrites. The

Table 1. Producing oil fields of Nevada with
cumulative production through April 1988
(from Montgomery, 1988b)

<u>FIELD</u>	<u>YEAR OF DISCOVERY</u>	<u>NUMBER OF PRODUCTIVE WELLS*</u>	<u>CUMULATIVE PRODUCTION</u>
Eagle Springs	1954	9(6)	3,868,850
Trap Springs	1976	26(21)	7,374,982
Bacon Flat	1981	1(1)	303,860
Blackburn	1982	4(3)	1,397,196
Grant Canyon	1983	3(2)	8,211,149**
Kate Springs	1985	2(1)	13,158
Tomera Ranch	1987	1(1)	3,699
North Willow Creek	1988	1(1?)	317
All Fields (Total)		48(36)	21,173,657

** SLIGHTLY MORE THAN 13,000,000 BARRELS THROUGH 1990

*numbers in parentheses refer to wells currently producing

ignimbrites are the principal reservoir rocks at the Trap Springs and Eagle Springs fields (Fig. 1; Bortz and Murray, 1979; Duey, 1979, 1983; Montgomery, 1988b), although one well at Eagle Springs yields oil from the underlying Pennsylvanian Ely Limestone; production from all oil-bearing lithologies is principally from fractures. The deepest well in the Eagle Springs field penetrated a felsic pluton at a depth of over 3 km; the lateral extent of this intrusive body remains unknown.

By contrast with Trap Springs and Eagle Springs, the recently discovered Bacon Flat, Grant Canyon and Kate Springs fields (Fig. 1) all produce primarily from fractured Paleozoic carbonates (Veal et al., 1988; Read and Zogg, 1988; Flanigan, 1988). At Grant Canyon and Bacon Flat, these carbonates are underlain by another felsic pluton, subsurface extensions of the exposed, Late Cretaceous Troy stock (Fryxell, 1988); Flanigan (1988) infers a similar pluton at depth beneath the Kate Springs field. The dolomite reservoir rock of the Grant Canyon field is intensely fractured and brecciated; quartz-lined fractures and intraclast vugs in breccias locally provide much of the rock's 20% total porosity (Read and Zogg, 1988). Porosities of up to 17% are reported in the productive carbonates at Kate Springs (Flanigan, 1988). All these eastern Railroad Valley reservoirs are apparently sealed laterally by high-angle normal faults and clay-rich Oligocene sedimentary rocks and ignimbrites (which also provide the necessary top seals). Our initial petrographic and X-ray diffraction studies at Grant Canyon indicate that these critical seals may in part represent hydrothermal argillic alteration.

Railroad Valley is thermally active. Although the average thermal gradient as measured in wells is curiously low, about 19°C/km (Duey, 1983), local thermal gradients are anomalously high. For example, a well near Warm Springs, about 30 km south-southwest of the Trap Springs field, shows a gradient of 115°C/km (Duey et al., 1983). At the Bacon Flat field, a gradient of 103°C/km was calculated; bottom-hole temperature at 1.66 km is currently 171°C (Veal et al., 1988). Since the presumed source rocks for the Railroad Valley oil reservoirs -- the Mississippian Chainman Shale and the Eocene Sheep Pass Formation (Bortz, 1983) -- are thermally submature in this area (Poole et al., 1983), it seems likely that geologically recent (and perhaps contemporary)

geothermal heating may have played an important role in source-rock maturation (Duey, 1983; Poole et al., 1983).

The oil fields of Pine Valley are aligned roughly north-south along the valley's eastern edge, adjacent to the Sulphur Spring Range at Blackburn and North Willow Creek (Fig. 2) and to the Piñon Range at Tomera Ranch (Fig. 1), about 21 km north of North Willow Creek. Pine Valley is flanked to the southwest by the Roberts and Simpson Park Mountains, and to the northwest by the Cortez Mountains (Fig. 2). Paleozoic sedimentary sequences representing both the allochthonous, siliceous, "western assemblage" (Appendix 1) and shelf carbonates of the autochthonous "eastern assemblage" account for most exposures of pre-Tertiary rock in all these ranges, but the northeastern Cortez Mountains are eroded principally from Jurassic to Cretaceous volcanic and volcanoclastic rocks (Fig. 2; Trexler, 1990; Stewart and Carlson, 1976; Roberts et al., 1967). The older rocks are disrupted by the Roberts Mountains overthrust, the northerly-trending leading edge of which may be situated about 20 km east of the Blackburn field (Bortz, 1983). All rocks are broken by high-angle Basin-and-Range normal faults and by low-angle faults which probably represent gravity sliding (Trexler, 1990). Felsic stocks of Jurassic to Miocene age are common in the Cortez Mountains but rarely occur in the Sulphur Spring and Piñon Ranges (Fig. 2). Where exposed, these stocks are commonly associated with hydrothermal ore mineralization. For example, the Cortez gold deposits (Fig. 2), about 37 km west-southwest of the Blackburn field, are hosted principally by fractured Devonian dolomite in contact with a felsic "quartz porphyry" stock of Oligocene age (Rye, 1985). At Mt. Hope (Fig. 2; Westra and Keith, 1981), about 50 km south of Blackburn, a deep molybdenite deposit occupies a hood of natural hydraulic fractures at the apex of a concealed, Oligocene stock of rhyolitic composition.

As reported by Allison and Hulen (1990), six and possibly seven of Nevada's eight commercially producible oil fields (Fig. 1) are associated with felsic stocks. Of the 12 wells in eastern Nevada that penetrate such stocks, at least 10 are productive or are situated within 1.6 km of production. In view of the fact that plutonic rocks account for less than 5% of outcropping rocks in this region (Maldonado et al., 1989), the oil/stock connection seems much more than

EXPLANATION

- Miocene to Quaternary sedimentary rocks and Quaternary surficial deposits, undivided
- Oligocene to Miocene volcanic rocks
- Jurassic to Miocene felsic plutons
- Jurassic to Cretaceous volcanic and sedimentary rocks, undivided
- Cambrian to Devonian siliciclastic and carbonate rocks
- High angle normal fault
- Overthrust fault, saw teeth on upper plate
- Mine or mining district (major, minor)

INDEX TO MTN. RANGES

- 1—SIMPSON PARK MTNS.
- 2—CORTEZ MTNS.
- 3—ROBERTS MTNS.
- 4—SULPHUR SPRING RA.
- 5—DIAMOND MTNS.

Figure 2. Regional geologic map of the Blackburn oil field and vicinity.

MH—MINERAL HILL; UN—UNION; BH—BUCKHORN;
CO—CORTEZ; HC—HORSE CANYON; RO—ROBERTS;
TS—TONKIN SPRINGS; MT—MT. HOPE; GB—GOLD BAR

coincidental. Our research to date in the Blackburn oil field strongly suggests that one reason for the connection is porosity-creating and -enhancing, high-temperature hydrothermal fracturing and brecciation.

BLACKBURN AND GRANT CANYON/BACON FLAT OIL FIELDS

The Blackburn and Grant Canyon-Bacon Flat oil reservoirs, although separated by more than 250 km (Fig. 1), are remarkably similar in geologic setting. At both fields, deeply concealed (beneath Cenozoic valley fill), highly fractured and brecciated Paleozoic carbonates are the principal reservoir rocks, and at both sites these carbonates are underlain by felsic stocks (Figs. 3-6). Hydrocarbons at both reservoirs were apparently derived from the organic-rich Mississippian Chainman Shale (Veal et al., 1988; Scott and Chamberlain, 1988). Maturation of this prolific source rock may have been enhanced by heating, accompanying both emplacement of the felsic plutons and (much later) development of still-active, moderate- to high-temperature geothermal systems.

Blackburn: The geologic setting of the Blackburn field is graphically summarized by Figures 3 and 4. Figure 4 depicts the interpreted stratigraphy and structure of the field along two representative and intersecting cross sections. Paleozoic formations shown on these sections beneath the limit of drilling to date are inferred as autochthonous "eastern-assemblage" rocks. (Appendix 1; Scott and Chamberlain, 1988), but allochthonous, "western-assemblage" strata could also be present.

Petroleum production at Blackburn is principally from fractured, locally brecciated, microcrystalline to fine-crystalline dolomites of the Devonian Nevada Group (Bortz, 1983; Scott and Chamberlain, 1988) in a deeply concealed horst beneath Pine Valley about 5 km west of the Sulphur Spring Range (Figs. 3 and 4). Organic-rich shales of the Mississippian Chainman Shale cap the horst and adjacent structural blocks (Fig. 4). Scott and Chamberlain (1988) suggested that here, the Chainman probably represents the upper plate of a low-angle detachment fault. Johannesen and Cole (1990), on the other hand, interpret the Chainman at Blackburn as

EXPLANATION

	QUATERNARY SURFICIAL DEPOSITS		HIGH-ANGLE NORMAL FAULT, SHOWING DISPLACEMENT IF KNOWN
	QUATERNARY TRAVERTINE		LOW-ANGLE DETACHMENT (?) FAULT, BOXES ON UPPER PLATE
	TERTIARY (?) GRANODIORITE		OVERTHRUST FAULT, SAW TEETH ON UPPER PLATE
	MISSISSIPPIAN CHAINMAN SHALE		PRODUCING OIL WELL
	DEVONIAN SILICICLASTIC AND CARBONATE ROCKS UNDIVIDED		NON-PRODUCING OIL WELL
	DEVONIAN NEVADA GROUP (DOLOMITE)		SURFACE HYDROCARBON SEEP
	SILURIAN LONE MOUNTAIN DOLOMITE		
	ORDOVICIAN VININI FORMATION		

Figure 3. Geologic map of the Blackburn oil field and vicinity. Geology of the immediate field area is subcrop beneath Tertiary-Quaternary valley-fill sedimentary and volcanic rocks.

Figure 4. Interpretive geologic sections through the Blackburn oil field.

- EXPLANATION -

○	Quaternary surficial deposits		High-angle normal fault, bar and ball on downthrown block
●	Oligocene ignimbrites		Low-angle thrust fault, saw teeth on upper plate
■	Cretaceous granite	●	Productive oil well
■	Pennsylvanian Ely Limestone	⊗	Non-productive oil well
■	Mississippian Chainman Shale		
■	Mississippian Joana Limestone		
■	Devonian Guilmette Limestone (dolomite)		
■	Cambrian siliciclastic and carbonate rocks, undivided		

Figure 5. Generalized geologic map of the Grant Canyon-Bacon Flat oil field, Nye Co., Nevada. Geology of the oil field, to the west, is subcrop beneath post-Oligocene valley-fill sedimentary rocks.

- EXPLANATION -

	Post-Oligocene valley-fill sediments and Quaternary surficial deposits, undivided		Normal fault, showing displacement
	Oligocene ignimbrites		Thrust fault, saw teeth on upper plate
	Cretaceous granite		Productive oil well showing principal producing interval
	Pennsylvanian Ely Limestone		Non-productive oil well
	Mississippian Chainman Shale		
	Mississippian Joana Limestone		
	Devonian Guilmette Limestone (dolomite)		
	Cambrian and Ordovician siliciclastic and carbonate rocks, undivided		

Figure 6. Geologic section through the Grant Canyon-Bacon Flat oil field.

autochthonous, overlying Nevada Group dolomites in normal stratigraphic succession. We will present evidence later in this proposal which strongly supports the Scott and Chamberlain (1988) model for Chainman emplacement. However emplaced, the Chainman at Blackburn is unconformably overlain, by the Oligocene Indian Well Formation, a felsic ignimbrite sheet which hosts minor amounts of oil in probable cooling joints and other fractures (Scott and Chamberlain, 1988; Johannesen and Cole, 1990).

The nature of the deep Nevada Group dolomite reservoir rock at Blackburn is summarized by Scott and Chamberlain (1988) and Johannesen and Cole (1990). The trap is structural, fundamentally a horst (Fig. 4) within which Scott and Chamberlain (1988) believe the dolomites may form a gentle local anticline. The dolomite reservoir's top seal is provided both by the Chainman Shale and by clay-rich Indian Well ignimbrite. Porosity in the Nevada Group dolomite is dominantly fracture-controlled, but enhanced by dissolution (Bereskin et al., 1989; Hulen et al., 1990); Scott and Chamberlain (1988) also reported minor intercrystalline porosity. Measured total porosity in the dolomite reservoir ranges from 2.9-7.7% (Johannesen and Cole, 1990) and averages about 5.3% (Scott and Chamberlain, 1988). Permeability ranges from 13 to 950 md (avg. about 21 md). Estimated ultimate oil recovery from the Blackburn field is 6 million barrels (Scott and Chamberlain, 1988).

Although only scattered, narrow igneous dikes have been mapped in the nearby Sulphur Spring Range (Roberts et al., 1967), principally in the Mineral Hill mining district (Fig. 2), three Blackburn wells penetrate granitic rock. Wells 1 and 6 (Figs. 3 and 4) bottom in hydrothermally altered (chlorite-sericite-calcite-epidote), medium-crystalline, biotite granodiorite (Hulen et al., 1990). Scott and Chamberlain (1988) reported this granodiorite as Tertiary in age; Johannesen and Cole (1990), who refer to the rock as quartz monzonite, cite unpublished K-Ar dates indicating that it is actually a late Cretaceous pluton.

The contact between the Blackburn granodiorite and the Paleozoic rocks of the oil field has been penetrated in only one well, Blackburn 5 (Figs. 3 and 4). Here, Chainman Shale immediately above the stock contains abundant mixed-layer illite/smectite with up to 35% smectite interlayers.

Since illite/smectite of this expandability typically indicates a formation temperature of $<150^{\circ}\text{C}$ (if hydrothermally formed; even less if developed gradually under typical deep-basin diagenesis; Pollastro, 1990), the Chainman in well 5 is not in intrusive contact with the Blackburn granodiorite; this relationship supports the gravity-slide model of Chainman emplacement proposed by Scott and Chamberlain (Fig. 4), but juxtaposition of the Chainman and the granodiorite by other types of faults cannot be ruled out.

Hydrothermal alteration and mineralization in the Sulphur Spring Range near the Blackburn field are as sparsely distributed as the exposed dikes previously mentioned. In the Mineral Hill mining district, however (Fig. 2), lead-silver-copper ores worth \$2.5 million (at then-prevailing prices) were produced from fractured and silicified Nevada Group dolomites (Roberts et al., 1967). The principal primary ore minerals in these ores were galena, sphalerite, tetrahedrite, and pyrite; associated nonmetallic gangue minerals included quartz, calcite, and barite. All these hydrothermal phases except tetrahedrite have now been discovered in cuttings and cores from deep dolomites of the Blackburn field (silver concentrations locally reach 0.75 oz/T in cuttings from well Blackburn 10 (Fig. 3).

Present temperature at the depth of the Blackburn dolomite reservoir is about 120°C (Johannesen and Cole, 1990), roughly double that predicted assuming the $30^{\circ}\text{C}/\text{km}$ geothermal gradient typical for this particular sector of the Basin and Range. In the absence of a young (<1 Ma), shallow, magmatic heat source, for which there is no evidence, this thermal anomaly requires convective heat transfer at depth, probably by upflow of geothermal waters along range-front normal faults at the western margin of the Sulphur Spring range. The present surface expression of this geothermal system is probably the methane-emanating, travertine-depositing Bruffey hot spring (90°C) and gas seep (Fig. 3). Analysis of geothermal waters collected from the oil-productive dolomite reservoir (2176-2198 m depth) in well Blackburn 3 yielded the following results: Na--619 ppm; Ca--56 ppm; Mg--23 ppm; Cl--536 ppm; SO_4 --226 ppm; HCO_3 --722; total dissolved solids--2182 ppm; pH--6.3 (Johannesen and Cole, 1990).

Grant Canyon/Bacon Flat: Figure 5 is a simplified geologic map of the Grant Canyon and

Bacon Flat oil fields and vicinity, at the eastern edge of Railroad Valley. The oilfield geology is interpreted subcrop immediately beneath Cenozoic valley fill (modified from Veal et al., 1988). Geology of exposed bedrock at the edge of the Grant Range, immediately to the east, is modified from Kleinhampl and Ziony (1985). In this portion of the range, gently folded mid-Paleozoic carbonate strata, including the Devonian Guilmette Limestone (the principal reservoir rock in both oilfields), are in thrust contact with underlying, locally metamorphosed Cambrian to Ordovician carbonate and siliciclastic rocks. A few km south of the map area, these rocks are intruded Late Cretaceous granite of the Troy stock. According to Fryxell (1988), the Troy stock and its host rocks display structures similar to those of the classic metamorphic core complexes (e.g. Armstrong, 1982) -- prominent low-angle faults, commonly separating the granite from overlying Paleozoic strata; relatively flat-lying shear zones and mylonites or protomylonites in the upper regions of the stock; and K-Ar ages indicating high-temperature re-heating of the stock during Miocene Time (about 22 Ma). However, Fryxell (1988) notes that the low-angle faults cutting the stock and its roof rocks disrupt metamorphic gradients and probably have displacements measurable in thousands of meters rather than the tens of kilometers typical of detachment faults related to true metamorphic core complexes. In spite of these observations and reservations, and in view of some of our findings from this year's field work at Grant Canyon, we believe that low-angle faulting must be given serious consideration in attempting to model the subsurface geology of the Grant Canyon and Bacon Flat fields.

An interpretive geologic section through the Grant Canyon and Bacon Flat oilfields, based on oil-well intercepts obtained from Garside et al. (1988) is shown as Figure 6. Veal et al. (1988) published three alternative reconstructions for this same section; a fourth along essentially the same line is presented by Read and Zogg (1988). Common to all these interpretations is the location and nature of the reservoir -- fractured Devonian dolomite capping a buried basement high immediately beneath and sealed by an impermeable, clay-rich, Miocene sedimentary sequence.

Current reservoir temperature in the Grant Canyon oilfield is about 120°C; at Bacon Flat, the temperature reaches 171°C (Veal et al., 1988). In addition to being prolific oil producers,

therefore, the fields, if hydraulically connected, would formally qualify as a moderate- to high-temperature geothermal system (Renner et al., 1975; Brook et al., 1979). In fact, hot water in the Bacon Flat No. 1 well (Fig. 3) commonly flashes to steam in transit to the surface (Veal et al., 1988). It seems likely that this active geothermal system could enhance the generation of large volumes of mature hydrocarbon from otherwise (in Railroad Valley; Poole et al., 1983) submature but organic-rich Mississippian source rocks in the Chainman Shale. We also have new evidence (to be discussed) from this research project that geothermal waters at Grant Canyon/Bacon Flat may have actually transported petroleum to ultimate entrapment sites.

Reservoir porosity at Grant Canyon is dominantly fracture-controlled, though earlier-formed dissolution vugs are locally present (Veal et al., 1988; Read and Zogg, 1988). At least four generations of fractures are represented, but one fracture set accounts for 60-90% of the total reservoir volume (Read and Zogg, 1988), and is locally responsible for much of the 20% porosity in the dolomite host rock. The fractures of this important set, along with intraclast vugs in associated breccias, are open, interconnected, and lined with cryptocrystalline to fine-crystalline quartz. Many of the breccias contain rounded clasts (Read and Zogg, 1988) in a rock-flour matrix. Read and Zogg (1988) suggest three possible origins for the productive Grant Canyon fractures and breccias: (1) tectonic disruption accompanying faulting; (2) solution brecciation developed in paleo-karst terrain; (3) "steam blast" brecciation due to heating of meteoric water in the Devonian dolomite by overlying Oligocene ignimbrite sheets, in turn leading to fluid overpressuring and resultant rock rupture. We have suggested a fourth alternative -- hydrothermal brecciation and hydraulic fracturing by high-temperature, meteoric- and perhaps even magmatic-hydrothermal fluid generated by intrusion of the underlying Cretaceous (?) quartz monzonite (the oil-bearing Grant Canyon dolomite breccias are texturally very similar to the hydrothermal breccias of the Blackburn field). To date, however, our fluid-inclusion and alteration studies at Grant Canyon have not supported this interpretation. Perhaps more importantly, though, the fluid-inclusion work has revealed that moderate- to high-temperature geothermal waters (perhaps still circulating) may have played a major role in evolution of the oil reservoir. It appears there are yet other geothermal

connections for the Basin-and-Range oilfields.

RESEARCH PROGRESS TO DATE

Our research to date has been focused on investigation of magmatically-driven, high-temperature hydrothermal fracturing as a porosity-creating mechanism for the Grant Canyon/Bacon Flat and Blackburn oilfields. Such secondary porosity is critical in the formation of these fields, and understanding its development remains a major goal. If it can be firmly established that some oil reservoirs in the Basin and Range are hosted by igneous-related hydrothermal breccias and stockwork fractures, then buried plutons in the province will become important additional petroleum exploration targets. As hinted above, results of our work have strongly suggested additional, perhaps even more important geothermal connections for the Basin-and-Range oilfields; these are discussed in the text which follows.

Our work at Blackburn and Grant Canyon/Bacon Flat has consisted of: (1) reconnaissance geologic mapping; (2) detailed logging of selected cuttings and cores from the fields, with emphasis on lithology, fracturing and brecciation, hydrothermal alteration, and mineralization; (3) petrographic studies, with the same emphasis as item 2; (4) detailed fluid-inclusion studies of oil-reservoir rocks.

Blackburn Results: Reconnaissance geologic mapping in the Blackburn area has been centered on the Mineral Hill mining district (Fig. 2; Emmons, 1910; Roberts et al., 1967), which we now believe to be an exposed analogue of the dolomite-hosted Blackburn oil reservoir itself.

The ores of Mineral Hill are hosted almost entirely by folded, steeply-dipping, locally overturned, dolomitic limestones of the Devonian Nevada Group (also the principal oil reservoir rock at Blackburn), overlain in thrust contact by siliceous shales and argillites of the Ordovician Vinini Formation. The Nevada Group carbonates are locally intruded by narrow, fine-crystalline, felsic dikes which petrographic and bulk XRD analysis show as totally altered to quartz and well-crystallized sericite. The Mineral Hill ores are veins, breccia cements, and replacement masses occurring irregularly within an area about 370 X 100 m in extent and reaching less than 50 m

below the present ground level. The veins, breccia cements, and associated stockwork veinlets are dominantly quartz with minor barite, calcite, and dolomite; primary metallic minerals comprise galena, pyrite, argentite, polybasite, tetrahedrite, sphalerite, and possible traces of molybdenite. Much of the ore is oxidized, and common secondary minerals include malachite, azurite, cerussite, smithsonite, cerargyrite, pyromorphite, and a variety of hydrous iron and manganese oxides.

The mineralized Mineral Hill breccias are of almost certain hydrothermal origin, based on their textures and association with high-temperature mineralization. The breccias, like those deep in the dolomites of the Blackburn field, have "jigsaw-puzzle" textures indicating forceful expansion of the shattered rock in three dimensions (e.g. Hedenquist and Henley, 1985; Sillitoe, 1985) rather than crushing and shearing along a fault. The clasts in these quartz-sulfide-sulfosalt-cemented breccias are sharply angular, with no sign of shearing whatsoever. Fluidized hydrothermal breccias with rounded clasts in rock-flour matrices were not observed, but may yet be discovered by detailed mapping. High temperatures ($>250^{\circ}\text{C}$) are indicated for the mineralization at Mineral Hill based on: (1) the presence of well-crystallized molybdenite (e.g. Westra and Keith, 1980); (2) the highly-ordered nature of sericite replacing feldspar in the Mineral Hill dikes (it is essentially $2M_1$ muscovite (e.g. Pollastro, 1990); (3) reconnaissance fluid-inclusion T_h for primary liquid-rich inclusions in the Mineral Hill breccias ($233\text{--}288^{\circ}\text{C}$).

The Mineral Hill mining district shares the following attributes with the deep oil reservoir at Blackburn: (1) a Devonian carbonate host rock -- essentially all dolomite at Blackburn, dolomitic limestone at Mineral Hill; (2) high-temperature hydrothermal fracturing and brecciation (to be discussed in detail below for Blackburn); (3) high-temperature hydrothermal mineralization--many of the Mineral Hill ore and gangue minerals are also found in the Blackburn dolomites; (4) the presence of igneous intrusions (magmatic heat sources) -- dikes at Mineral Hill, a small stock at Blackburn. In short, the Mineral Hill district appears to be a fortuitously exposed version of the deep Blackburn dolomite-hosted oil reservoir, providing an excellent opportunity to gather additional, otherwise unobtainable information about how such reservoirs are developed. We plan to map the Mineral Hill district in detail when the area is free of snow early in the Spring of 1991.

We have obtained all cores and cuttings for the Blackburn field from Amoco Production Company in Denver. A full set of these samples was unavailable from the Nevada Bureau of Mines; only archival samples remained for several of the production wells, and these were not available for destructive analyses. The cores and cuttings are being logged in detail, and selected samples are being petrographically characterized and analyzed for fluid-inclusion microthermometry. Logging of the cores was the first task accomplished, since only they preserve the large-scale textures and paragenetic relationships necessary for reconstruction of the reservoir rocks' tectonic and hydrothermal evolution.

Cores and cuttings from the deep oil reservoir at Blackburn are principally microcrystalline to fine-crystalline dolomites, extensively fractured, brecciated, and hydrothermally veined. These features were developed in several different stages, based on cross-cutting relationships and vein- or vug-filling sequences. The sequence of development is interpreted as follows (Fig. 7; see also Hulen et al. 1990). After recrystallization (to essentially a fine-grained marble), the dolomite was extensively hydrothermally fractured and brecciated (as at Mineral Hill, based on diagnostic textures and mineralization). After the first event, fractures and breccias were partially to completely cemented with coarsely-crystalline "saddle" dolomite. Following the second event, the dolomite was dissolved, and the resulting open spaces partially and locally cemented with hydrothermal quartz with minor amounts of pyrite, sphalerite, and galena. After an unknown length of time, hydrothermal barite was deposited in much of the open space which remained. A third episode of fracturing and brecciation was followed by partial dissolution of barite, then by sparse precipitation of quartz, pyrite, and an unknown opaque organic material. These late veinlets were also fractured, allowing ingress of acidic solutions which locally enlarged fractures by dissolution of dolomite and pyrite but also locally clogged porosity by depositing the kaolin-family mineral dickite. Finally, an unknown length of time after dickite deposition, oil migrated into all available pores.

Open spaces along some of the Blackburn fractures and veinlets contain trace amounts of sand-size, variably rounded epidote, quartz, and feldspar grains as well as shredded, chloritized

Figure 7. Paragenesis of vein mineralization and petroleum entrapment, Blackburn oil field.

biotite. These grains only rarely occur embedded in other secondary minerals, and reliable determination of their age, origin, and significance requires further investigation. However, the aggregate composition of these stringers closely mimics that of the underlying, altered, Blackburn granodiorite. It is possible that these minerals were transported from the granodiorite to their present positions as hydrothermally fluidized clastic debris (e.g. Fournier, 1983; Hulen and Nielson, 1988; Phillips, 1972, 1973; Burnham, 1979).

The temperatures and compositions of the fluids circulating during disruption and mineralization of the deep Blackburn dolomites have been investigated by fluid-inclusion microthermometry. These paleo-fluid packets are especially numerous in early vein dolomite, commonly forming three-dimensional arrays of primary origin in crystal growth zones. Blackburn barite lacks these growth zones, but three-dimensional arrays of inclusions are common, and these are also of probable primary origin. Hydrothermal quartz observed to date contains usable inclusions only where intergrown with sphalerite and galena (also present at Mineral Hill), and these are generally of ambiguous origin. None of the Blackburn vein minerals host petroleum inclusions, indicating that oil migration and entrapment probably followed vein mineralization by an unknown length of time.

All the Blackburn fluid inclusions were two-phase (liquid plus vapor) and either liquid-rich or vapor-rich at room temperature. The liquid-rich inclusions homogenized to the liquid phase upon heating to the appropriate temperature; the vapor rich inclusions could not be analyzed because they were too small (diameter < 1 micron).

Results of fluid-inclusion microthermometry for the Blackburn samples are summarized on Figure 8. Primary liquid-rich inclusions in early vein dolomite homogenize in a surprisingly high temperature range (351-400°C); primary quartz-hosted inclusions at 224°C and 235°C; and primary barite inclusions at 115-131°C. Secondary inclusions and those of ambiguous origin in these minerals homogenize at corresponding or generally lower temperatures (Fig. 8). The high paleotemperatures recorded by the early vein dolomite crystals (and probably those by the earliest quartz) are not only more than sufficient for hydrothermal brecciation (assuming other variables

Figure 8. Homogenization temperatures of fluid inclusions in vein-and vug-filling minerals, Blackburn oil field.

such as state-of-stress and rock tensile strength are favorable; e.g. Hulen and Nielson, 1988), but also require a magmatic heat source -- more than likely the underlying and adjacent Blackburn stock (Figs. 3 and 4). It is significant that none of the Blackburn fluid inclusions examined to date contain oil, a prominent constituent of fluid inclusions in the Grant Canyon field. This relationship strongly suggests that oil migration and entrapment at Blackburn followed vein mineralization after an unknown length of time.

Results of our initial work on selected cores and cuttings from the dolomite reservoir rock of the Blackburn field (summarized in Hulen et al., 1990) have confirmed prior suspicions that rupture of the rock was in part due to high-temperature, magmatically-driven, hydrothermal fracturing and brecciation. A high-temperature hydrothermal system once circulated where oil is now concentrated. Besides the presence of a small pluton -- once a vigorous heat engine -- other factors in support of hydrothermal brecciation at Blackburn are as follows: (1) high-temperature fluids, conducive to natural hydrothermal rock rupture, once circulated in the reservoir rock -- early vein dolomite was precipitated at temperatures greater than 350°C, quartz at greater than 225°C; (2) planes of vapor-rich inclusions in the early vein dolomite permissively indicate that the mineralizing fluids boiled intermittently, possibly due to the pressure release that would accompany hydrothermal brecciation; (3) the epidote-chlorite-quartz-feldspar stringers in the dolomite could indicate hydrothermal fluidization, entrainment, and transport of rock debris from the underlying Blackburn granodiorite. It remains to be determined just how extensive hydraulic rock rupture was in the deep Blackburn dolomites, how deep and under what pressure the rupture took place, and how to explore for similarly disrupted carbonate reservoirs where concealed elsewhere in the Basin and Range. The affects of an ancient (Late Cretaceous?) hydrothermal system at Blackburn in creating porosity for the petroleum reservoir are becoming ever more apparent. Our research to date on this field has also revealed evidence that more recent hydrothermal systems may have played an important role in the field's evolution. For example, petrographic and XRD studies have shown that non- to moderately welded Oligocene ignimbrites directly overlying the Chainman Shale in several wells (Fig. 4) are intensely altered to smectite, kaolin, quartz, and marcasite --

essentially no primary feldspar remains, and secondary clay minerals commonly account for >50 wt. % of these tuffs.

These intensely argillized ignimbrites (and associated volcaniclastic sedimentary rocks) certainly help provide top and side seals for the Nevada Group dolomite-hosted and Chainman Shale-hosted portions of the Blackburn reservoir. The age of the argillization (beyond post-Oligocene) is unknown, but deserves investigation. (Potassium-bearing secondary phases have not been found in Blackburn cuttings and cores, but any are discovered they will be considered for dating by K/Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ methods; young carbonates conceivably could be dated by uranium-disequilibrium methods). The argillic alteration assemblage represented by the Blackburn caprock suggests a low to moderate formation temperature (<150°C), compatible with current field conditions (about 120°C at 2100 m; Johannesen and Cole, 1990). Could trap sealing and oil migration/entrapment at Blackburn have taken place in a geologically recent, moderate-temperature geothermal system? This suggestion is supported by the nearby presence of the Bruffey hot spring/petroleum seep (Fig. 3), which issues at a temperature of about 90°C (Foster et al. 1979), and actually produces significant quantities of methane; shallow wells drilled near the Spring produced small (non-commercial) amounts of oil (Foster et al., 1979).

We suggest that the Blackburn oil field may have had a dual or multiple hydrothermal origin: An early, high-temperature system hydrothermally fractured what were to become the reservoir rocks; a subsequent, lower-temperature system (or systems) may have top- and side-sealed the fractured reservoir rock by argillically altering Oligocene ignimbrites and volcaniclastic rocks; the same or an even younger (and maybe even contemporary) system may have transported petroleum to the entrapment site.

Grant Canyon/Bacon Flat Results: Numerous wells in the Grant Canyon oil field have penetrated a concealed granitic pluton (Fig. 5) which Read and Zogg (1988) believe is probably the subsurface extension of the Late Cretaceous (with Miocene reheating) Troy stock exposed in the Grant Range a few km south-southeast of the field. The nature of the contact of the deep pluton at Grant Canyon with overlying Paleozoic rocks (including the oil-bearing Devonian dolomite breccia) remains speculative. Veal et al. (1988) suggest that it

could be either an intrusive or low-angle fault contact. Read and Zogg (1988) favor the latter interpretation. Results of our reconnaissance mapping in the low hills just south of the map area (Fig. 5) also suggest that the stock/Paleozoic contact may be structural in nature. The contact in that area, exposed by numerous adits and prospect pits, is a subhorizontal, two-meter-thick mylonite zone separating highly sheared granite from overlying, complexly folded Paleozoic limestones, argillites, and quartzites. This relationship, if verified for the Grant Canyon field, has important implications for the origin of the Devonian dolomite breccias hosting most of the field's petroleum reserves. If these carbonates are simply the upper plate of a low-angle detachment fault above granitic rock, then a magmatic heat source for hydrothermal brecciation of the (now) oil-bearing dolomites is less likely than we initially envisioned (however, this does not rule out the possibility that high-temperature fluids heated by another sector the pluton hydrothermally ruptured the carbonates prior to detachment faulting). Understanding the nature of the pluton/Paleozoic contact in the Grant Canyon field remains one of our highest priorities during the coming field season.

Textures of the oil-bearing Devonian dolomite breccias at Grant Canyon are nearly identical to those of the Blackburn field (though the Blackburn breccias are far more complexly mineralized). It was this similarity, and the subjacent occurrence of felsic plutons at both fields, that led us to propose a common origin for the breccias -- high-temperature, igneous-related hydrothermal rock rupture. As outlined above, petrographic and fluid-inclusion studies have strongly supported this hypothesis for the Blackburn field. However, results are inconclusive for Grant Canyon. Although the Grant Canyon and Blackburn breccias are texturally very similar, fluid-inclusion T_h are far lower for the Grant Canyon rocks than for their Blackburn counterparts (less than 161°C (most less than 135°C) vs up to 408°C for Blackburn). While hydrothermal brecciation may have rubblized the Grant Canyon reservoir rocks, there is no evidence yet that the brecciating fluids were magmatically heated. Fluid inclusions at Grant Canyon do, however, provide surprising direct evidence that petroleum migration and entrapment in this prolific oil field may have occurred in a moderate- to high-temperature hydrothermal system.

Figures 9 and 10 graphically portray the results of our Grant Canyon fluid-inclusion studies to date. All the inclusions measured occur in the brecciated dolomite reservoir rock at an average depth of about 1350 m. The inclusions are hosted by relatively early (pre-breccia), coarsely-crystalline, "saddle" dolomite and by late-stage euhedral quartz cementing the breccia. The inclusions in these two minerals are two- and three-phase (liquid water and/or oil plus vapor). Primary inclusions with a wide range of oil/water ratios are commonly found in individual growth zones of a single quartz crystal, indicating entrapment from a dispersion of oil droplets in aqueous solution.

All the Grant Canyon fluid inclusions we have measured homogenize to the liquid phase at relatively low temperatures (Fig. 9) -- aqueous inclusions in saddle dolomite at 96.2-161.3°C; primary oil, water, and oil/water inclusions in quartz at 103.8-120.9°C; and secondary inclusions containing oil and water in various proportions in both dolomite and quartz at 90.4-120.9°C.

There are two temperature maxima apparent on the T_h vs frequency plot for the Grant Canyon inclusions -- one at about 120°C, the other at about 150°C (Fig. 9). Note that all quartz-hosted inclusions and virtually all oil-bearing inclusions are associated with the lower-temperature maximum. These relationships become even clearer when only primary-inclusion T_h data are plotted (Fig. 10). On this plot, it is apparent that: (1) only the dolomite-hosted inclusions homogenize at relatively higher temperatures; (2) all the quartz-hosted fluid inclusions homogenize at relatively lower temperatures; (3) only quartz-hosted primary inclusions contain oil. From this latter observation, it follows that initial oil entrapment post-dated saddle dolomite deposition and accompanied precipitation of hydrothermal quartz. Ice-melting temperatures of the inclusions indicate that while the fluids responsible for saddle dolomite mineralization were high-salinity brines, those which later carried oil and precipitated hydrothermal quartz were relatively dilute (<2.2 wt. % equiv. NaCl).

Current reservoir temperatures at Grant Canyon are similar to those implied by T_h of primary fluid inclusions in quartz -- about 120°C; reservoir temperatures at a little over 1600 m in

Figure 9. Homogenization temperatures of primary and secondary fluid inclusions in vein- and vug-filling quartz and dolomite from the Grant Canyon oil field.

Figure 10. Homogenization temperatures of primary fluid inclusions in vein- and vug-filling quartz and dolomite from the Grant Canyon oil field.

the nearby Bacon Flat field have been measured at 171°C (Veal et al., 1988). Moreover, aqueous fluids associated with the Bacon Flat and Grant Canyon oil reservoirs, like the aqueous inclusions in the Grant Canyon quartz, are relatively dilute (Read and Zogg, 1988).

Publications: Some of the results of our Blackburn and Grant Canyon/Bacon Flat research have been presented in the AAPG Bulletin as follows:

Hulen, J.B., Bereskin, S.R., and Bortz, L.C., 1990, High-temperature, natural hydraulic fracturing as a reservoir control in the Blackburn oil field, Nevada -- Implications for petroleum exploration in the Basin and Range province (abs.): AAPG Bull., 74, 769.

Hulen, J.B., Bereskin, S.R., and Bortz, L.C., 1990, High-temperature hydrothermal origin for fractured carbonate reservoirs in the Blackburn oil field, Nevada: AAPG Bull., 74, 1262-1272.

Allison, M.L., and Hulen, J.B., 1990, Oil and igneous intrusions in Nevada (abs.): AAPG Bull., 74, 1313.

Hulen, J.B., Bereskin, S.R., and Lemieux, M.M., 1990, Timing and temperature of petroleum entrapment in the Grant Canyon oil field, Nevada (abs.): AAPG Bull., 74, 1328.

HYPOTHESIS: THE ROLE OF ACTIVE AND PALEO-HYDROTHERMAL SYSTEMS IN EVOLUTION OF THE BASIN-AND-RANGE OILFIELDS

Our research was originally designed to investigate high-temperature hydrothermal fractures and breccias as reservoir controls for the Basin and Range oil fields (Appendix 2). Initial results have confirmed these features as sources of critical secondary porosity in the Blackburn field; their influence at Grant Canyon/Bacon Flat remains to be fully evaluated. In the course of our fracture/breccia studies, however, we have discovered evidence that hydrothermal mechanisms may have exerted a much greater and more comprehensive influence over Basin-and-Range oil-reservoir evolution than initially envisioned. Moreover, the fact that both the Blackburn and Grant Canyon/Bacon Flat fields are intimately associated with active geothermal phenomena (e.g. petroleum-bearing hot springs, high subsurface water temperatures) suggests the intriguing possibility that hydrothermal oil-reservoir genesis may be an ongoing phenomenon (more below) in the Basin and Range.

Figure 11 schematically illustrates this concept for the Grant Canyon/Bacon Flat field. Recharge for both active and prior hydrothermal systems at this site is envisioned as meteoric and

Figure 11. Schematic east-west geologic section through the Grant Canyon/Bacon Flat oil field, illustrating the role of a hypothetical, moderate- to high-temperature meteoric-hydrothermal system in oil migration and entrapment as well as top-and side-sealing of the reservoir traps.

originating in the lofty (up to nearly 3500 m elev.) Grant Range to the east. These meteoric waters percolate downward into Railroad Valley along fracture networks and both low-angle faults (Mesozoic overthrust faults and Oligocene-to Miocene-age detachment faults; Kleinhampl and Ziony, 1985; Fryxell, 1988) and Miocene- to Quaternary-age, moderate- to high-angle, Basin-and-Range normal faults at the Grant Range's north-south-trending western front. As they descend into the fractured basement flooring Railroad Valley, they are gradually heated under the influence of an anomalously high geothermal gradient (there is no evidence of a young (<1 Ma), magmatic heat source). Upon warming, the waters dissolve silica and other constituents from the rocks through which they percolate. As they encounter favorable structural conduits, these silica-charged thermal waters buoyantly ascend, and in transit to the surface incorporate oil. (The oil may actually dissolve in the hot hydrothermal waters or may be incorporated as droplets or globules). The source of the deep oil is the Mississippian Chainman Shale (as "fingerprinted" by Veal et al., 1988), but the nature of the deep oil accumulation is unknown. Even though high temperatures prevail at depth beneath Grant Canyon/Bacon Flat, it is unlikely that large quantities of petroleum are now being generated from the Chainman. (However, Kvenvolden and Simoneit, 1990, have documented contemporary oil generation at high (350°C ?) temperatures near the Guaymas Basin spreading center in the Guaymas Basin in the Gulf of California). It is much more likely that the hypothetical Grant Canyon hydrothermal system simply remobilized oil from an older and deeper reservoir.

Upon encountering the highly porous dolomite breccias at the tops of the Bacon Flat and Grant Canyon horsts (Fig. 11), the petroleum-charged fluids would begin to migrate laterally beneath a cap of Oligocene ignimbrites and volcanoclastic rocks. This natural seal would be enhanced by hydrothermal argillic alteration and calcite flooding induced by the circulating thermal fluids (ignimbrites immediately overlying the Bacon Flat reservoir contain little or no fresh glass and up to 25% calcite and 30% sodium-rich smectite -- note also that sodium-rich smectites are highly prone to swelling in dilute waters, thereby further enhancing the oil-reservoir seal). Silica would precipitate in the porous breccias as euhedral quartz, entrapping both dilute waters and

entrained oil droplets as fluid inclusions. The anomalously low temperature of this quartz precipitation -- probably about 120°C -- may have something to do with the presence of the oil itself (this phenomenon also deserves further investigation).

Because of a density differential, oil entrained in the thermal fluids would tend to accumulate at the tops of the Grant Canyon and Bacon Flat horsts; as the bases of the resulting oil reservoirs descended with time, quartz precipitation would cease. Oil-depleted and now-cooling waters would continue circulating --out into Railroad Valley to the west; perhaps downward to rejoin fresh meteoric recharge waters to the east (Fig. 11).

The suggested scenario for oil-reservoir formation is somewhat different for the Blackburn field, where no oil inclusions have been found to date in any hydrothermal mineral (Hulen et al., 1990). It seems likely that here, oil migration and entrapment probably followed much or all of the vein mineralization. However, the fact that a 90°C, petroleum-bearing hot spring issues very near the field suggests that hydrothermal processes other than high-temperature hydraulic fracturing may have promoted oil accumulation. For example, our reconnaissance XRD and petrographic analyses show that Oligocene ignimbrites capping the field contain up to 65% smectite, 10% kaolin, and 3% marcasite. Surely, such hydrothermally altered rock forms a highly effective secondary top seal for the deeper Blackburn oils, even though the ignimbrite itself locally hosts minor oil concentrations (Scott and Chamberlain, 1988). Remaining to be determined at Blackburn: When did this alteration take place, and in what way (if any) is it related to the presently circulating geothermal system?

Geothermal systems have long been a common feature of the region now known as the Basin and Range province. Fossil systems, for example, are well represented by the region's rich, disseminated precious-metal deposits (e.g. Percival et al., 1988; Bonham, 1988). Contemporary systems are also plentiful, and most, like Beowawe near Battle Mountain (Sibbett, 1983), owe their existence to deep circulation of meteoric waters in a broad zone of anomalously high geothermal gradient (Blackwell, 1983). We suggest, based on results of our research to date, that both active and fossil systems may have been far more instrumental in the formation of these

reservoirs than we initially proposed. Not only have these systems locally induced critical secondary porosity (hydrothermal fractures and breccias), they may also have: (1) matured petroleum in otherwise submature source rocks; (2) transported petroleum to entrapment sites by convection in moderate- to high-temperature dilute aqueous solutions; (3) sealed reservoir traps by hydrothermal argillic (and other) alteration of overlying ignimbrites and volcaniclastic rocks. We propose to expand our current, OBES-sponsored, hydraulic-fracture research at the Blackburn and Grant Canyon/Bacon Flat oil fields to encompass the broader role of active and fossil hydrothermal systems in Basin-and-Range oil-reservoir evolution.

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APPENDIX 1.

REGIONAL GEOLOGY OF THE EAST-CENTRAL BASIN AND RANGE PROVINCE

Nevada's productive petroleum reservoirs are confined to the east-central Basin and Range physiographic province, a land characterized by narrow, northerly-trending, fault-block mountains and intervening, deeply-alluviated valleys. The Basin and Range owes its present structural configuration to still-active, east-west-directed, regional extension which commenced at about 20 Ma (Stewart, 1983). Geologic mapping of the ranges and deep drilling of the valleys, however, have revealed an intricate prior geologic history recorded by rocks as old as late Proterozoic (Burchfiel and Davis, 1972, 1975; Speed, 1983). Paleozoic geologic history of the Basin and Range in a plate-tectonic framework has been summarized by Burchfiel and Davis (1972, 1975) and Speed (1983) in papers from which most of the following brief account is abstracted. These accounts explain, from different viewpoints, the dominant pre-Mesozoic tectonic events of the region: In Late Devonian-Early Mississippian and Late Permian-Early Triassic times, siliceous eugeoclinal strata were thrust up to 130 km eastward (here and throughout this proposal directions refer to present coordinates) over miogeoclinal carbonate rocks of equivalent age deposited on the Paleozoic continental shelf of North America.

According to Burchfiel and Davis (1972, 1975), much of what is now the Basin and Range between mid-Ordovician and Permian time may have been occupied by a marginal basin, flanked on the east by continental North America and on the west by the Klamath oceanic island arc (developed above an east-plunging subduction zone). Shallow-marine, miogeoclinal carbonates accumulated on continental crust east of the marginal basin while deep-marine, eugeoclinal, siliceous sediments and volcanic rocks were deposited on oceanic crust in the basin itself. During late Devonian and early Mississippian time, the basin began to close, and a second subduction zone, northerly-trending and eastward-plunging, may have formed at the basin's eastern margin (Burchfiel and Davis, 1975); as oceanic crust was subducted to the east, overlying, western-assemblage siliceous rocks were apparently obducted eastward up to 130 km over eastern-assemblage carbonate strata to form the famous Roberts Mountains overthrust, or allochthon (Merriam and Anderson, 1942; Roberts, 1949). Contemporaneously, the Antler highland or orogenic belt (Roberts, 1949) was elevated parallel to and immediately east of the inferred marginal-basin subduction zone. Siliciclastic sediments shed eastward from the Antler belt accumulated above the Roberts Mountains allochthon during Mississippian time in a marine foreland basin. Among these sediments were distal, organic-rich clays and silts destined to become the Chainman Shale, one of the world's best petroleum source rocks (Bortz, 1983; Pekarek, 1988) and a formation present at or near all eight producing Nevada oilfields.

The Antler highland was overlapped in early Permian time by continental marine carbonates. Burchfiel and Davis (1972, 1975) believe that during the late Permian and early Triassic, a second closure of the marginal basin discussed above led to the Sonoma orogeny (Silberling and Roberts, 1962; Roberts, 1968), a virtual repetition of the Antler tectonic episode but centered about 100 km west of the older disturbance. Like the Antler event, the Sonoma orogeny was characterized by eastward thrusting (obduction) of a siliceous, marine sequence (on the Golconda overthrust) over continental carbonate strata of equivalent age, and perhaps by contemporaneous eastward subduction of the oceanic crust on which these siliceous sediments were deposited. The Sonoma orogeny marked the closure of the Paleozoic marginal basin (Burchfiel and Davis, 1975), and the Klamath island arc to the west was accreted to the North American continent.

Speed's (1983) reconstruction of the Antler and Sonoma orogenies differs significantly from that of Burchfiel and Davis (1972, 1975). According to Speed, both disturbances were the

result of collisions of major oceanic magmatic arc systems with the passive margin of westward-drifting continental North America. In this interpretation, the Roberts Mountains and Golconda allochthons do represent eastward obduction of siliceous accretionary prisms over coeval shelf carbonates, but during westward subduction of underlying oceanic crust prior to arc-continent collisions.

Between 235 and 215 Ma (late Triassic), the andean-type Sierran continental magmatic arc emerged in eastern California and western Nevada (Hamilton, 1969). North of what is now the "bend" in Nevada's western border, this new arc was oriented north-northeast, parallel to the Paleozoic tectonic trends discussed above. South of the "bend", however, the arc was aligned northwest-southeast, truncating the older trends (probably the result of either rifting across a spreading center or transform faulting; Burchfiel and Davis, 1975). This arc was active until at least 80 Ma, and its granitic roots are presently preserved as the Sierra Nevada batholith.

East of the Sierra magmatic arc, during and shortly following its active phase, the North American foreland (including most of Nevada) suffered pronounced regional compression, resulting in development of a series of mostly northerly-trending fold-and-thrust belts (e.g. Burchfiel et al., 1970; Burchfiel and Davis, 1972, 1975; Armstrong, 1968; Speed, 1983; Cameron and Chamberlain, 1987). These include the late Jurassic to Paleocene Sevier Belt of central and southwestern Utah (Armstrong, 1968; Royce et al., 1975) and, in eastern Nevada, the Eureka belt, which as illustrated by Speed (1983) encompasses the productive Nevada oil reservoirs illustrated on Figure 1.

Although concentrated in the Sierran magmatic arc, felsic plutonism in Mesozoic time also occurred throughout the continental foreland of Nevada, between about 165 and 70 Ma. By contrast with the huge Sierra Nevada batholith, Mesozoic plutons in Nevada are widely scattered and with few exceptions are small stocks a few kilometers in diameter. Many of these plutons (for example, those of the Ely porphyry copper district in east-central Nevada) are associated with valuable, magmatic- or meteoric hydrothermal ore mineralization.

Stewart (1983) has summarized Cenozoic evolution of the northern Basin and Range. During the Paleocene and Eocene, much of this region was apparently a broad highland within which large, sedimentary basins with internal drainage locally formed. Organic-rich lacustrine sediments deposited in some of these basins, perhaps in part during latest Cretaceous time, are believed to have formed petroleum source rocks in eastern Nevada second only in importance to the Mississippian Chinle Shale (Bortz, 1983).

Cenozoic igneous activity in the Basin and Range commenced at about 43 Ma in the northern portion of the province, spreading southward within convex-to-the-south, east-west-trending belts and ending in southern Nevada at about 6 Ma (Snyder et al., 1976; Stewart et al., 1977; Cross and Pilger, 1978). Volcanic rocks erupted during this period range in composition from rhyolite to basalt, and include voluminous Oligocene ignimbrite sheets. Felsic stocks are also locally present, and like their Mesozoic counterparts many of these are associated with rich, base- and precious-metal mineralization.

Low-angle faulting of several different styles began to modify the northern Basin and Range in the early Miocene (Stewart, 1983). Many of these faults flank and were generated above Miocene metamorphic core complexes (Armstrong, 1982; Stewart, 1983). Others are low-angle gravity slides, some of which have emplaced large, tabular, range-derived Paleozoic blocks above thick alluvial sequences in adjacent valleys. For example, Bortz and Murray (1979) report a one km-long, 100 m-thick Paleozoic block in the Quaternary-Tertiary basin-fill above the Eagle Springs oil field in Railroad Valley.

The north-south-oriented, extensional block faulting characteristic of the Basin and Range today was probably initiated at about 10 Ma and, as demonstrated by scarps in recent alluvium, continues to this day. The Basin and Range structural style is characterized by normal faulting at the margins of and to a lesser extent within elevated mountain blocks and associated, downdropped valleys. In some places, the fault blocks may represent simple horst-and-graben structures; in others, they may have developed through rotation along downward-shallowing listric faults.

APPENDIX 2.

EVIDENCE FOR HIGH-TEMPERATURE HYDROTHERMAL FRACTURING AS A RESERVOIR CONTROL IN BASIN-AND-RANGE OIL FIELDS

Diagnostic textures of many fractures and breccias in the Blackburn oil reservoir suggest an explosive rather than a tectonic origin (e.g. Hulen et al., 1990; Hedenquist and Henley, 1985; Sillitoe, 1985). Fluid-inclusion data from Blackburn show that high-temperature hydrothermal fluids, favorable for hydraulic rock rupture, once circulated in the reservoir rocks (Hulen et al., 1990). Hydraulic fracturing and brecciation above and around felsic plutons at Blackburn and perhaps several other eastern Nevada oil fields apparently created significant, secondary, interconnected porosity, eventually to be occupied by commercial concentrations of oil.

Natural hydraulic fracturing and hydrothermal brecciation around plutons and in associated hydrothermal systems are discussed in Reynolds (1954), Phillips (1972, 1973), Norton and Cathles (1973), Koide and Bhattacharji (1975), Burnham (1979, 1985), Fournier (1983), Sillitoe (1985), Hedenquist and Henley (1985), Nielson and Hulen (1987), and Hulen and Nielson (1988). Sillitoe (1985) classifies the fractures and breccias as magmatic-hydrothermal and phreatic- or meteoric-hydrothermal. Those of magmatic-hydrothermal origin form as a direct consequence of the exsolution of magmatic volatiles (mostly water vapor) at pluton tops. As crystals form here in magma over a restricted temperature range, volatile concentration increases in the residual melt, leading to an increase in vapor pressure. When this vapor pressure exceeds confining forces, vesiculation, or retrograde boiling (Phillips, 1973) occurs. If the confining pressure is the lithostatic load on the pluton, retrograde boiling eventually may cause explosive rupture of the pluton's consolidated shell and enclosing host rocks. Such disruption leads to formation of a "hood" of hydraulic fractures above and around the top of the intrusive body (Koide and Bhattacharji, 1975; Burnham, 1979); it can also produce breccia pipes and dikes of several different varieties. Some of these breccia bodies are formed by fluidization and entrainment of clastic debris during outward escape of the magmatic volatiles along pre-existing zones of weakness (Reynolds, 1954; Phillips, 1972, 1973). Others may result from collapse of the pluton roof into a large, underlying, exsolved vapor bubble (Norton and Cathles, 1973).

Meteoric-hydrothermal fractures and breccias form in the high-temperature hydrothermal systems developed above and around the cooling plutons discussed above. The plutons heat large volumes of meteoric (and in some cases probably connate) waters in overlying host rocks, thereby generating convective geothermal systems (White et al., 1971). As the waters are heated deep in these systems, they become less dense and therefore buoyant, ascending along favorable conduits such as fault zones. As they approach the surface, these fluids cool, increase in density, and, if not removed from the system (in rivers, for example) may descend along its margins, be augmented by cool-water recharge, and be reheated to begin the cycle anew. Hot fluids deep in the system readily dissolve silica and other compounds from the host rocks through which they ascend. As these hot fluids reach shallower levels, they may cool, boil, or mix with other waters, processes which promote deposition of minerals such as quartz and various carbonates in open spaces (e.g. Fournier, 1983; Hedenquist and Henley, 1985). In this fashion, formerly open passages can be blocked, or sealed by secondary phases. However, the hydrothermal system beneath these blocked conduits can remain vigorous long after they are sealed. A renewed heating event can cause the vapor pressure of the fluid beneath the seal to exceed the confining pressure (Fournier, 1983), leading to rock rupture. Tectonic breakage of the seal similarly promotes the rapid release of the trapped, suddenly overpressured fluids (e.g. Hulen and Nielson, 1988). As in the deeper magmatic environment, both hydraulic fracture networks and hydrothermal breccias can be formed during these episodes (Hedenquist and Henley, 1985). Like their deeper counterparts these fractures and breccias are known to provide much of the critical, interconnected open space required to form hydrothermal ore deposits. As outlined above, we suggest that such permeability and porosity is equally favorable for the subsequent entrapment of liquid hydrocarbons. |