Text and references to accompany Nevada Bureau of Mines and Geology OF11-2

Qualitative Petroleum Potential Map of Nevada

by

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METHODS

The assessment of mineral and energy resources provides valuable information for land use planning. Such studies must make use of the best available scientific data; nonetheless, the accuracy and utility of potential maps and supplementary data are scale dependent, like other geologic data. Additionally, they are dependent on the information available at the time of the study. The evaluation of petroleum potential is a measure of the likelihood of the presence of petroleum accumulations that might be recovered in the foreseeable future; present economic conditions or technology are not a consideration. This report and map were compiled using data available in 2007; a few changes were made to the text in 2010.

Assessment methods that provide named levels of favorability (e.g., low, medium, high) for areas of minerals or petroleum occurrence are expert knowledge driven. According to Goudarzi (1984): "An aggressive and basically optimistic approach to resource evaluation is required–one with imagination and even daring. Undiscovered resources will remain undiscovered as long as investigations are limited to an inventory of known deposits or fail to suggest the potential for resources that are not proven but that are likely to be present."

The selection of categories of qualitative petroleum potential and the division of a region into areas of different potential is a subjective process. No attempt was made to estimate endowment (the sum of identified and undiscovered resources), or where such an endowment will be found. See USGS (2005) for the most recent estimate of oil and gas resources of the eastern Great Basin. The data used for this study were from sources having a wide range of scales and positional accuracy. Data compilation was at a scale of 1:1,000,000. Although the boundaries between areas of different potential are probably positionally accurate to about 1–2 km, these boundaries were commonly drawn to separate large-scale geologic features, such as basins and ranges; some of these boundaries are subject to considerable interpretation. The regional scale of this study should be kept in mind by users; it is inappropriate to use a regional (small-scale) map to evaluate the petroleum potential of local areas. Detailed studies are required to analyze the potential of such areas. In cases where boundary lines of different potential cross or are in close proximity to a small area of interest, the most reasonable interpretation of the potential for that area is that it may be in either category, or both.

The petroleum potential of Nevada has been predicted in a very general fashion (Garside and others, 1988, fig. 3; Garside and Weimer, 1986) based on known production, shows of oil or gas in exploratory wells and at the surface, proximity to areas of potential source and reservoir rocks, and the thermal maturity of the source rocks (e.g., Sandberg, 1983a, b). Areas of medium or high potential are located in the eastern part of the state, where the majority of the potential source rocks are found, and where these rocks have not been heated beyond the petroleum generation window to temperatures where hydrocarbons would be destroyed. Western Nevada consists predominantly of rocks which are not good source rocks, either because they are overmature or, in the case of some Tertiary sedimentary units, undermature due to lack of deep burial. Because the Basin and Range province is a structurally and stratigraphically complex region, its geology is relatively poorly understood in comparison to petroleum provinces in basins with simpler relationships and considerably more subsurface information. Because there are a great variety of potential reservoir types in the Basin and Range, petroleum potential is best evaluated by outlining areas containing source rocks which are within the petroleum generation window, and thus may have provided petroleum to adjacent reservoirs. Rocks which are thermally overmature are not known to be associated with preserved petroleum provinces elsewhere in the world. The presence of traps, by themselves, is not enough evidence to rate an area prospectively valuable for petroleum. It must first be demonstrated that adequate source rocks exist, and then that they may have been heated enough to generate petroleum. As reported by French (1994), the search for hydrocarbons in this region is essentially a source-rock driven play.

The qualitative petroleum potential boundaries on the map were drawn first by evaluating whether or not potential source rocks are nearby, and if they have not been heated beyond the point of further petroleum generation or the destruction of previously generated petroleum. These data were compared with a 1983 map and description of the petroleum potential of certain Nevada wilderness lands (Sandberg, 1983a, b), and near the boundaries of the state, with similar reports for Arizona, Utah, and Idaho (Ryder, 1983; Molenaar and Sandberg, 1982; Sandberg, 1982). The 1:500,000-scale geologic map of Nevada (Stewart and Carlson, 1978) was the main source of data on mapped geologic units, although some more detailed sources were consulted. Data on conodont coloration (CAI values) were used to evaluate if these potential source rocks were overmature (Harris and Crafford, in press). The minimum CAI values reported by Harris and Crafford (2007) are displayed in three numeric ranges on the map. The analysis of petroleum-potential areas underlain by certain rock types or tectonic or volcanic features (e.g., granitic plutons, metamorphic core complexes, calderas) that are commonly very unlikely to act as reservoirs for petroleum were considered to have very low-to-no potential. These are discussed in more detail below. The boundary between low and very low-to-no potential was commonly drawn based on the presence of potential source rocks in the mountain ranges and the possibility that they are found in the adjacent valley areas. Parts of this boundary were drawn at the margin of the valley beyond the occurrence of source rocks, and adjacent to a range without such rocks. In these areas, we consider the entire valley to be permissive for the presence of source rocks, and thus to all have the same potential. This method may overemphasize the potential for parts of such valleys; a more conservative method would require dividing the valley at its midpoint. Petroleum shows in oil exploration wells are another useful factor in evaluating potential. They indicate that petroleum has been generated from source rocks and migrated at least some distance. If the shows were deemed credible, areas of low-to-high potential were commonly drawn to include them. Areas of medium and high potential were drawn based on the presence of even more favorable conditions. For example, areas with producing fields or significant shows were considered high potential, and moderate potential areas may have two or more potential source rocks, or may include rocks that are considered to have more petroleum generative capacity.

AREAS OF VERY LOW-TO-NO POTENTIAL WITHIN AREAS OF HIGHER POTENTIAL

Plutonic igneous rocks

Plutonic igneous rocks of Mesozoic and Cenozoic age as shown on the geologic map of Stewart and Carlson (1978) are considered very poor potential reservoir rocks. The outcrop areas of these rocks are considered to be in the "very low-to-no" potential category. We made no attempt to determine areas where these rocks may be concealed by younger units; in any case, such younger units could act as reservoir rocks. There is a slight chance that a Jurassic pluton could be cut and displaced by a Cretaceous thrust (for example, thrusts of the Central Nevada thrust belt of Taylor and others, 2000). The Windemere thrust of northeast Nevada and the Keystone thrust of southeast Nevada were also apparently active during this time (references in DeCelles, 2004). We consider the possibility of this as quite low, and thus consider the area under all exposed Jurassic plutonic rocks to have very low-to-no petroleum potential. The plutonic igneous rocks, which include granitic and dioritic rocks of various ages, are represented by the following map units of Stewart and Carlson (1978): TJgr, Tgr, Mzgr, Kgr, Kjd, Jgr, and TRgr.

Mesoproterozoic and Paleoproterozoic metamorphic and granitic rock

Precambrian granitic rocks and medium and high grade metamorphic rocks, mainly exposed in southern and eastern Clark County are not suitable source or reservoir rocks. They are shown as very low-to-no potential, as are some areas of adjacent shallow alluvium. The Precambrian rocks are units Ygr and Xm of Stewart and Carlson (1978).

Metamorphic complexes in eastern Nevada

Areas of extensive regional metamorphism of amphibolite grade in eastern Nevada where middle crustal rocks were brought to the surface along major mid-Cenozoic low-angle normal faults (metamorphic core complexes) have very little likelihood of trapped petroleum. Nevada's core complexes include: most of the Ruby Mountains and adjacent Wood Hills, portions of the Snake Range, and several areas in western Nevada that are considered very low-to-no potential for other reasons (i.e., Bullfrog, Silver Peak, and Trappman Hills). We also include in this category an area of amphibolite grade rocks in the central Pilot Mountains (Miller and Hoisch, 1995). We did not include areas of greenschist grade metamorphism, including the Toano Range, nor did we consider contact metamorphic aureoles around plutons. We list some evidence and references for these areas below:

1. Ruby Mountains, East Humboldt Range (Elko County): This core complex includes rocks formed at high pressures (6-7 kilobar; Miller and Hoisch, 1995). It is essentially coincident with unit KJim of Stewart and Carlson (1978). However, we used maps from several sources (Satarugsa and Johnson, 2000, fig. 1; Camilleri, 1998, fig. 2; Howard, 1980, figs. 1, 2) to digitize the boundary based on faults and unit contacts of Stewart and Carlson (1978).

2. Wood Hills (Elko County, southeast of Wells): The core complex rocks in this area formed at 5-6 kilobar (Miller and Hoisch, 1995). Camilleri (1998, fig. 2) showed the Wood Hills to include an area of Tertiary mylonite, an area of upper amphibolite facies rocks, and an area of lower amphibolite facies rocks. Snoke and Miller (1988, figs. 23-5) show a small area of metamorphosed Paleozoic strata under the Wood Hills “thrust” in the northern Pequop Mountains just east of the Wood Hills.

3. Northern Snake Range: The Snake Range is recognized as a core complex by Howard (1980, fig. 1) and Stewart (1980, fig. 40). Conrad (2005) reported metamorphic conditions consistent with 30–34 km paleodepths. The lower plate rocks, below the northern Snake Range décollement, were shown by Miller and others, 1999b, fig. 2). The outline of the complex was traced at 1:500,000 (Stewart and Carlson, 1978) by use of their figure. Klippe within the complex outline were ignored.

4. Southern Snake Range (southeastern White Pine County): Stewart (1980, fig. 40) showed a part of the southern Snake Range in his Snake Range metamorphic core complex, and Conrad (2005) mentioned it as well. The footwall Precambrian-Paleozoic strata and the Mesozoic plutons are shown by Miller and others (1999b, fig. 3). Contacts on the Stewart and Carlson (1978) map were selected to outline the core complex.

5. The east side of the central Pilot Range (eastern Elko County) consists of amphibolite-facies rocks (Miller and Hoisch, 1995). We included these rocks in the low-to-no potential group along with those in other core complexes. There are greenschist-facies rocks in the western Pilot Range; however, we did not use this metamorphism here or elsewhere to exclude areas from low or greater petroleum potential.

Tertiary Calderas

Calderas pose a more difficult problem for petroleum potential classification. Ludington and others (1996) reported that the Nevada Tertiary calderas are unlikely to preserve any basement rocks in the upper 1 km of the crust. It appears that all or nearly all of Nevada’s produced petroleum has migrated to traps after Miocene extension. Almost all calderas north of the southern Nevada volcanic field are pre-Miocene. So, the calderas were present during Neogene petroleum generation and migration. Plutons that formed below calderas are poor areas for oil accumulation, and the plutons probably cooked hydrocarbons out of some surrounding rock as well, requiring any caldera-trapped oil to migrate a considerable distance. Still, the porosity in the outflow tuffs that are one of the reservoir types in Railroad Valley is thought to be related mainly to cooling fractures. Such cooling fractures also develop in intracaldera tuffs, and migration paths to such tuffs are possible, particularly where calderas have been faulted into valleys. Calderas almost certainly have a lower probability of hydrocarbon traps than adjacent stratified rocks; but some may have a qualitatively higher probability than core complexes or plutons. Additionally, some calderas were filled by younger outflow tuffs from nearby or distant calderas. If these were faulted into valley areas, the younger tuffs would be suitable reservoir rocks (like the Trap Spring field), although lateral petroleum migration paths would be required. Because the dense compaction and widespread propylitic alteration of intracaldera tuff make these rocks more resistant to erosion, they commonly form inverted topography (Best and others, 1993). Best and others (1989, 1995) reported more that 60 calderas in Nevada. It appears very unlikely that calderas exposed in mountain ranges formed by Basin and Range extension have collected significant amounts of petroleum. The petroleum would have to migrate laterally into them, and suitable trap seals do not appear likely. However, calderas that are in graben areas may form traps in intracaldera tuffs, caldera fill, or ponded outflow tuffs from younger calderas. Seals would be the same as those for many Nevada oil fields: clay-rich ash or weathered tuff at the base of the valley fill, possibly in combination with degraded oil. Caldera boundaries on the petroleum potential map were taken from the digital data of Ludington and others (1996), who list sources of data for each caldera. They do not report the scale of compilation, but it is probably 1:1,000,000. With the exception of six of their calderas, we show all of the calderas of Ludington and others (1996) as very low-to-no potential. We describe the reasons for our categorization of the oil potential of these six calderas below. There are calderas that we know are missing from this compilation, and some caldera boundaries may not be shown correctly. We did not attempt to exclude or modify the calderas of Ludington and others (1996) within the very low-to-no potential areas.

1. The source caldera for the Stone Cabin Formation was shown by Ludington and others (based on Best and others, 1989, fig. 7) to be completely concealed by valley alluvium in the northern part Railroad Valley (northeastern Nye County). However, Best and others (1980, table 2 list a geographic coordinate for the caldera that is about 32 km to the southwest. Also, John (1994) reported the source caldera for the Stone Cabin to be in the Central Nevada Caldera Complex, also to the southwest in the vicinity of Morey Peak and the southern Pancake Range. French (1994) reported that the Stone Cabin Formation produces oil in the central part of the Trap Spring oil field, and overlies Devonian or Mississippian rocks. Oil

exploration wells (NBMG files) penetrate Paleozoic rocks below ash-flow tuffs in the area of the proposed caldera, rather than only tuff, as would be expected in an intracaldera setting. For the above reasons, we suggest there probably is no caldera under northern Railroad Valley, and if there is, it predates oil migration in the area and may act as a reservoir or contain later outflow tuffs that could be reservoir rocks. We include the area in the high potential category, similar to the adjacent area..

2. Another completely concealed caldera was shown by Best and others (1989) near the eastern boundary of the state, centered on T8N, R70E (White Pine County). One oil exploration well in the center of the proposed caldera encountered Paleozoic rocks below 120 m of tuff. A well to the south encountered probable thick outflow tuff from a caldera to the south (NBMG files). This evidence suggests that there probably is not a caldera in this area. Even if one is present somewhere in the area, it could be filled with outflow from a younger caldera and overlain by Tertiary sedimentary rocks, both of which are potential reservoirs.

3. A caldera under Crater Flat (southern Nye County), west of Yucca Mountain (the Crater Flat-Prospector Pass caldera) as shown by Ludington and others (1996, fig. 5-1 and table 5-1) has been disputed (Scott, 1990; Faulds and others, 1994) and French (2000) considered Crater Flat to be an area that could contain sediments capable of oil generation. For those reasons, we include that area west of Yucca Mountain in the low potential category.

4. A proposed source caldera for the Kalamazoo Tuff has been proposed beneath valley fill east of the northern Schell Creek Range (White Pine County; Ludington and others, 1996, fig. 5-1, table 5-1). The tuff consists of four cooling units (Hagstrum and Gans, 1989), apparently exposed very near the area of the proposed caldera. An alternate explanation is that the tuffs could be thick in this area because of preexisting topography. Even if the caldera is present, intracaldera tuffs have some potential as reservoirs below valley fill. We map the area of the speculative caldera as low potential.

5. A speculative caldera, inferred on the basis of gravity data in northern White River Valley (southern White Pine County; Ludington and others, 1996, table 5-1, no. 29) is shown as low potential for reason similar to those given above for other completely concealed or speculative calderas.

6. Ludington and others (1996, fig. 5-1 and table 5-1, no. 13) show a speculative caldera about 20 km northeast of Tuscarora, based on a gravity signature coincident with volcanic rocks. We know of no other evidence for this caldera. The area is a continuation of the depositional area of the Eocene sedimentary rocks of the Bull Run Basin, which were deposited in a fault-controlled basin (Clark and others, 1985). The low density rocks suggested by the gravity data may be a thick section of Eocene sedimentary rocks. We consider the area to have low potential, similar to the adjacent area outside the speculative caldera.

MOUNTAIN RANGES VS. VALLEYS

All of Nevada's oil production has been from traps in the Neogene basins. However, the Neogene ranges are difficult to exclude from at least some potential because subsurface information in the ranges is relatively limited. A recent assessment of eastern Great Basin petroleum potential (http://pubs.usgs.gov/fs/2005/3053/pdf/FS-2005-3053.pdf) concluded that a significant portion of the undiscovered petroleum is in the ranges.

SOURCE ROCKS

A number of stratigraphic units in Nevada are well known as potential source rocks. These include parts of the Ordovician Vinini and Devonian Woodruff Formations, Mississippian Chainman Shale and equivalent rocks, Pilot Shale, Cretaceous Newark Canyon Formation, Paleogene Elko and Sheep Pass Formations and related rocks (Poole and Claypool, 1984, and many other references). Other possible source rocks include Permian rocks that include equivalents to the Phosphoria Formation in northeastern Elko County (Maughn, 1984), and the lower part of the Pennsylvanian-Permian Bird Spring Formation of Clark County (Longwell and others, 1965, p. 160). In western Nevada, deeply buried Neogene sedimentary rocks (Barker, 1996; Barker and others, 1996) and possibly the Cretaceous King Lear Formation (Willden, 1979) could be considered potential sources of petroleum.

CONODONT COLORATION ALTERATION INDICES (CAI)

Conodonts are the apatitic hard parts (teeth) of an extinct group of marine worm-like animals. They range in age from Cambrian to Triassic, and are excellent biostratigraphic zone indicators. They contain trace amounts of organic matter that changes color with increasing temperature. Conodont coloration alteration indices (CAI) are a measure of organic and mineral metamorphism (Epstein and others, 1977). Thus, these indices are useful in interpreting the heating history of petroleum source rocks, and because the thermal history is a key factor in hydrocarbon generation and preservation, CAIs provide one measure of oil and gas potential. Harris and Crafford (2007) reported maximum and minimum CAI values for collections of Nevada conodonts. Most collections did not exhibit a range, and the maximum and minimum values were the same. However, some samples exhibited a range of 0.5 to 4 or more. We plotted the minimum values reported by Harris and Crafford (2007). There are arguments for and against the use of each; using the minimum value is probably a somewhat less conservative approach. For example, it has been suggested that if any of the conodonts were heated to a higher level in the host rock, then any associated hydrocarbons would have also reached those temperatures (Repetski and others, 2005). We do not think the difference in CAI values between these two methods for the few affected points on the map would change any petroleum potential boundaries.

NMBG SOURCE-ROCK THERMAL MATURITY DATABASE

Hess (1992) reported source-rock maturity data for certain NBMG well cuttings samples analyzed by a variety of individuals and companies. The Rock-Eval (TMAX), vitrinite reflectance ($R_{0)}$, or Thermal Alteration Index (TAI) values reported were compared to commonly accepted values for maturation levels of source rocks (Barker, 1996, table 1; Humble Geochemical Services unpubl. table). UTM locations for the wells were taken from Hess (2004). Only one well contained no analyzed samples that were considered to be within the oil preservation window. Locations of the wells with analyzed samples are shown on the map.

OIL AND GAS SHOWS

Oil and gas shows in petroleum exploration wells as reported in Hess (2004) and wells with no shows or no data were plotted at 1:1,000,000 scale as a qualitative aid in drawing lines separating areas of different potential. In general, areas of numerous shows or several significant shows were included in areas of moderate or high potential, and all authentic shows were at least included in areas of low potential.

SEEPS

The term “seep” is used to refer to shows of oil, gas, or solid bitumen at the surface, in springs, and in non-petroleum wells. Data were taken from Garside and others (1988), with additional data from Barker (1996), Hulen and others (1999, 1994), and Schalla and others (1994).

REFERENCE LIST

The list of references includes all sources of data that were used to evaluate Nevada’s petroleum potential. Many are not cited above, but were used to estimate potential in specific areas.

MAP

The qualitative petroleum potential map displays the digital data sets used to outline four areas of petroleum potential. On the map we display the outlines of calderas (from Ludington and others, 1996), the rock units we considered to have very low-to-no potential (plutonic rocks, Mesoproterozoic and Paleoproterozoic metamorphic and granitic rocks, and metamorphic core complexes), and petroleum exploration wells (shows and no shows or no data). We also show the conodont coloration index (CAI) data, and the organic maturity data (or absence of data) in oil wells (Hess, 1992).

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