Salym - Potential giant oil field in West Siberia; Possible reservoir stimulation experiment using a nuclear explosion

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Abstract

A seismic event of October 4, 1979, east of the Ural Mountains was described by the U. S. Department of Energy as an underground nuclear explosion. The location of this event by the U. S. Geological Survey places it in the oil-rich Middle Ob region of West Siberia in the vicinity of the Salym oil field. The field, which was discovered in 1965, has seven oil pools, of which the main pay is the bituminous shale of the Upper Jurassic Bazhenov Formation. This formation is one of the few examples of a primary oil-bearing pelite reservoir having a high content of organic matter that was also the source of the oil. A characteristic of the Bazhenov Formation is the wide range of fracture permeability and oil flow rates. Where fracture permeability is high, wells yield more than 2,100 bbl/day. Elsewhere, wells yield less than 35 bbl/day or are dry. The seismic event of October 4, 1979, may have been an underground nuclear explosion experiment designed to stimulate production by fracturing the tight bituminous shale. Previous attempts to stimulate oil production in the U.S.S.R. by using nuclear explosions were carried out in carbonate reservoirs.

Introduction

Regional setting. The Salym oil field is on the Lempa high of the Salym uplift in the eastern part of the Khanty-Mansiysk depression in the Middle Ob region of West Siberia (Dorofeyeva et al., 1979a, p. 20; Kirgintseva, 1976, p. 7-9; Volkov et al., 1968, p. 58). The Salym uplift is about 50 km long and 45 km wide and trends north (Volkov et al., 1968, p. 58). The Lempa high is 25 km long and 16 km wide; closure is 150 m (Tereshchenko, 1972, p. 158). The Salym field is about 275 km west of the giant Samotlor field.

Stratigraphy. The sedimentary cover overlying the Paleozoic Hercynide basement in the Middle Ob region consists of Jurassic, Lower and Upper Cretaceous, Paleogene, and Quaternary marine and continental sediments (Kirgintseva, 1976, p. 7). No volcanic rocks, evaporites, or reef limestones are present in the section. Total thickness of the sedimentary cover is 3,100-3,300 m. Although seven pay zones are present in Salym oil field, only that within the Bazhenov Formation of the Volzh Stage of the Upper Jurassic is an important producer.

The Bazhenov Formation is present over an area (Fig. 1) more than 1,000 kilometers long from north to south and several hundred kilometers wide from east to west (Pluman, 1971, p. 718). Total areal extent of the formation is about 1 million square kilometers (Lebedev et al., 1979, p. 200). It is generally 28-42 m thick; however, in some places it is as thick as 60 m (Dobrynin and Serebryakov, 1978, p. 188). Zaripov and Nesterov (1977, p. 23) recognized three parts in this formation: The lower part is predominantly calcareous shale and thin beds of marl and limestone; the middle part is massive, highly bituminous shale; and the upper part is thin-bedded shale. The bituminous shales are the main oil-bearing rock and are the main subject of this report.

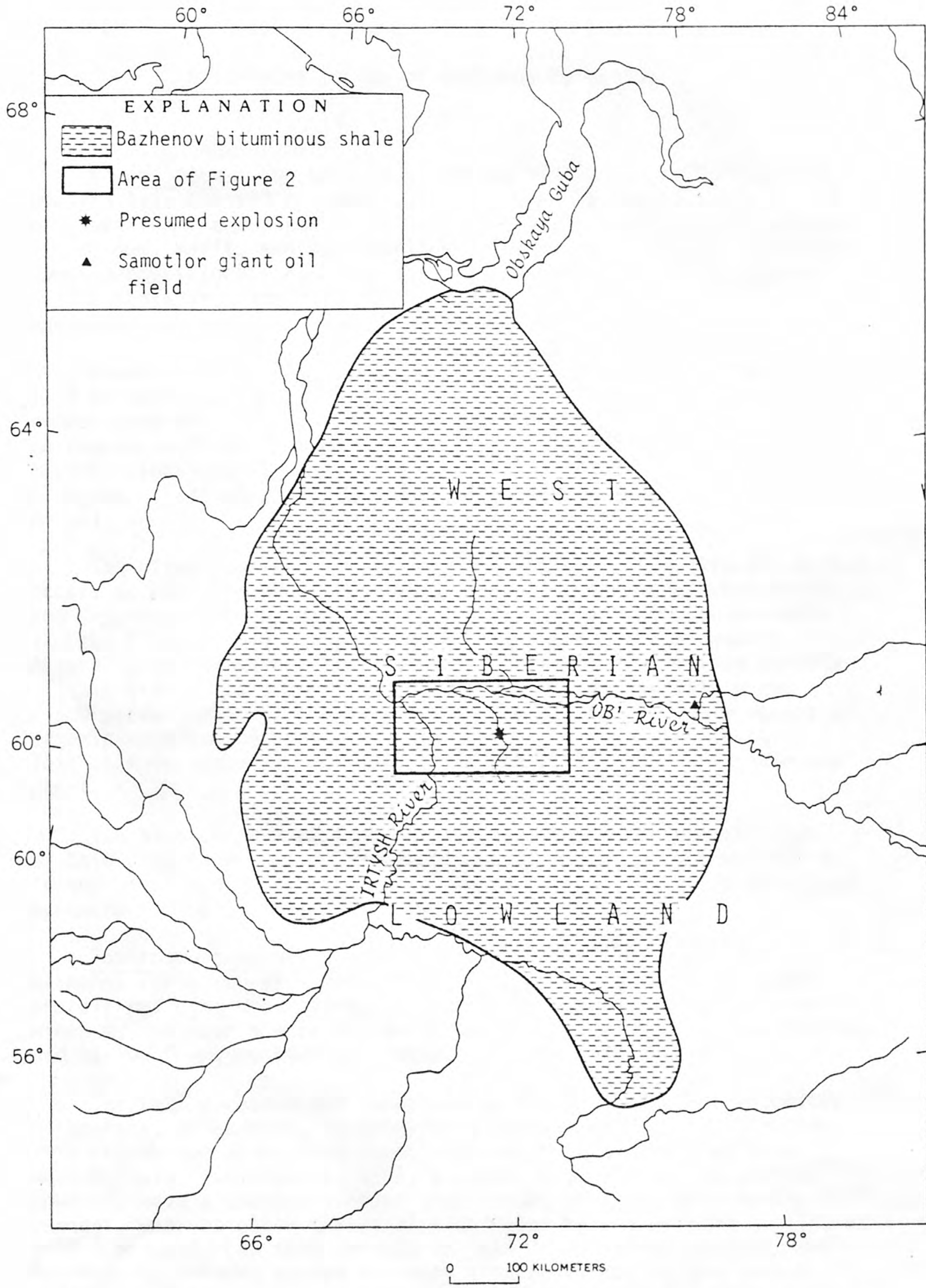


FIGURE 1. Distribution of Bazhenov bituminous shale, West Siberia.

Composition. The bituminous shales of the Bazhenov Formation contain less than 10 percent silt, are commonly horizontally bedded, are pyritized, and contain thin clayey siltstones, clayey bituminous limestones, marls, and radiolarites. The clay fraction is hydromica; some montmorillonite and chlorite are present. Individual layers of the shale are limy and high in microcrystalline syngenetic calcite and glauconite.

Average content of organic matter in the Bazhenov Formation is 8 percent (Zaripov and Nesterov, 1977, p. 20); that for the most common type of bituminous shale in the formation is 13 percent. Some petrographic thin sections contain as much as 80 percent organic matter. This organic matter is irregular in form and is commonly elongate. Particle size is 0.01-0.06 mm (Veber and Kotseruba, 1979, p. 16).

The bituminous shales are characteristically silicified. Silica occurs as rounded and elliptical precipitated masses of chalcedony and cryptocrystalline quartz disseminated within the clay minerals (Korzh, 1978, p. 64). This free silica is not detrital quartz. According to Dorofeyeva etal(1979a, p. 21), the most common variety of this bituminous shale contains 37-40 percent free silica and 27-30 percent clay fractions. Silica also occurs as replacements of organic remains, as sponge spicules, and as radiolarian tests. This rock is probably intermediate in composition between shale and chert.

The high content of free silica may account for the ability of this rock to maintain open fractures at depths of 2,800-3,000 m. In the usual type of shale, fractures at such depths would be closed by overburden pressure.

Environment of deposition. The bituminous shales of the Bazhenov Formation were deposited as clay in a marine basin under sharply reducing conditions. Relief of the basin floor was at a minimum, the source area had undergone intensive chemical weathering, and marine transgression was maximum (Korzh, 1978, p. 65).

The Late Jurassic sea contained an abundant fauna of ammonites, belemnites, pelecypods, foraminifers, ostracodes, and radiolarians. This assemblage shows that deposition was in a normally aerated marine basin (Kontorovich, 1967, p. 356). The bituminous shales, however, have a uranium content that ranges from 1×10^{-3} to 7×10^{-3} percent, whereas other shales of the region have a uranium content of $n \times 10^{-4}$ percent. In this respect as well as in sulfur content, the Bazhenov bituminous shales are very similar to the modern botton sediments of the hydrogen sulfide zone of the Black Sea (Pluman, 1972, p. 717-718; Pluman and Zapivalov, 1977, p. 115-116). This Late Jurassic basin, therefore, is interpreted to have been euxinic, although the water above the sea floor was oxygenated.

Description of the Salym Field

Exploration. The Lempa high, on which Salym field is located, was outlined by seismic-reflection surveying in 1959. Drilling began in 1964, and the discovery was made in 1965 by the first wildcat drilled (Nesterov et al., 1971, p. 276).

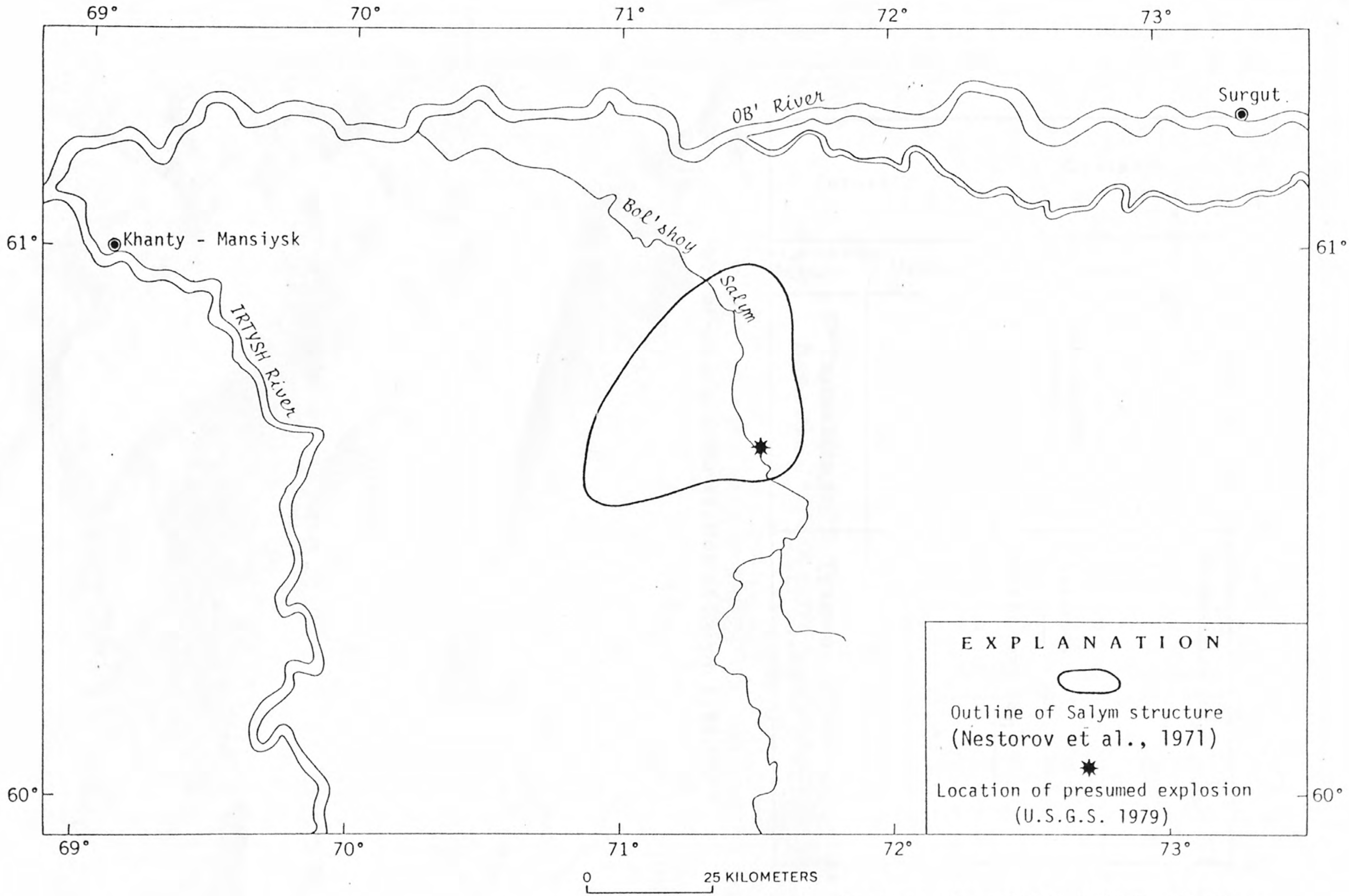
Structure. Closure on the top of the Upper Jurassic (top of the Bazhenov Formation) is 150 m on the Lempa high of the Salym structure (fig. 2). Both of the two crests on this high have a closure of 30 m on the -2700 m structure contour. Closure decreases upward stratigraphically and is 15 m on the Eocene sediments.

Pay zones. Seven oil pools have been found in Salym field. Their stratigraphic range is from lower Callovian of the Middle Jurassic to Hauteriv-Barremian of the Lower Cretaceous (Nesterov, et al., 1971, p. 276). The main pay is stratum J_0 within the Bazhenov Formation. The Bazhenov is sealed below by massive, highly bituminous shales, marls, and limestones of the Geogriyev Formation of Kimmeridgian age (fig. 3); it is sealed above by thick shales of the Achimov Formation of Berriasian-early Valanginian age (Zaripov and Nesterov, 1977, p. 24).

Reservoir properties. Porosity of the Bazhenov bituminous shales ranges from 2 to 16 percent; average effective porosity is 8 percent. Average permeability is 2.4 md. No porous reservoirs of the usual type are present as no sandy beds and only a few silty beds occur in the section (Gurari and Gurari, 1975, p. 230). The reservoir capacity of the rock is attributed to fractures and pores that formed during diagenesis.

Density of horizontal fractures is 0.5-1.5 per centimeter, and that of vertical fractures is 0.15-0.20 per centimeter. The calculated porosity attributable to fractures alone is 0.3 percent, much too samll to contribute significantly to the capacity of these reservoirs (Dorofeyeva et al., 1979a, p. 20-21; 1979, p. 148). The fractures are open and not mineralized, apparently because of a total absence of formation water. No significant flows of water have been observed from the Bazhenov Formation in any well (Lebedev et al., 1979, p. 206). All but the hygroscopic water appears to have been driven off during diagenesis.

Secondary porosity of the Bazhenov Formation formed by redistribution of mineral components during diagenesis. Tests of macrofauna and microfauna were dissolved, and leaching took place along the walls of fractures. Amorphous silica disseminated in the clay-mineral mass may also have been leached to some extent. This secondary porosity due to leaching appears to provide most of the effective porosity, and the fractures provide the permeability. Oil can actually be observed to leak out of horizontal fractures when cores are squeezed along the vertical axis (Gurari and Gurari, 1975, p. 231).



Base map from ONC-D-5 (U.S. Air Force, Aeronautical Chart and Information Ctr.)

FIGURE 2. Location of Salym structure, West Siberia.

<table>
<tr><th></th><th></th><th>Stage</th><th colspan="2">Formation</th></tr>
<tr><td rowspan="2">Creta-ceous</td><td rowspan="2">Lower</td><td>Hauteriv-Barremian</td><td colspan="2">Vartov</td></tr>
<tr><td>Berriasian-Valanginian</td><td colspan="2">Achimov</td></tr>
<tr><td rowspan="4">Jurassic</td><td rowspan="3">Upper</td><td>Volzh</td><td colspan="2">Bazhenov J_0</td></tr>
<tr><td>Kimmeridgean</td><td>Geogriyev</td><td rowspan="2">Abalak</td></tr>
<tr><td>Callovian-Oxfordian</td><td>Vasyugan</td></tr>
<tr><td>Lower-Middle</td><td>Pliensbachian to Bathonian</td><td colspan="2">Tyumen</td></tr>
</table>

Fig. 3. Part of stratigraphic section of Salym area.

The Bazhenov Formation is one of the few examples of a primary oil-bearing pelite reservoir having a high content of organic matter that was also the source of the oil (Veber and Kotseruba, 1979, p. 15).

Anomalously high formation pressure. The formation pressure in the oil pool in the Bazhenov Formation at Salym oil field at a depth of 2,800-3,000 m is 421 atm; this exceeds the normal hydrostatic pressure at these depths by 132-136 atm (Nesterov et al., 1971, p. 277). The pool is sealed above by 100 m of argillitic rocks of the Berriasian stage, and it is separated from the underlying permeable Middle Jurassic Tyumen Formation by the impermeable Abalak (Geogriyev) Formation of Late Jurassic age (Dobrynin and Serebryakov, 1978, p. 118).

These anomalously high formation pressures do not exist over the entire region; rather, they are in a north-south belt paralleling the axis of the Lempa high. This belt is 6 km wide and has been explored for a length of 26 km (Stepanov and Tereshchenko, 1973, p. 69). The formations above and below the Bazhenov do not have anomalous pressures (Dobrynin and Martynov, 1979, p. 36).

The belt of anomalously high formation pressures coincides with a belt of anomalously high temperatures. Formation temperatures at the top of the Jurassic sediments are 127°-134°C in the anomaly zone, whereas they do not exceed 118°C outside this zone (Melik-Pashayev et al., 1973, p. 26).

The development of the anomalously high formation pressures and temperature has been attributed to heat transfer by hot fluids along a fault that extends into the basement (Tereshchenko, 1972, p. 158-159; Stepanov and Tereshchenko, 1973, p. 69). Heat from this source is believed to have caused expansion of the oil to produce the anomalously high pressures (Melik-Pasheyev et al., 1973, p. 27; Melik-Pasheyev, 1979, p. 13).

Gurari and Gurari (1975, p. 230) emphasized the association of the anomalously high formation pressures with the hydrodynamic isolation of the Bazhenov Formation. They also pointed out the low density of faulting in the area. Volkov et al. (1968, p. 58) noted that the anomalously high formation pressures are associated with the Lempa structure where vitrine reflectance shows a higher temperature of maturation on the Lempa than on surrounding structures. The Lempa structure indeed seems to have once been at the deepest part of the Khanty-Mansiysk depression. The anomalous formation pressures might then be in part residual from a time of deeper burial.

The anomalously high formation pressure is probably due for the most part to gases generated from the organic matter by the maturation process. These gases were sealed within the Bazhenov Formation by seals both above and below.

Production. All wells that penetrate the Bazhenov Formation in the zone of anomalously high formation pressure have moderate to high oil flows, which range from 180 to 2,220 bbl/day through an 8-mm choke. Wells outside this zone of high pressure flow at 5-35 bbl/day or are dry (Stepanov and Tereshchenko, 1972, p. 69). This zone of high-yielding wells also coincides with the area where fracturing of the Bazhenov Formation is at a maximum; density of fracturing is four times greater inside than outside this zone (Dobrynin and Martynov, 1979, p. 41).

A characteristic of the reservoirs of the Bazhenov Formation of Salym field is their low permeability. If the difference between well-head pressure and formation pressure is increased, the yield of oil does not increase; rather, it decreases. When oil is allowed to escape from the reservoir too rapidly, the horizontal fractures close up, pressure drops, and flow ceases. If such a well is shut in, pressure is restored comparatively rapidly (Kontorovich et al., 1975, p. 502).

As of January 1, 1977, 25 wells were producing from the Bazhenov Formation. Cumulative production at that time stood at 11 million barrels, 10 million of which had been produced in 1976 (Oil and Gas Journal, 1977, v. 75, no. 35, p. 102).

Resources. Estimates of reserves of Salym oil field are as high as 10 billion barrels (Oil and Gas Journal, 1979, p. 44). Much depends on developing ways to recover this oil. If recovery techniques are improved sufficiently, the Bazhenov Formation is potentially very productive; indeed, Lebedev et al. (1979, p. 200) stated that most forecasters consider the Bazhenov Formation a major new exploration target. Kontorovich (1967, p. 354) calculated that the liquid fractions of petroleum of the Upper Jurassic bituminous shales of West Siberia total 2×10^{12} tons. No estimates have been made of how much of these materials might be recovered, but the source-rock potential is significant.

Underground Nuclear Explosion

A seismic event on October 4, 1979, was described by the U. S. Department of Energy (1979) as an underground nuclear explosion in the Soviet Union, east of the Ural Mountains. The U. S. Geological Survey (1979) in the monthly publication "Preliminary Determination of Epicenters" reported the event as magnitude Mb 5.4 and located at latitude 60.650° N, longitude 71.525° E. This location is in the oil-rich Middle Ob region of West Siberia in the vicinity of the Salym field about 275 km west of the giant Samotlor field. The accuracy of location, based on 115 reporting seismic stations, is considered to be good. The aseismicity of the region gives high confidence to the conclusion that this event was in fact an underground explosion.

For comparison, nuclear explosions conducted by the United States in the Gasbuggy and Rulison gas stimulation experiments had teleseismic magnitudes of Mb 4.7 and 4.9 (K. King, U. S. Geological Survey, oral communication, 1980) and yields of about 29 and 43 kilotons respectively.

At a series of international meetings sponsored by the International Atomic Energy Agency (IAEA) and in several publications (Kedrovskiy, 1970; Kedrovskiy et al., 1971; Kedrovskiy et al., 1975), the Soviet Union has disclosed an active program for devising peaceful uses of nuclear explosions. Nordyke (1975) summarized this program, which has included experiments in excavation, underground storage cavities, extinguishing runaway gas-well fires, and petroleum stimulation. The Soviet Union's attitude and technical criteria concerning enhanced petroleum production by the use of contained underground nuclear explosions was stated by Kedrovskiy and Mangushev (1967) and Mangushev and Zolotovitskaya (1969) and was reviewed at the 8th World Petroleum Congress (Orudjev et al., 1971).

Terman (1973) thoroughly reviewed the nuclear-explosion petroleum-stimulation projects of both the United States and the Soviet Union. In that paper, he described in detail the various experiments in both countries and presented site geology as well as post-explosion data on rock fracturing, production, etc. The reader is referred to this comprehensive discussion for the technical data on the effects of contained underground nuclear explosions and details of past Soviet experiments on petroleum stimulation.

The proximity of the presumed explosion of October 4, 1979, to the Salym oil field suggests another experiment concerned with petroleum development. Past Soviet experiments with nuclear explosions in the immediate vicinity of petroleum deposits include: 1) oil stimulation, and 2) underground storage. Because of the relatively undeveloped stage of the Salym field and the absence of thick salt deposits in the section, this explosion probably was not intended to produce a storage cavity. Previous Soviet attempts at oil stimulation were in carbonate reservoirs at depths of only 1,200 to 1,350 m (Terman, 1973). The United States Rulison experiment (Terman, 1973), however, was at a depth of 2,567 m, and the Soviets have reported conducting nuclear explosions of about 40 kilotons at a depth of 2,500 m (Nordyke, 1975) to extinguish a runaway gas-well fire. The Bazhenov Formation, at a depth of about 2,800 m, has a wide range of fracture permeability and oil-well yields. The explosion at the Salym field may have been an experiment to stimulate production by extensive fracturing of the tight bituminous shales; such an explosion could in effect produce a rubble chimney and fracture envelope tens of meters in radius. This fracturing could raise production rates, make larger or additional areas of the Bazhenov Formation susceptible to production, and decrease exploitation costs. Possibly this fracturing could also reduce or eliminate the problem described above of decreased flow to conventional wells when oil is produced rapidly.

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