G601483

EIA ANALYSIS BRIEF: THE FORMER SOVIET REPUBLICS

- Armenia
- Azerbaijan
- Belorussia
- Estonia
- Georgia
- Kazakhstan
- Kirghizia
- Latvia
- Lithuania
- Moldavia
- Russia
- Tadzhikistan
- Turkmenistan
- Ukraine
- Uzbekistan

Energy Information Administration

12-Feb-92

ERRATA SHEET - Former Soviet Republics

Areas of Former Soviet Republics

	('000 Sq. Km)	('000 Sq. Miles)
Armenia	29.8	11.5
Azerbaijan	86.6	33.4
Belarus	207.6	80.1
Estonia	45.1	17.4
Georgia	69.7	26.9
Kazakhstan	2717.3	1048.9
Kyrgyzstan	198.5	76.6
Latvia	64.6	24.9
Lithuania	65.2	25.2
Moldova	33.7	13.0
Russia	17075.4	6591.1
Tajikistan	143.1	55.2
Turkmenistan	488.1	188.4
Ukraine	603.7	233.0
Uzbekistan	447.4	172.7
Total	22275.8	8598.5

Notes:

Uzbekistan's net material product in 1989 was 25.06 billion rubles.

Belorussia is now Belarus; Kirghizia is Kyrgystan; Moldavia is Moldova; and Tadzhikistan is Tajikistan.

Contacts:

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1. Estonia
2. Latvia
3. Lithuania
4. Belorussia
5. Moldavia
6. Georgia
7. Armenia
8. Azerbaijan
9. Turkmenia
10. Uzbekistan
11. Tajikistan
12. Kirghizia
Barents Sea
Kara Sea
Russia
1
2
3
4
POLAND
Ukraine
5
ROMANIA
BULGARIA
Black Sea
GREECE
TURKEY
6
7
8
8
Caspain Sea
Kazakhstan
Aral Sea
10
12
9
11
SYRIA
IRAQ
IRAN
AFGHANISTAN

Armenia

REPUBLIC PROFILE

President: Levon Ter-Petrosyan
Population (1989): 3.3 million
Size/Location: 11,500 square miles. Situated in the southern part of Transcaucasia, surrounded by Georgia on the north, Azerbaijan on the east, and Turkey on the west.
Ethnic Groups: Armenian(93%), Azeris (6.1%)
Major Cities: Yerevan (capital), Leninakan

ECONOMIC PROFILE

Net Material Product (1989): 6.95 billion rubles
NMP Growth Rate (1989): 9.9%

ENERGY PROFILE

SUPPLY:

Armenia possesses no indigenous fossil fuel resources, and is therefore totally dependent on imports for its oil, gas, and coal demand. Most of these imports come through Azerbaijan, with which Armenia has strained relations, thus making Armenian energy supplies potentially vulnerable. Armenia's sole nuclear power plant at Metsamor was closed in early 1989, reducing the republic's output of electric power by about 40%.

CONSUMPTION:

Oil (1989E): 80,000 barrels per day
Natural Gas (1989E): 184 billion cubic feet
Coal (1989E): 500,000 short tons
Electricity (1989E): 11 billion kilowatt hours
Total (1989E): 0.39 quadrillion BTUs

ECONOMIC CONDITIONS

Armenia's economy centers around subtropical agriculture, mining, and some manufacturing. Armenia is heavily dependent upon trade, with exports to other republics accounting for 63.4% of Armenia's NMP produced, and imports from other republics accounting for 79% of Armenia's consumption of goods. Armenia's trade consists primarily of light industrial goods, machinery, chemicals, and petrochemicals. It also imports significant amounts of oil and natural gas.

HISTORY AND RECENT EVENTS

The Armenians have been dominated by the Arabs and the Turks with only brief periods of independence. In 1920, Turkey and the Soviet Union divided up Armenian lands and in December of that year an Armenian Soviet Republic was declared. Armenia declared sovereignty on August 23, 1990, and is scheduled to vote on independence on September 21, 1991. President Levon Ter-Petrosyan favors independence with economic ties to other republics. Ethnic conflict between Christian Armenians and Shiite Muslim Azeris poses a serious and chronic problem for the republic.


Georgia
Alaverdi
Amasiya
Kirovakan
Dilizhan
Leninakan
Azerbaijan
Razdan
Ozero Sevan
Yerevan
Vardenis
Armenia
Dzhermuk
TURKEY
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
IRAN
Azerbaijan
Goris
Kadzharan

Azerbaijan

REPUBLIC PROFILE

President: Ayza Mutalibov
Population (1990): 7,145,600
Size/Location: 86,600 square miles. Occupies the eastern part of Transcaucasus region with the Caspian Sea on the east, Russia and Georgia to the north, Armenia to the west, and Iran to the south
Ethnic Groups: Azeris (78%), Russian (8%), Armenians (8%),
Major Cities: Baku(capital), Gyandzha, Sumgait
Major Import Products: Grain and other agricultural products, machinery and equipment, steel products

ECONOMIC PROFILE

Net Material Product (1989): 11.95 billion rubles
NMP Growth Rate (1989): -1.8%

ENERGY PROFILE

SUPPLY:
Oil (1990E) 244,000 barrels per day
Natural Gas (1989E): 318 billion cubic feet
CONSUMPTION:
Oil (1989E) 225,000 barrels per day
Natural Gas (1989E) 610 billion cubic feet
Coal (1989E): 300,000 short tons
Electricity(1989E): 19.6 billion kilowatthours
Total (1989E): 1.07 quadrillion BTUs

OIL INDUSTRY

ORGANIZATION:
Azerbaijan Production Association (Azneft) and **Kaspmorneftegaz** share responsibility for the oil and gas industries.

OIL PRODUCTION:
Azerbaijan is one of only four republics that is a net exporter of petroleum. During 1990, Azerbaijan accounted for about half of the decline in oil production of 380,000 barrels per day in the other oil-producing republics outside Russia. The decline was due to an offshore oilwell fire in 1989 that devastated the No. 2 platform in the April 28 field. The damaged platform was repaired, and the April 28 field received a new platform and new pumping station in early 1991. Offshore oil production represents 72 percent of Azerbaijan's oil production. An oil discovery in the Caspian Sea, about 65 miles south of Baku, was reported in September 1990.

Onshore, 36 oil and gas fields are being operated by **Azneft**. A recent development has been the successful redrilling of old wells to increase production levels. Reservoirs are believed to still hold 40 percent of their original reserves because of past development practices.

REFINERIES:
Azerbaijan has almost 800,000 barrels per day of crude oil refining capacity at the refinery center in Baku. The recent unrest in Baku reduced the output of these refineries, which typically run at only half of their capacity under normal circumstances.

Azerbaijan's refineries are supplied from three sources: western Siberian crude delivered by pipeline; Iranian crude received in exchange for refined petroleum product; and local production. Refined petroleum products are sent by barge and train to the Ukraine and central Russia.

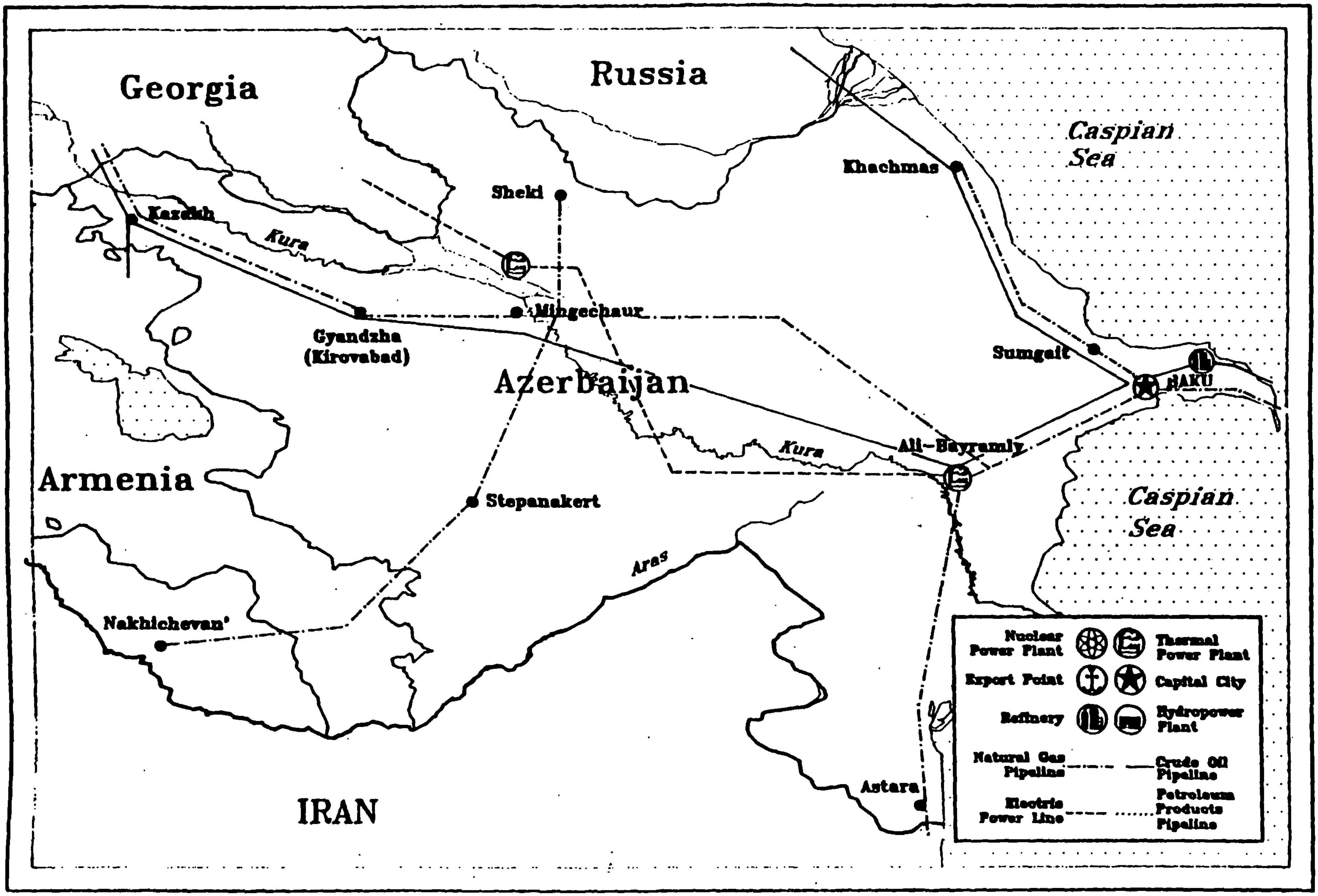
ECONOMIC CONDITIONS

Azerbaijan is rich in natural resources, especially crude oil, and is an important supplier of oil industry equipment and other machinery. It has substantial metal, chemical, petrochemical, and agricultural (grain and cotton) industries.

To exercise its claim of sovereignty, Azerbaijan established a foreign trade association for marketing oil abroad. Known as **Daniz**, its members are *Kaspmorneftegaz*, *Azneft*, and the *Caspian Sea Fleet*.

HISTORY AND RECENT EVENTS

The Azerbaijan Republic was formed on April 28, 1920, joined the USSR on December 30, 1922, and declared its independence in September, 1991.


Georgia
Russia
Caspian Sea
Khachmas
Sheki
Kazakh
Kura
Mingechaur
Gyandzha (Kirovabad)
Azerbaijan
Sumgait
BAKU
Ali-Bayramly
Kura
Caspian Sea
Armenia
Stepanakert
Aras
Nakhichevan'
IRAN
Astara
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Belorussia

REPUBLIC PROFILE

President: N/A
Population (1989): 10,200,000
Size/Location: 207,600 square miles.
Lithuania and Latvia to the northwest, Russia to the northeast, the Ukraine to the south, and a short border with Poland to the west.
Ethnic Groups: Belorussian (79.4%), Russian (11.9%), Polish (4.2%),
Major Cities: Minsk (capital), Bobruysk, Brest
Major Industries: Machine tools and machinery, grain and fodder

ECONOMIC PROFILE

Net Material Product (1989): 27.48 billion rubles
NMP Growth Rate (1989): 5.7%

ENERGY PROFILE

SUPPLY:

Belorussia produces only a small portion of its energy requirements. Around 40,000 barrels per day of oil, along with peat and a small volume of natural gas, consitute the only domestic energy sources. All domestic electricity generation is from four thermal plants. All nuclear and hydro-generated electric power is imported.

CONSUMPTION:

Oil (1989E) 579,000 barrels per day
Natural Gas (1989E) 323 billion cubic feet
Coal (1989E): 4.0 million short tons
Electricity (1989E): 39 billion kilowatthours
Total (1989E): 1.7 quadrillion BTUs

OIL REFINING:

Belorussia has a total of almost 800,000 barrels per day of crude oil refining capacity located at two refineries in Mozyr' and Polotsk. These refineries operate at about 80 percent of capacity and have little capability to upgrade residual oil into the lighter products used in the transportation sector.

The Belorussian refineries are supplied from three sources: Western Siberian crude delivered by pipeline; Volga-Urals crude delivered by pipeline; and local production. The petroleum products produced in the Belorussian refineries are supplied to local markets and to markets in the Ukraine.

ECONOMIC CONDITIONS

Belorussia's major industries are chemicals, machine-building and light industrial. Most of the economic development has occurred since the end of World War II.

HISTORY AND RECENT EVENTS

The Belorussian republic was formed on January 1, 1919, and joined the USSR on December 30, 1922. Belorussia declared its sovereignty on July 27, 1991 and recently declared independence. On August 25, 1991, President Nikolai Dementei resigned under pressure for not opposing the coup. Belorussia is a member of the United Nations in its own right.

Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
Latvia
Russia
Polotsk
Polotsk
Daugava
Vitebsk
Nervis
Lukoml'
Orsha
Lida
Mogilev
Grodno
Minsk
Neman
Sozh
Osipovichi
Bobruysk
Belorussia
Berezina
Dneper
Kobrin
Berezovskaya
Gomel
Vasilevichi
Pripyat'
Brest
Mozyr'
Ukraine

Estonia

COUNTRY PROFILE

Head of State: Arnold F. Ruutel
Population (1989): 1.57 million
Location/ Size: Baltic / 12,252 square miles
Ethnic Groups: Estonian(61.5%), Russian (30.3%), Ukrainian (3.1%), Finn (1.1%), and Belorussian (1.8%)
Major Cities: Tallinn (capital) and Tartu
Major Port: Tallinn

ECONOMIC PROFILE

Net Material Product (1989E): 4.4 billion rubles (0.7% of USSR total)
NMP Growth Rate (1989E): 5.2%

ENERGY PROFILE

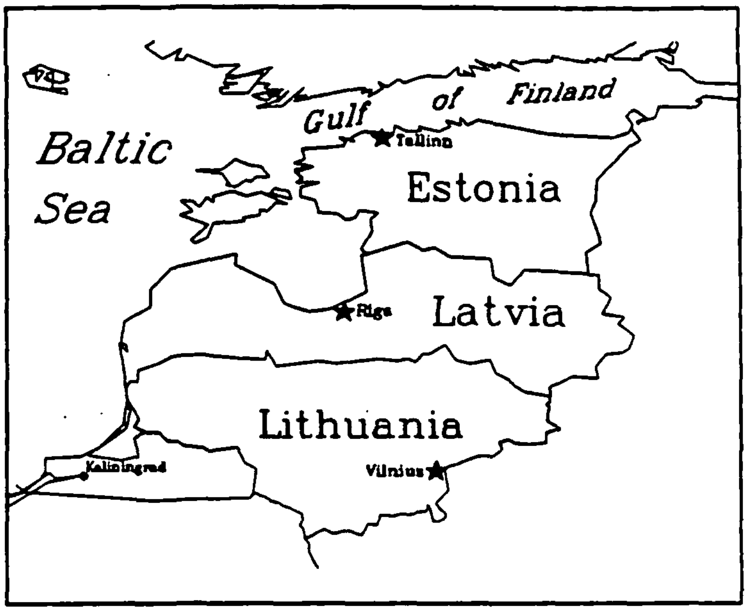
SUPPLY:

Oil shale is produced domestically and is used to generate electricity. Estonia is highly dependent, however, on gas, coal, and oil imports from Soviet republics, particularly Russia.

Electricity (1989): 17.6 terawatthours
Peat (1989): 229,000 short tons

CONSUMPTION:

Oil (1989E): 64,000 barrels per day
Natural Gas (1989E): 56 billion cubic feet
Coal (1989E): 500,000 short tons
Electricity(1989E): 9 terawatthours
Total (1989E): 0.36 quadrillion BTUs



ECONOMIC CONDITIONS

Primarily an agricultural and dairy region, Estonia also has textile, shipbuilding, timber, paper, mining equipment and oil shale industries. Estonia is relatively rich, possessing the second highest per capita income among the former Soviet republics. Estonia is highly dependent on trade, with imports from other former Soviet republics accounting for 65 percent of Estonian NMP.

HISTORY AND RECENT EVENTS

Estonians, who are closely related to the Finns, were dominated by the Germans, Danish, Scandinavians, and Russians until independence in 1918. Estonia remained independent until the Hitler-Stalin pact of 1940, which led to its annexation by the USSR. President Arnold F. Ruutle declared independence in August 1991. Following the failed coup, the Republics of Georgia and Russia recognized Estonia's independence. On September 2, 1991, the United States formally recognized Estonia's independence.


FINLAND
Helsinki
Gulf of Finland
Baltic Sea
Tallinn
Hiiumaa
Estonia
Lake Peipus
Saaremaa
Pärnu
Tartu
Gulf of Riga
Latvia
Riga
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Georgia

REPUBLIC PROFILE

President: Zviad Gamsakhurdia
Population (1989): 5.4 million
Size/Location: 18,950 square miles. Situated in west and central Trancaucasia, with Russia to the north, Armenia to the south, and Azerbaijan to the west.
Ethnic Groups: Georgian(68.8%), Armenian(9%), Russian(7.4%), Azeri(5.1%), Ossetian(3.2%), and Abkhazian(1.7%)
Major Cities: Tbilisi (capital) and Batumi

ECONOMIC PROFILE

Net Material Product (1989): 10.79 billion rubles
NMP Growth Rate (1989): -3.6%

ENERGY PROFILE

SUPPLY:

Georgia is dependent upon imports for most of its fossil energy needs, although it does produce over 1 million short tons of coal per year. Georgia also has significant hydroelectric power resources, producing around 16 billion kilowatthours in 1989. Production of oil and gas is negligible.

CONSUMPTION:

Oil (1989E): 135,000 barrels per day
Natural Gas (1989E): 208 billion cubic feet
Coal (1989E): 1.6 million short tons
Electricity (1989E): 15.6 billion kilowatthours
Total (1989E): 0.62 quadrillion BTUs

OIL REFINING:

Georgia has a single, 120 thousand barrels per day capacity refinery, with no real capability to upgrade residual oil into the lighter products used in the transportation sector. Locally produced crude oil, along with supplemental supplies from Azerbaijan, is refined in the facility at Batumi. The refined petroleum products are then distributed within Georgia.

ECONOMIC CONDITIONS

Georgia grows most of the Soviet Union's tea, as well as citrus fruits, grapes, silk, bamboo and tobacco. It is famous for its wineries. The republic contains the largest manganese mines in the world, and is rich in timber and coal. Its major industries include mining, metallurgy and textiles.

HISTORY AND RECENT EVENTS

A Georgian empire arose in the 13th century, was crushed by the Mongol invasion, and fell subsequently under Turkish and Persian overlords. Russia annexed most of Georgia in the early 19th century. Georgia declared independence in 1918 and was recognized by the Allies. But in 1921, the Red Army entered Tbilisi and a Soviet republic was formed under Stalin, himself a Georgian. Georgia declared full independence in April 1991, and has annulled the autonomous status of some ethnic groups wishing to stay in the USSR. Ethnic conflicts in the republic exist between Georgians and Ossetians in the north and between Georgians and Azeris in the south.


Russia
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
Sukhumi
Dzhvari
Poti
Kazbegi
Georgia
Black Sea
Zhinvani
Kutaisi
Kura
Borzhomi
TBILISI
Batumi
Bustavi
Gardabani
Azerbaijan
TURKEY
Armenia

Kazakhstan

REPUBLIC PROFILE

President: Nursultan Nazarbayev
Population (1990): 16,500,000
Size/Location: 1,050,000 square miles. Second largest Soviet republic; borders Russia to the north, China to the east, Uzbekistan, Turkmenia, and Kirghizia to the south.
Ethnic Groups: Russian (41%), Kazakh (36%), Ukrainian (6%), Tatar (2%)
Major Cities: Alma-Ata(capital), Karaganda
Major Import Products: Machinery, light industrial goods, chemicals and petrochemicals, oil and gas

ECONOMIC PROFILE

Net Material Product (1989): 27.8 billion rubles
NMP Growth Rate (1989): 1.3%

ENERGY PROFILE

Oil Industry Organization

Kazahkstan, as the largest oil-producing republic after Russia, has four oil production enterprises - *Embaneft'*, *Mangyshlakneft'*, *Aktyubinskneft'*, and *Tengizneftegaz.*

SUPPLY
Oil (1990E): 490,000 barrels per day (b/d)
Natural Gas (1989E): 250 billion cubic feet (bcf)
Refining Capacity (1991E): 600,000 b/d
CONSUMPTION
Oil (1989E): 470,000 b/d
Natural Gas (1989E): 400 billion cubic feet
Coal (1989E): 88 million short tons
Electricity (1989E): 91 terawatthours
Total (1989E): 3.08 quadrillion BTUs

OVERVIEW

Kazakhstan is a resource-rich producer of primary products, especially coal, but also oil and gas. The Ekibastuz and Karaganda basins in northeast Kazakhstan comprise the third largest coal-producing area in the USSR. Kazakhstan is one of only four republics that is a net exporter of energy.

OIL AND GAS PRODUCTION

Significant amounts of oil and natural gas are produced in the northwest part of the republic near the Caspian Sea. Future oil production potential depends largely on the development of the relatively deep, high-sulphur deposits of the remote and inhospitable Guryev region of northwest Kazakhstan, particularly the Tengiz field. Although Tengiz was discovered in 1979, and may contain 20 billion barrels of oil, test production began only in April 1991. Soviet drilling and production equipment has proven unsuitable for handling either the highly corrosive sour crudes or the abnormally high downhole pressure of the Tengiz field. The involvement of foreign oil companies in providing technology and expertise for the development of Tengiz thus seems inevitable and potentially advantageous to both sides. Chevron currently is heavily involved in finalizing an exploration and production deal for the area.

OIL REFINING

Kazakhstan has three refineries - in Chimkent, Gur'yev, and Pavlodar - which supply population centers in Kazakhstan, Kirghizia and southern Siberia. Chimkent and Gur'yev operate near capacity levels and have throughputs of about 150 and 120 thousand barrels per day, respectively. Pavlodar operates at only half of its 360 thousand barrel per day capacity. All three refineries are supplied by Western Siberian crude transported by pipeline.

HISTORY AND RECENT EVENTS

The Kazakh Republic was formed as an autonomous republic within the Russian Federation on August 26, 1920, and reconstituted as a Union Republic on December 5, 1936. Conservative Kazakhstan declared its sovereignty on October 25, 1990, but only after 13 other republics had done so.


Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
Russia
Kazakhstan
Kustanay
Aktyubinsk
Gur'yev
Shevchenko
Pavlodar
Pavlodar 2
Ekibastuz 1
Yermak
Tselinograd
Semipalatinsk
Ust'-Kamenogorsk
Serebryansk
Karaganda
Zhartas 2
Dzhezkazgan
Dzhambul
Alma-Ata
Chimkent
Uzbekistan
Kirghizia
Turkmenia
Tajikistan
CHINA
IRAN
AFGHANISTAN
PAKISTAN
INDIA

Kirghizia

REPUBLIC PROFILE

President: Askar Akayev
Population (1990): 4,372,000
Size/Location: 76,640 square miles. Borders Russia to the north, China to the southeast, Uzbekistan to the west, and Tajikistan to the southwest.
Ethnic Groups: Kirghiz (52.4%), Russian (21.5%), Uzbeks (12.9%)
Major Cities: Frunze(capital), Osh
Major Import Products: Machinery, light industrial goods, food, chemicals and petrochemicals, oil and gas

ECONOMIC PROFILE

Net Material Product (1989): 5.97 billion rubles
NMP Growth Rate (1989): 5.3%

ENERGY PROFILE

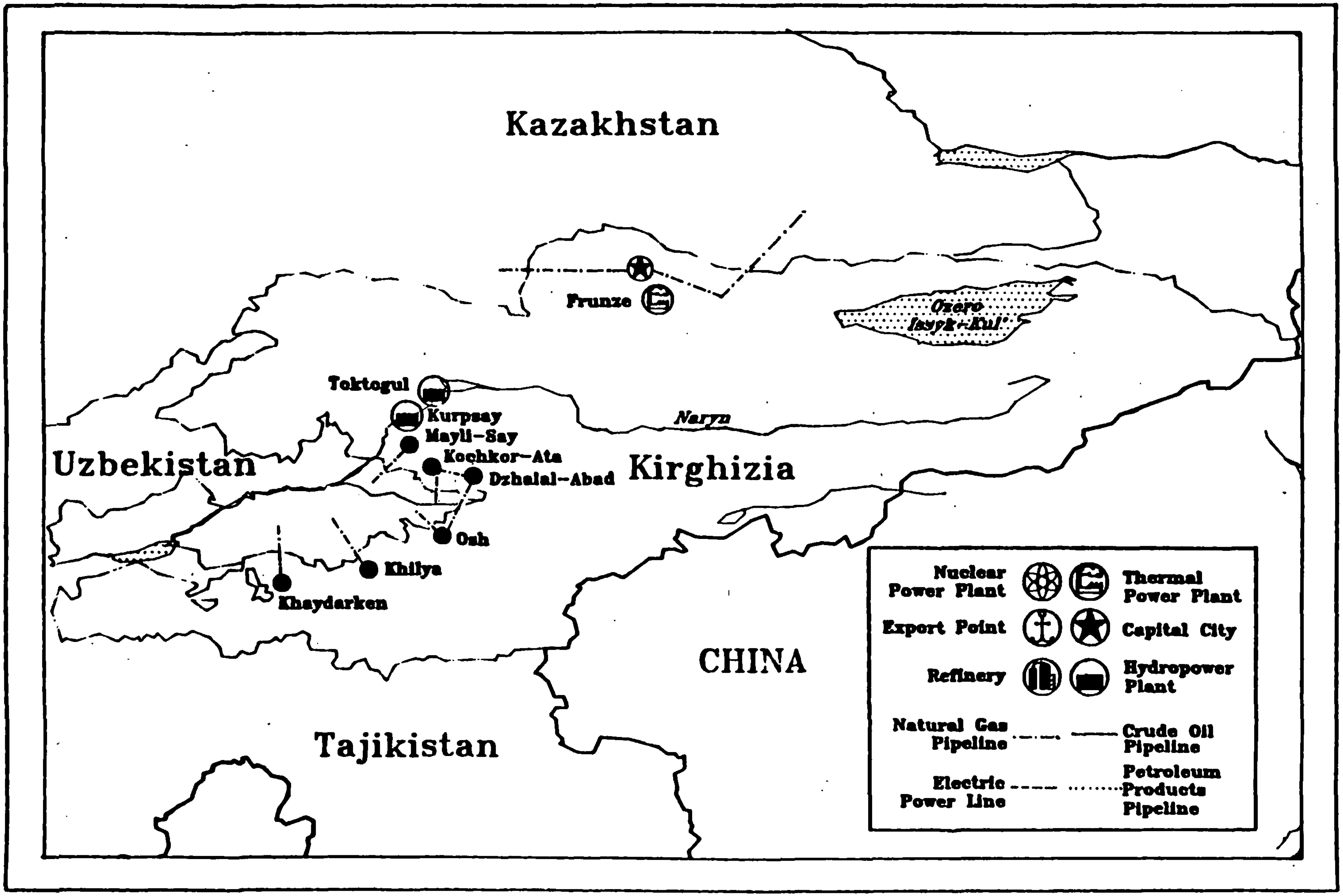
SUPPLY:
Oil (1990E) 4,000 barrels per day
Coal (1989E): 4 million tons
Natural Gas (1989E): 4 billion cubic feet
CONSUMPTION:
Oil (1989E) 60,000 barrels per day
Coal (1989E): 4.8 million short tons
Natural Gas (1989E): 64 billion cubic feet
Electricity (1989E): 7.5 billion kilowatthours
Total (1989E): 0.3 quadrillion BTUs

ECONOMIC CONDITIONS

The republic is a major producer of wool, livestock, and other agricultural goods. Light industries include machine and instrument making. Domestic coal resources and hydroelectric generation make Kirghiz self-sufficent in electric power. A liberalization drive was launched in October 1990 by President Akayev, with the the goal of initiating market oriented reforms. However, the republic remains mired in proverty, with high unemployment, land shortages, and ethnic conflicts.

HISTORY AND RECENT EVENTS

Kirghizia was made an Autonomous Republic within the Russian Federation on February 1, 1926, and reconstituted as a Union Republic on December 5, 1936. Kirghizia declared its sovereignty on December 12, 1990, and its independence on September 7, 1991.


Kazakhstan
Frunze
Ozero Issyk-Kul'
Toktogul
Kurpsay
Mayli-Say
Kochkor-Ata
Dzhalal-Abad
Naryn
Uzbekistan
Kirghizia
Osh
Khilya
Khaydarken
CHINA
Tajikistan
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Latvia

COUNTRY PROFILE

Head of State: Anatolijs V. Gorbunovs
Population(1989): 2.68 million
Location/ Size: Baltic. 17,547 square miles
Ethnic Makeup: Lett (51.8%), Russian (33.8%), Ukrainian (3.4%), Polish (2.3%), and Belorussian (4.5%)
Major Cities: Riga (capital), Ventspils, and Liepaja
Major Port: Ventspils

ECONOMIC PROFILE

Net Material Product (1989E): 8.14 billion rubles (1.3% of USSR total)
NMP Growth Rates (1989E): 5.0%

ENERGY PROFILE

SUPPLY:

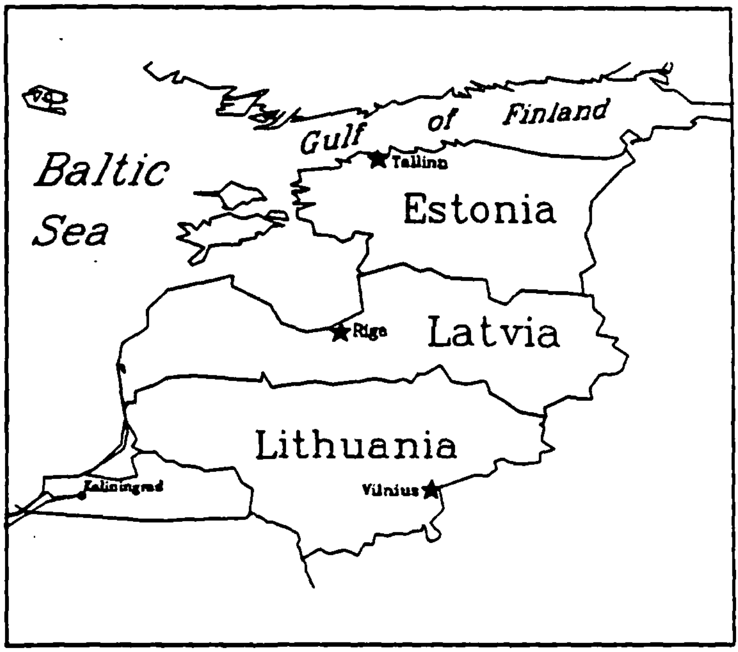
Latvia is almost totally dependent on imports to satisfy its energy demand, producing only small amounts of hydroelectricity and peat.

CONSUMPTION:

Oil (1989E): 116,000 barrels per day
Natural Gas (1989E): 109 billion cubic feet
Coal (1989E): 80,000 short tons
Electric Power (1989E): 9 terawatthours
Total (1989E): 0.46 quadrillion BTUs

ECONOMIC CONDITIONS

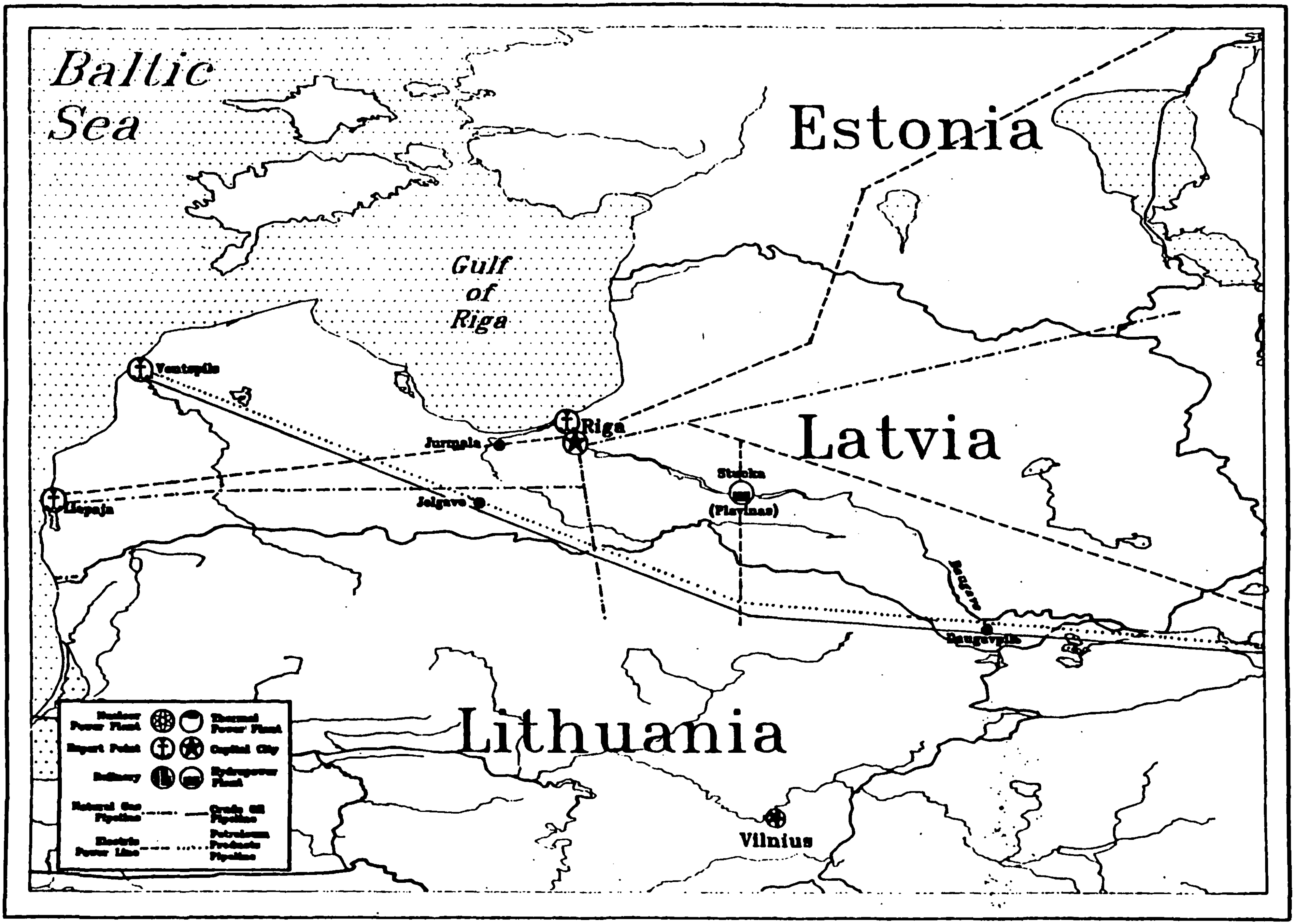
Latvia's primary industries are machine-building and metalworking, food, and light manufacturing. Major products include radio receivers and washing machines. Other industries include glass, wood, paper, chemicals, and petrochemicals. The Riga area is a major manufacturing region, which historically has supported a diversity of industries.



Latvia is an active trader, primarily with other Soviet republics. It exports about 70 percent of its production while importing about three-quarters of its consumption. Latvia imports and exports machinery. It also exports food products and small volumes of electric power, and imports coal from neighboring Poland.

HISTORICAL AND RECENT EVENTS

Latvia was annexed by the Soviet Union in 1940 under the Hitler-Stalin pact, after a 20-year period of independence. Although it had originally favored a step-by-step break with Moscow, Latvia declared full independence from the Soviet Union during the August 1991 coup attempt. Soon after, Denmark sent the first ambassador to a Baltic country in 50 years. This was followed by U.S. recognition of Latvia's independence on September 2, 1991.


Baltic Sea
Estonia
Gulf of Riga
Latvia
Lithuania
Ventspils
Riga
Jurmala
Liepaja
Jelgava
Stucka
(Plavinas)
Daugava
Daugavpils
Vilnius
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Lithuania

COUNTRY PROFILE

Head of State: Vytautas Z. Landsbergis
Population (1989): 3.69 million
Location/ Size: Baltic / 17,700 square miles
Ethnic Makeup: Lithuanian (80.1%), Russian (8.6%), Polish (7.7%), and Byelorussian (1.5%)
Major Cities: Vilnius (capital), Klaipeda, Kaunas, and Siauliai
Major Port: Klaipeda

ECONOMIC PROFILE

Net Material Product (1989): 9.8 billion rubles (1.5% of total USSR)
NMP Growth Rate (1989): 2.9%

ENERGY PROFILE

SUPPLY

Electricity Production (1989E): 29.2 terawatthours

CONSUMPTION

Oil (1989E): 180,000 barrels per day
Natural Gas (1989E): 194 billion cubic feet
Coal (1989E): 1.5 million short tons
Total (1989): 0.64 quadrillion BTUs

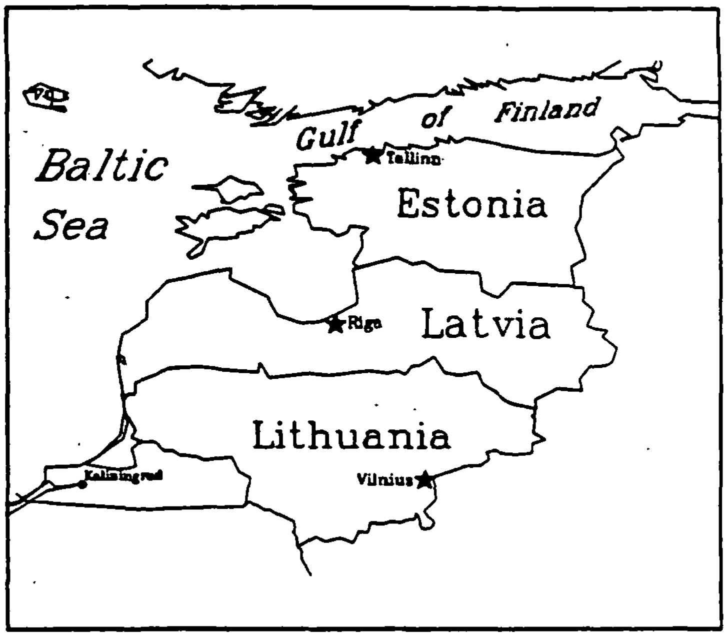
OIL REFINING:

Lithuania has a 270,000 barrel per day refinery in Mazeikiai which operates close to peak capacity. The refinery receives oil by pipeline from Western Siberia and provides product to the Baltics republics. In addition, the Mazeikiai refinery is able to produce distillate fuel oil for export.

OVERVIEW:

Lithuania is nearly totally dependent on imports for its fossil fuel demands. Oil accounts for nearly 60 percent of Lithuania's energy consumption, while natural gas supplies around 28 percent.

The Ignalina nuclear power plant provides electric power to Lithania and to neighboring republics.

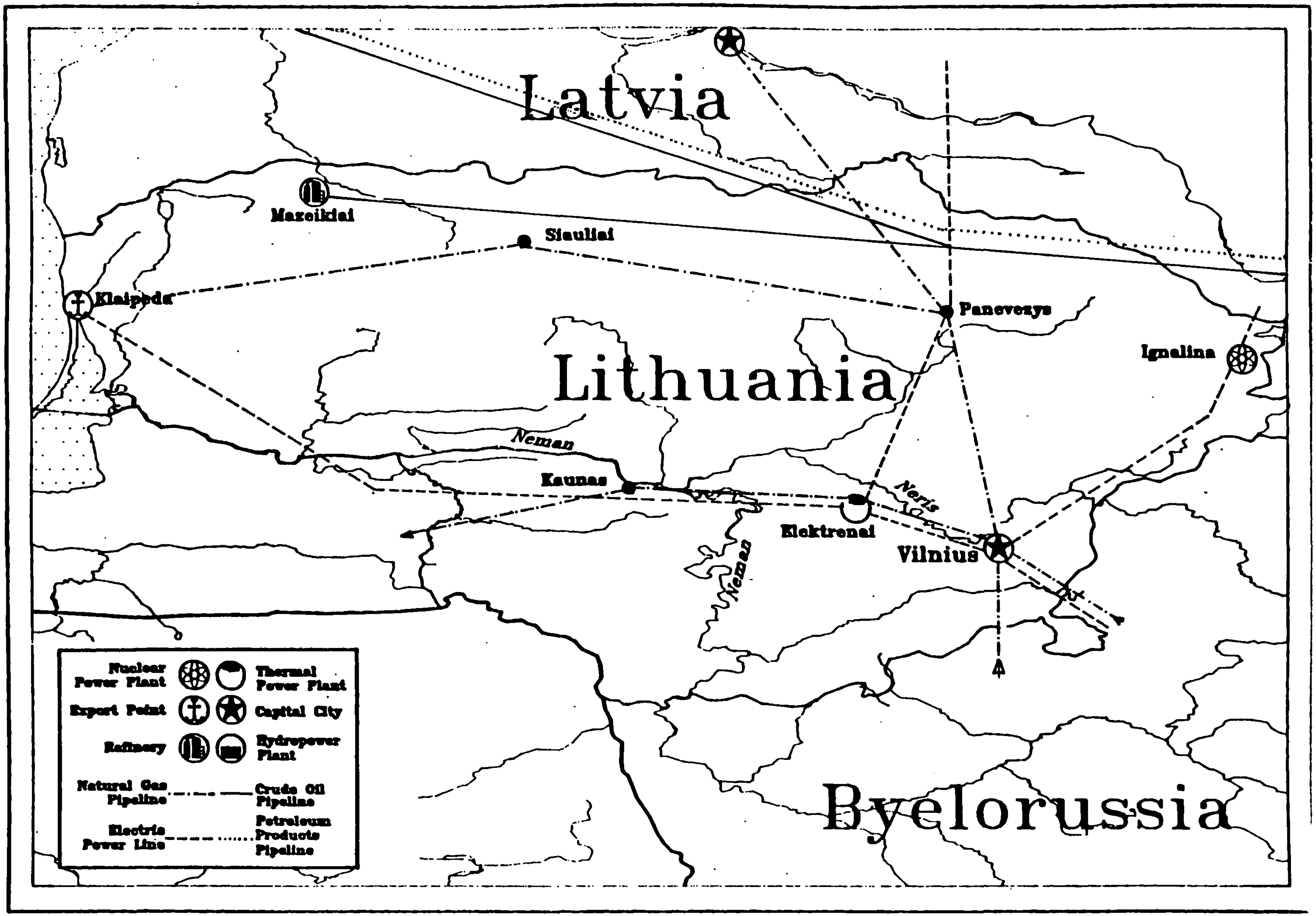


ECONOMIC CONDITIONS

Traditionally an agricultural region, Lithuania has become increasingly industrialized since World War II. As a Soviet republic, Lithuania has been a producer of machine tools, appliances, and televisions. Lithuania is a relatively rich republic, ranking fourth in per capita income.

HISTORY AND RECENT EVENTS

In 1918 an independent state was proclaimed as the defeat of the then-occupying Germans drew near. In 1940, the Hitler-Stalin pact resulted in Lithuania's annexation by the Soviet Union. In March, 1990, Lithania became the first Soviet republic to declare independence. Soviet authorities responded to this by cutting off oil supplies. On September 2, 1991, in the aftermath of the failed coup, the United States formally recognized Lithuania as an independent state.


Latvia
Mazeikiai
Siauliai
Klaipeda
Panevezys
Lithuania
Ignalina
Neman
Kaunas
Neris
Elektrenai
Vilnius
Neman
Byelorussia
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Moldavia

REPUBLIC PROFILE

President: Mircea Snegur
Population (1990): 4,340,000
Size/Location: 9,155 square miles.
Situated in the southwestern part of the Soviet Union, with Romania to the west and the Ukraine to the east.
Ethnic Groups: Moldavian (64%), Ukrainian (14%), Russian (13%)
Major Cities: Kishinev (capital)
Major Import Products: Machinery, light industrial goods, chemicals and petrochemicals, oil and gas

ECONOMIC PROFILE

Net Material Product (1989): 8.2 billion rubles
NMP Growth Rate (1989): 3.9%

ENERGY PROFILE

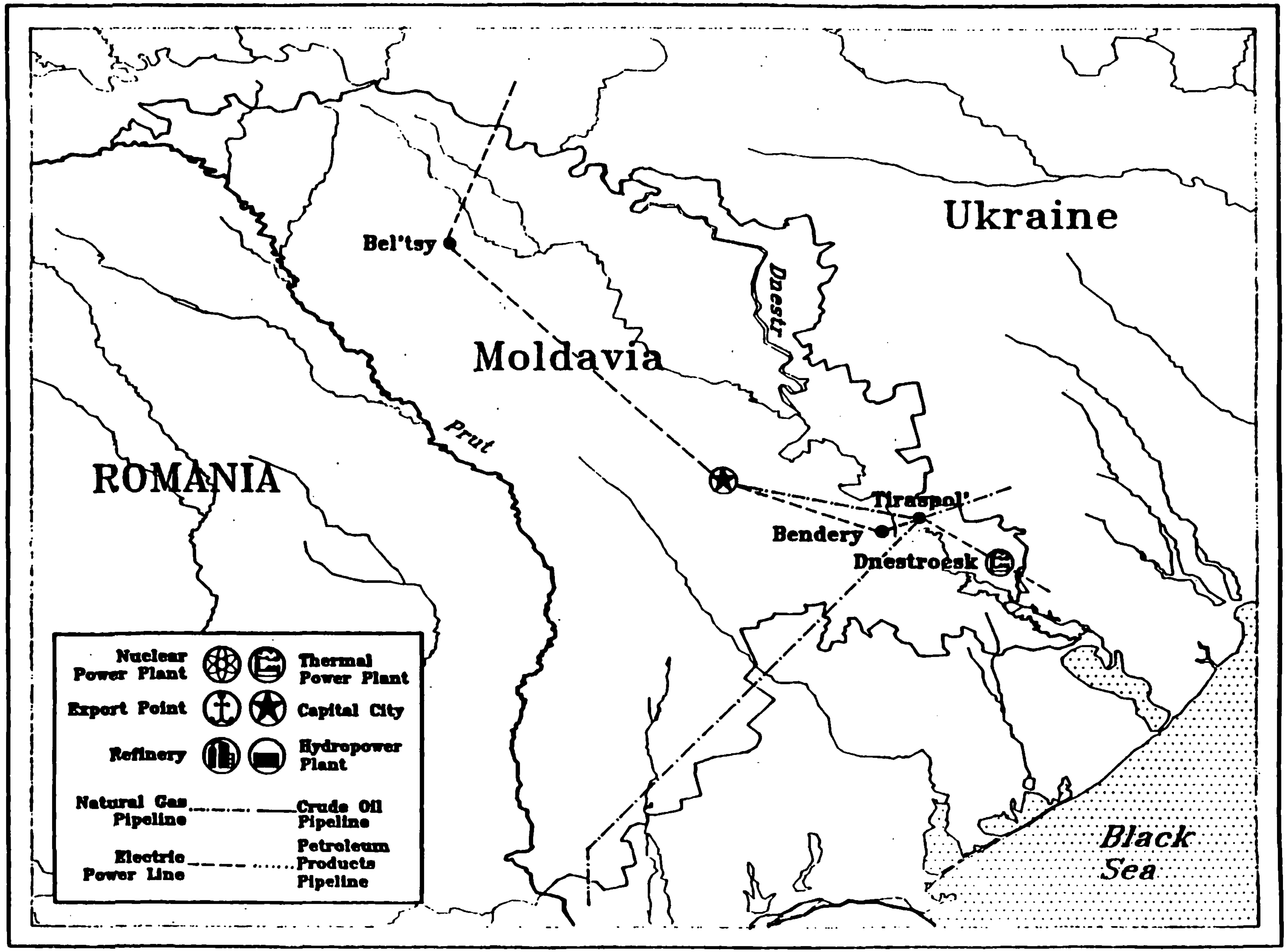
Supply:
No indigenous fossil fuel resources.
Consumption:
Oil (1989E): 100,000 barrels per day
Natural Gas (1989E): 136 billion cubic feet
Coal (1989E): 6 million short tons
Electricity (1989E): 10.2 terawatthours
Total (1989E): 0.38 quadrillion BTUs

ECONOMIC CONDITIONS

Primarily an agricultural region with rich vineyards and tobacco fields, Moldavia imports nearly all of its energy needs from Russia and the Ukraine. However, Moldavia is a net exporter of electricity.

HISTORY AND RECENT EVENTS

The Moldavian Republic was formed as an autonomous republic on October 12, 1924, and joined the USSR on August 2, 1940. Moldavia has close cultural links to Romania, with which it was joined before 1940. Parliament voted for independence in early September.


Ukraine
Bel'tsy
Dnestr
Moldavia
Prut
ROMANIA
Tiraspol'
Bendery
Dnestroesk
Black Sea
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Russia

REPUBLIC PROFILE

President: Boris Yeltsin

Population (1989): 147 million (51% of the USSR)

Size/Location: 4,618,000 square miles (76% of the USSR). Between the Baltic Sea and Arctic Ocean in the north, China and Mongolia in the south, and the Pacific Ocean in the east.

Ethnic Divisions: Russian (82.6%), Tatar (3.6%), Ukrainian (2.7%), Chuvash (1.2%), and 100 other nationalities (9.9%)

Major Cities: Moscow(capital), St. Petersburg, Arkhangelsk, Vladivostok

ECONOMIC PROFILE

Net Material Product (1989) : 381 billion rubles (59% of USSR total)

Sectoral Share in USSR Output: Agriculture (18% of USSR total); Industry (62% of USSR total); Foreign Exports (71% of USSR total); Foreign Imports (69% of USSR total).

ENERGY PROFILE

Organization

The Russian Energy Ministry oversees the management of energy resources.

Energy Minister

Anatoliy Dyakov

CONSUMPTION

Oil (1989E): 5.2 million barrels per day (MMBD)
Gas (1989E): 16.8 trillion cubic feet (TCF)
Coal (1989E): 475 million short tons (MST)
Electricity (1989E): 906 terawatthours (TWh)
Total (1989E): 38.4 quadrillion BTU

SUPPLY

Oil (1990): 10.3 MMBD (91% of USSR total)
Gas (1990): 22.6 TCF (79% of USSR total)
Coal (1990): 435 MST (56% of USSR total)
Electric (1990): 1082 TWH (63% of USSR total)

Overview

By itself, Russia would be the world's largest oil producer, and would contain the largest natural gas reserves, and one of the largest coal reserves. Russia contains between 80 and 90 percent of total Soviet oil reserves of 58 billion barrels, and a similar share of Soviet natural gas reserves of 1500 trillion cubic feet. Russia accounts for over half of total Soviet coal production.

Oil and Gas Production

Russian oil production is centered mainly in West Siberia, specifically the Tyumen Oblast. Production in the older Russian oil fields in West Siberia is declining. Russian oil exports to Eastern Europe are transported primarily by pipeline, and to Western Europe via tanker through ports in the Black Sea and the Baltics. Russian oil exports dropped 36 percent in the first quarter of 1991 from the first quarter of 1990.

Russian natural gas production, like oil production, is concentrated in West Siberia, particularly the giant Urengoi field. Vast amounts of natural gas are also believed to lie beneath the Arctic Ocean. Russian natural gas export capacity is now limited to the area of Europe served by pipelines from western Siberia and the Urals. Future possibilities include links to Japan and Korea.

For both oil and natural gas, future production will come largely from relatively inaccessible fields, necessitating a major exploration and development effort requiring huge investments of capital.

Refineries

Total Russian crude oil refining capacity is about 8 million barrels per day, constituting two-thirds of total Soviet refining capacity. Russian refineries are relatively antiquated and technically unsophisticated, operating at only 75 percent capacity utilization (compared to 91 percent in the United States). In addition, Russian refineries have much less reforming and cracking capacity than U.S.

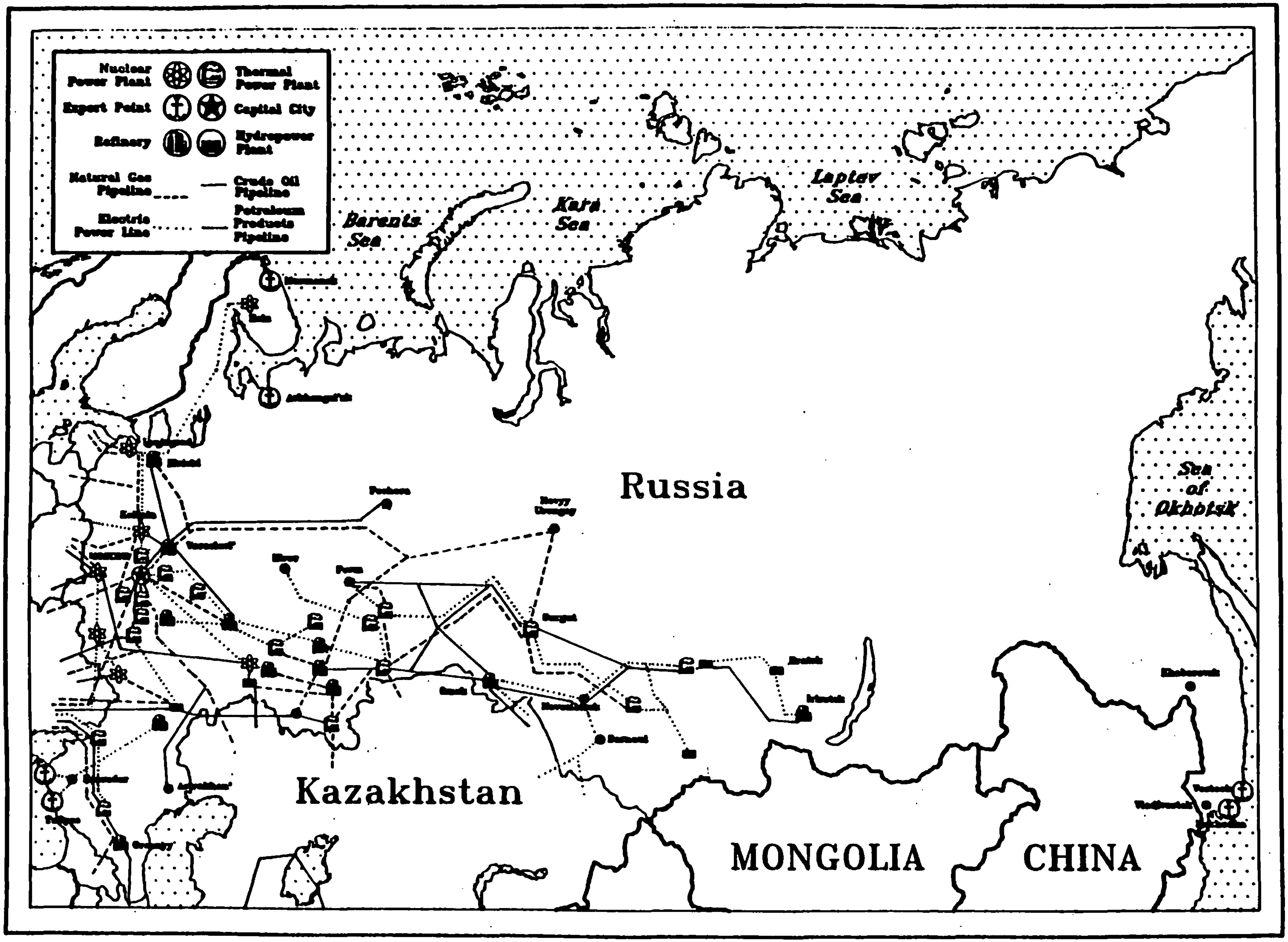
refineries, meaning that a much lower percent of distilled crude can be turned into light products.

Most Russian refineries rely on western Siberian crude delivered by pipeline, although the Groznyy refinery, one of the larger and more advanced refineries, supplies the Ukraine by pipeline. Most refined products are transported by train, although several refineries in the Volga-Urals region are connected to a pipeline that carries product to the central continent.

HISTORY ANDRECENT EVENTS

The Russian Republic was formed on November 7, 1917 and joined the USSR on December 30, 1922. With 76% of the area, 51% of the population, a majority of Soviet energy and industrial production, and enormous military power, Russia is by far the most important Soviet republic. In the aftermath of the recent coup attempt, Boris Yeltsin, as president of Russia, appears for now to be the dominant political figure in the USSR, having assumed much of the power that was the Kremlin's.

It is obvious, however, that a new system of economic, political, and military relationships between Russia and the smaller republics will need to be hammered out in coming months. Whether this will take the form of a commonwealth of independent states, a modified Union, or some other form remains to be seen. It also remains to be seen whether this transformation can be accomplished without a deterioration into ethnic conflict as in Yugoslavia. Already, Russia has warned other Soviet republics, particularly Ukraine and Kazakhstan, that it would not allow them to secede from the union taking areas with heavy Russian populations with them.


Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
Barents Sea
Kara Sea
Laptev Sea
Sea of Okhotsk
Russia
Kazakhstan
MONGOLIA
CHINA
Murmansk
Kola
Arkhangel'sk
Pechora
Novyy Urengoy
Kirov
Perm
Surgut
Omsk
Novosibirsk
Barnaul
Bratsk
Irkutsk
Khabarovsk
Vladivostok

Tadzhikistan

REPUBLIC PROFILE

President: Kakhar Makhamov
Population (1989): 5,112,000
Size/Location: 55,250 square miles. Part of the Central Asia region, with Kirgizia to the north and east, China to the east, Uzbekistan to the north and west, and Afghanistan to the south.
Ethnic Groups: Tadzhiks (59%), Uzbeks (23%), Russians (10%). Tadzhiks are Aryans and speak a Persian language. Tadzhikistan is a predominately Muslim republic.
Major Cities: Dushanbe(capital)

ECONOMIC PROFILE

Net Material Product (1989): 5.5 billion rubles (0.8% of Soviet Union). Per capita income of $2,340 is the lowest in the Soviet Union.
NMP Growth Rate (1989): 0%; volatile from year to year reflecting the performance of the agricultural base.

ENERGY PROFILE

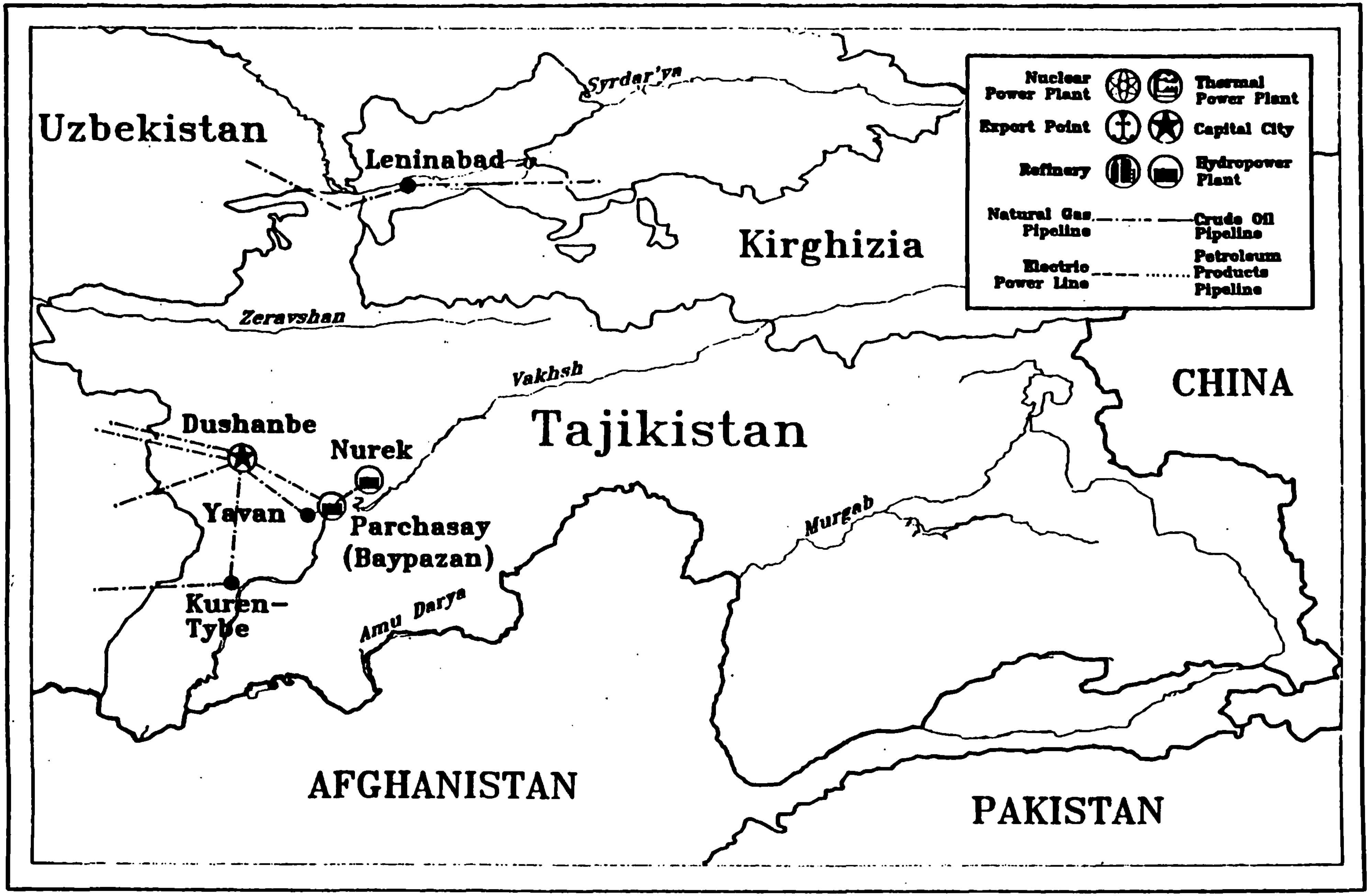
Supply:
Oil (1990E): 4,000 barrels per day (b/d)
Natural Gas (1989E): 7 billion cubic feet
Coal (1989E): 800,000 short tons
Consumption
Oil (1989E): 50,000 barrels per day
Natural Gas (1989E): 64 billion cubic feet
Coal (1989E): 1,100,000 short tons
Electricity (1989E): 15.4 terawatthours
Total (1989E): 0.37 quadrillion BTUs

ECONOMIC CONDITIONS

The republic is mainly agricultural, specializing in fruit, cattle, and sheep. Some cotton, grain, and rice is also grown. Hydroelectric power is plentiful, and dams are especially important in the dry climate of Central Asia for both irrigation and power. The 2,700 MW Nurek power station on the Varksh river is complete, and construction of the 3,600 MW Rogun station on the same river is underway. The presence of cheap hydropower has attracted an aluminum industry.

HISTORY AND RECENT EVENTS

The Tadzhik republic was formed as an autonomous republic on October 14, 1924, and became a Union republic on October 16, 1929. The republic declared its sovereignty on August 25, 1990, and its independence in early September 1991.


Uzbekistan
Syrdar'ya
Leninabad
Kirghizia
Zeravshan
Vakhsh
CHINA
Tajikistan
Dushanbe
Nurek
Yavan
Parchasay
(Baypazan)
Kuren-Tybe
Amu Darya
Murgab
AFGHANISTAN
PAKISTAN
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Turkmenistan

REPUBLIC PROFILE

President: Saparmurad Niyazov

Population (1990): 3,621,700 (1.3% of the USSR)

Size/Location: 188,455 square miles. Occupies the southwest part of Central Asia with the Caspian Sea on the west, Uzbekistan to the east, Kazakhstan to the north, Iran to the south, and Afghanistan to the southwest

Ethnic Groups: Turkmen (68%), Russian (13%), Uzbek (9%). The republic is predominately Muslim, with ethnic ties to Iran.

Major Cities: Ashkhabad (capital)

ECONOMIC PROFILE

Net Material Product (1989): 5.47 bil. rubles (0.7% of Soviet Union). Per capita GNP of $3,370 is fourth lowest in the Soviet Union

NMP Growth Rate (1989): 3.2%; volatile from year to year reflecting the performance of the agricultural base.

ENERGY PROFILE

SUPPLY

Oil (1990E): 100,000 barrels per day (b/d)

Natural Gas (1989E): 3,101 billion cubic feet (11% of Soviet Union)

Oil Refining Capacity (1991E): 240,000 b/d

CONSUMPTION

Oil (1989E): 100,000 barrel per day

Natural Gas (1989E) 376 billion cubic feet

Coal (1989E): 0.8 million short tons

Electricity (1989E): 7 terawatthours

Total (1989E): 0.55 quadrillion BTUs

OIL INDUSTRY

The republic is considering establishing an independent energy company (Turkmenneftegazprom) to end the Russian dominance of the republic's gas industry. There are currently no joint ventures with foreign companies operating in the republic. However, the republic has taken the step of offering western companies the opportunity to bid on tracts in the South Caspian and Amu-Dar'ya basins.

Oil and Natural Gas Production

Oil output has been stable, with most of the production coming from the Chelken district that includes the Kotur-Tepe supergiant field (discovered 1956) and the Nebit-Dag giant field (discovered 1934). There is a small amount of offshore production in the Caspian Sea. Most of the republic's hydrocarbon production is from the Kopet Dag Trough that extends along the mountains that form the border between Iran and the Soviet Union. The Trough contains mostly gas, helping make Turkmenistan the second largest gas producing republic in the Soviet Union, after Russia. The Amu-Dar'ya district contains two supergiant fields and 9 giant fields. Coal production is negligible.

Refineries

Turkmenistan had one refinery currently operating. This refinery, located in Krasnovodsk, has the capacity to process 240 thousand barrels per day of crude oil, but typically refines little more than half that amount. The cracking facilities at the Krasnovodsk refinery allow for greater production of light petroleum products. The refinery relies on local production. Recent shortages in crude oil shipments to the refinery have resulted in product shortages in Turkmenistan and other republics surrounding the Caspian Sea. Neftezavodsk is the site of another Turkmenistan refinery, but has yet to open after 15 years of construction. This refinery is to be supplied by pipeline from Western Siberia.

ECONOMIC CONDITIONS

Turkmenistan is mainly agricultural, producing cotton, dates, olives, figs, and sesame. The republic is known for carpets, horses, and sheep, although chemicals and minerals are also produced.

HISTORY AND RECENT EVENTS

The Turkmenistan Republic was formed on October 27, 1924, and declared its sovereignty on August 22 ,1990. As of the end of August 1991, however, it had not yet declared its independence.


Kazakhstan
Uzbekistan
Tashauz
Zaliv Kara-Bogaz-Gol
Krasnovodsk
Nebit-Dag
Turkmenia
Cheleken
Caspian Sea
Okarem
Ashkhabad
Chardzhou
Amu Darya
Mary
Murgab
Kelif
IRAN
AFGHANISTAN
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Ukraine

REPUBLIC PROFILE

President: Leonid Kravchuk
Population (1989): 52 million (18% of the USSR - the second largest Soviet Republic)
Size/Location: 164,000 sqare miles. Bordered by Poland, Czechoslovakia, Hungary, and Romania to the West, Russia to the East, Belorussia to the North, and the Black Sea to the South.
Ethnic Groups: Ukrainian(70%); Russian(20%) Belorussian, Moldavian and Polish (10%)
Major Cities: Kiev (capital)

ECONOMIC PROFILE

Net Material Product (1989): 109 billion rubles (17% of USSR total)
Exports to Other Republics (% of Republic NMP): 39%
Foreign Exports (% of Republic NMP): 7%
Foreign Imports (% of Republic NMP): 14%
Sectoral Share in USSR Output: Agriculture (23% of total); Industry (18% of total); Foreign Exports (14% of total); Foreign Imports (15% of total).

ENERGY PROFILE

CONSUMPTION:
Oil (1989E): 1.2 million barrels per day (MMBD)
Gas (1989E): 4,086 billion cubic feet (BCF)
Coal (1989E): 198 million short tons (MST)
Electricity (1989E): 245 terawatthours (Twh)
Total (1989E): 11.38 Quadrillion BTU (Quads)
SUPPLY:
Oil Production (1990): 0.1 MMBD (1% of USSR)
Gas Production (1990): 1 TCF (4% of USSR)
Coal Production (1990): 182 MST (24% of USSR)
Electric Power Production (1990): 305 TWH (18% of USSR)

Overview

The Ukraine plays a significant role in the Soviet energy picture. First, the Ukraine possesses the Donets Basin, which is the USSR's largest coal producing area. Second, the republic is the Soviet Union's major source of iron and steel, based on Donets coal and iron ore from Krivoy Rog. Third, the Ukraine is a major center for heavy machinery and industrial equipment, producing around one third of the Soviet Union's steel pipes, and nearly 17% of its oil production machinery. Finally, although the Ukraine is a net energy importer, the republic serves an important function as the major export route for energy exports (mainly from Russia) to Eastern and Western Europe. For instance, although the Ukraine produces only about 17% of Soviet electricity, it accounts for nearly 70% of Soviet electric power exports.

The Ukraine also contains a heavy concentration of nuclear power plants, with 15 of the Soviet Union's 43 nuclear generating units situated in the republic. Overall, nuclear power makes up about 20% of the Ukraine's electric generating capacity.

Refineries

The Ukraine has 1.1 million barrels per day crude oil refining capacity, or 10% of total Soviet refining capacity. Although Ukrainian refineries are relatively modern compared to Russia's, they are still technically unsophisticated, containing far less capacity than comparable U.S. refineries for production of light products. Most Ukrainian refineries receive crude oil by pipeline from western Siberian oil fields in the Russian republic. Much of Ukrainian refined petroleum products are sent by train to other areas of the Ukraine. In addition, the Ukraine receives refined petroleum products from referineries in Azerbaijan, Belorussia and Russia.

HISTORY AND RECENT EVENTS

The Ukrainian Republic was formed on December 25, 1917 and was incorporated into the USSR on December 30, 1922. The Ukraine is critical to the USSR, serving both as the "breadbasket of the USSR" and as an industrial powerhouse in its own right, and ranking second in importance only to Russia.

Along with Russia and Belorussia, the Ukraine comprises one of three Slavic republics which can be considered as forming the core of the Soviet Union. The Ukrainian parliament declared independence from the Soviet Union in the immediate aftermath of the August 1991 coup attempt; a referendum on the issue is scheduled for December 1, 1991. On August 29, the Ukraine agreed with Russia to form a temporary economic and military alliance. Despite this agreement, however, disagreement exists between the two sides on many issues, particularly borders and the ultimate status of nuclear forces on Ukrainian territory.


Belorussia
Russia
Ukraine
ROMANIA
Moldavia
Sea of Azou
Black Sea
Chernobyl'
Kiev
Tripol'ye
Rovno
Ternopol'
Ladyzhin
South Ukraine
Sumy
Poltava
Kremenchug
Krivoy Rog
Nikolayev
Kherson
Simferopol'
Kerch'
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline

Uzbekistan

REPUBLIC PROFILE

President: Islam Karimov

Population (1989): 19,906,000 (6.9% of USSR)

Size/Location: 172,740 square miles (2.0% of Soviet Union), occupies the southern part of the Soviet Union, in Central Asia with Kirgizia on the east, Kazakhstan to the north, Turkmenia to the southwest, and Afghanistan and Tadzhikistan to the south

Ethnic Groups: Uzbeks (69%), Russians (11%), and Tatars, Kazakhs and Tadzhiks (each about 4%). Uzbek Muslims are the third largest Soviet nationality, and there is a strong nationalist movement.

Major Cities: Tashkent (capital), Nukus

ECONOMIC PROFILE

Net Material Product (1989): 11.95 billion rubles (3.3% of Soviet Union). Per capita income of $2,750 is the second lowest in the USSR.

NMP Growth Rate (1989): 3.4%; volatile from year to year reflecting the performance of the agricultural base.

ENERGY PROFILE

SUPPLY:

Oil (1990E): 50,000 barrels per day (b/d)

Natural Gas (1989E): 1,441 billion cubic feet

Coal Production (1990E): 7 million short tons

Oil Refining Capacity (1991E): 180,000 b/d

CONSUMPTION:

Oil (1989E) 227,000 b/d

Coal (1989E): 6.7 million short tons

Natural Gas (1989E) 1,483 billion cubic feet

Electricity (1989E): 46 terawatthours

Total (1989E): 2.04 quadrillion BTUs

OIL INDUSTRY

Uzbekistan currently has 18 joint ventures with foreign companies operating in the republic.

Fossil Fuel Production

Oil output has been rising steadily since 1980, receiving a boost in 1990 from the addition of a new oil producing area in the Karshi Steppe region. The Amu-Dar'ya district in western Uzbekistan and eastern Turkmenistan is a major gas bearing area. Production of Angren coal was above plan in 1990 despite problems stemming from poor planning and implementation in expanding open-pit mines of Angren lignite. The availability of fossil fuels has resulted in the development of thermal power stations. The Novo-Angren power plant increased its capacity in January 1991 to 1800 MW, and the Takhiatash power plant added units in 1990 to raise capacity to 730 MW.

Refineries

The two refineries in Uzbekistan are supplied by rail shipments of crude oil from Western Siberia. The refinery in Fergana operates close to its peak capacity of 140 thousand barrels per day, while the Alty-Arky refinery operates at about half its 40 thousand barrel per day capacity. Neither of the two refineries has much capability to upgrade residual oil into the lighter petroleum products used in the transportation sector.

Uzbekistan supplies product for local consumption. Recent shortages in crude oil shipments to the Uzbekistan refineries have resulted in product shortages.

ECONOMIC CONDITIONS

With water from the Aral Sea and a conducive climate, Uzbekistan has become the world's third largest producer of cotton, as well as a producer of rice, silk, and hemp. Industries include iron, steel, tractors, textiles, and television and radio sets. Despite its assets, Uzbekistan is generally poor, with high unemployment, social and ethnic unrest, and enviromental problems.

HISTORY AND RECENT EVENTS

The Uzbek republic was formed on October 27, 1924, and declared its sovereignty on June 20, 1990. Uzbekistan declared its independence on September 7, 1991.


Kazakhstan
Nuclear Power Plant
Thermal Power Plant
Export Point
Capital City
Refinery
Hydropower Plant
Natural Gas Pipeline
Crude Oil Pipeline
Electric Power Line
Petroleum Products Pipeline
Aral Sea
Kungrad
Urgench
Uzbekistan
Charvak
Tashkent
Angren
Namangan
Andizhan
Bekabad
Khamza
Fergana
Dzhizak
Bukhara
Navoi
Samarkand
Mirdesh
Mubarek
Turkmenia
Tajikistan
Sherabad
IRAN
AFGHANISTAN

FAX (One pages)

TO:- Dr. Phillip M. Wright,
Univ. of Utah Research Institute,
391-C Chipeta Way, Salt lake City, UT 84108 U.S.A.
FAX No: 0011 (801) 584 4453
FROM:- Wilfred Elders,
Beppu Geophysical Research Laboratory,
Kyoto University, Noguchibaru, Beppu 874, Japan.
FAX No: 81 (977) 22 0965 Telephone No: 81 (977) 22 0713
Date: 19 January 1994

Subject:- Russian American Monograph

Dear Mike,

As I have had no answer to my fax of 2 December asking about the status of your contribution to the Russian American Monograph, I am writing again. When can I expect the text of Chapter 1.4, entitled "Exploration Geosciences, (geology, geophysics, geochemistry)" ? I hope that you can send your manuscript to me as soon as conveniently possible. I will remain here in Japan until 31 March 1994 working on geothermal research. You can contact me at the above address and fax number or at my email address:- G53444@JPNKUDPC.BITNET.

Sincerely,

Wilf

Wilfred Elders
Visiting Professor, Kyoto University

Kathy

may be canceled!

Eval of Hydrothermal Resources input by Mike

BEPPU GEOPHYSICAL RESEARCH LABORATORY
KYOTO UNIVERSITY
NOGUCHIBARU, BEPPU 874, JAPAN
TEL. 0977-22-0713, TELEFAX. 0977-22-0965

Telefax (Two Pages)

TO: Dr. Vladimir I. Kononov,
Laboratory of Geoenergetics and Hydrochemistry,
Geological Institute, Russian Academy of Sciences,
Pyzhervsky per. 7, Moscow, 109017, Russia.
FAX No: 001-7-95-231-81-06

c.c.	Paul Kruger, Stanford University	0011 415 725 8662
	Denis Nielson, UURI	0011 801 584 4453
	David Blackwell, SMU	0011 214 768 4289
	Philip Wright, UURI	0011 801 584 4453
	Donald Campbell, Mesquite Inc.,	0011 714 525 2852

FROM: Wilfred A. Elders,
Beppu, Japan.
FAX No: 81-977-22-0965 8 December 1993

Dear Dr. Kononov,

I was very pleased to receive your telefax of 3 December and reassured by being in touch with you directly at last. I am sorry for the delay caused by the non-delivery of my letter to you dated 16 September, but now you have received a copy of it faxed and also airmailed to you on 18 November.

I have discussed your the contents of your telefax with Paul Kruger. He confirms that he received the new Russian text by A.A. Shpak (in two parts labelled IV and V) and is arranging to get it translated quickly into English. Your letter referred to this as being for Chapter 5, "Evaluation of Hydrothermal Resources". However, in a letter to the person arranging the translation, Paul referred to Dr. Shpak's new manuscript as being intended for Chapter 1.3, with co-author W. A. Elders. He means Chapter 3 as in the table of contents of Volume One as originally agreed. That is the version of the table of contents which is on page two of my letter of 16 September, where Chapter 1.3, entitled "Resource Base and Resource Types" was to be written by A.A. Shpak and me (replacing Patrick Muffler).

TO: Dr. Vladimir Kononov (c.c. Wright)

As I mentioned in my letter of 16 of September, I can see the logic of the changes in the table of contents with respect to the material written by Dr. Polyak and Dr. Neilson, as their approaches to the topic of "The Nature of Geothermal Energy" are very different. However, I did not understand why the version of the table of contents which you gave me in St. Petersburg ignored the *topic* of "Resource Base and Resource Types", about which I was supposed to write. My September 16 letter also explained that I sent some material I had written on that topic to Dr. Shpak from St. Petersburg. Dr. Shpak referred to that manuscript in a telefax he sent to me here on 17 November. I planned to adapt that material both to conform to Dr. Shpak's ideas and by adding the appropriate numbers for the estimated resource base of the USA. However the table of contents which you and Dr. Polyak gave me in St. Petersburg eliminates the topic of "Resource Base and Resource Types".

Paul Kruger in a telefax to me today makes a very good suggestion which I propose we adopt. He suggests that you and I go ahead with Volume One independently and that I try to arrange to have first drafts of Chapters 2, 3, 4 and 5 written as soon as possible. He further suggests that when you and I have assembled the first drafts from both sides, we should have an editors meeting (via mail, or if possible, in person) to mutually agree on a second version of the table of contents, based on the actual first drafts at hand.

My opinion is that, in some cases, the chapters written by the Russian and American authors may be easy to harmonize by interaction between the authors. In other cases the Russian and American chapters might better stand alone as separate topics, and if necessary it would be up to us, as editors, to arrange that some appropriate linking material is written. But these decisions can only be taken when we have the texts of the first drafts translated and can compare them.

Based on Paul Kruger's suggestion, I am continuing to encourage the American authors Blackwell, Wright and Campbell to complete their assigned writing, as soon as possible, by sending them a copy of this letter.

Best wishes for the Holiday Season and for the year ahead!

Yours sincerely,

Wilfred A. Elders

Wilfred A. Elders,
Visiting Professor of Geology, Kyoto University, Japan.

FAX (Two pages)
TO:- Dr. Phillip M. Wright,
Univ. of Utah Research Institute,
391-C Chipeta Way, Salt lake City, UT 84108 U.S.A.
FAX No: 0011 (801) 584 4453
FROM:- Wilfred Elders,
Beppu Geophysical Research Laboratory,
Kyoto University, Noguchibaru, Beppu 874, Japan.
FAX No: 81 (977) 22 0965 Telephone No: 81 (977) 22 0713
Date: 2 December 1993

Subject:- Russian American Monograph

Dear Mike,

I am writing to ask about the status of your contribution, Chapter 1.4, entitled "Exploration, Geosciences, (geology, geophysics, geochemistry)". As you know, in St. Petersburg it was suggested that the first drafts of chapters should be completed by November 30 1993. However in view of all uncertainties in, and after, the St. Petersburg meeting, and the fact that I was here trying to start new research, I hesitated about taking the time to write my own chapter. Also I had not received an answer to my letter to my co-editor Kononov, seeking to clarify our different perspectives about the table of contents of Volume 1. However, at last we have some encouraging news! Email from Paul Kruger yesterday indicated he has received the Russian texts for Chapters 1.4 and 1.5 of Volume 1 and is arranging their translation into English before sending them on to me. Presumably this implies that the Russians are, after all, following the original version of the table of contents for Volume 1.
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I hope that you can send your manuscript to me as soon as conveniently possible. I will remain here in Japan until 31 March 1994 working on geothermal research. You can contact me at the above address and fax number or at my email address:- G53444@JPNKUDPC.BITNET.
Best Wishes for the Holidays!

Sincerely,

Wilf Elders

Wilfred Elders
Visiting Professor, Kyoto University

Russian-American Monograph on Geothermal Energy

To Co-Editors: Wilfred Elders ←
Hugh Murphy
John Lund
Date: 15 November 1993
Subject: NewsMemo No. 13

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With the very Best Wishes for the Holiday Season,

Paul Kruger

FAX (Two pages)
TO:- Dr. Phillip M. Wright,
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Date: 2 December 1993

Subject:- Russian American Monograph

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RECEIVED 12/7/93

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Paul Kruger

Chapter 2.1

CHARACTERISTICS OF GEOTHERMAL RESERVOIRS

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(First Draft)
(15Sep93)

I. Introduction

Geothermal resources have been developed for electric power generation in the United States, the former Soviet Union, and many other geothermal countries of the world as a twentieth-century technology. As described in Volume I, geothermal resources in nature occur in a variety of forms. Their characteristics for reservoir development can, for convenience, be divided into 6 groups:

(1) Hydrothermal, comprising all-steam, two-phase, and all-steam systems;
(2) Hot Dry Rock, stimulated formations with artificial circulating systems;
(3) Hot Wet Rock, inadequate hydrothermal systems augmented by stimulation;
(4) Geopressured Deposits, deep systems associated with natural gas;
(5) Magmatic Bodies, the ultimate thermal source in the Earth's crust;
(6) Normal Gradient Rock, comprising the main thermal cover of the Earth.

Descriptions of these resource types developed for commercial exploitation have been given in the proceedings of several international symposia (e.g., UN,1975; GRC,1985; GRC,1990). During this century, only the few high-temperature hydrothermal resources at readily attainable depth have been commercially developed for electric power generation and thermal water applications. In general, the technology for development and management of hydrothermal resources have been based on techniques adopted from hydrologic and petroleum engineering industries. The result has been a focus on fluid extraction performance rather than heat extraction efficiency. An alternate focus could be the mining industry, where the extracted product (thermal energy) can be evaluated in mining terms of resource size (reservoir volume heat content), concentration (temperature) distribution, and needed extraction rate. For long-term development of a significant geothermal industry, production should be evaluated in terms of thermal extraction rate (kJ/s) by a heat-carrier fluid (either in-place or circulated) at a needed thermal energy concentration (enthalpy).

For general description of the characteristics of geothermal reservoirs, this chapter will focus on high-temperature hydrothermal reservoirs (HTHR) and hot dry rock (HDR) reservoirs with artificial circulation systems.

A. Engineering definition of a geothermal reservoir

Although description of HTHR and HDR systems in the literature vary considerably, a geothermal reservoir may be defined, generally, as a rock formation of adequate size (volume) containing sufficient thermal energy (heat content) above a given temperature suitable for the intended application (such as electric power generation or direct thermal heating).

(1) High-Temperature Hydrothermal Reservoirs

rmeable

For high-temperature hydrothermal reservoir (HTHR) utilization, the reservoir may be considered as a fractured formation that was heated convectively by hot fluid flowing from a distant magmatic heat source. The total heat content in the original formation is given by the heat stored in the rock volume in thermal contact with the fluid plus the heat stored in the fluid, given by

$$HC = (\rho_r(1-\Phi)C_r + \rho_f \Phi C_f) V (T_o - T_a) \qquad (1)$$

where $\rho_{r,f}$ = density of the rock, fluid (kg/m^3)
Φ = reservoir porosity
$C_{r,f}$ = specific heat of the rock, fluid (J/kg-C)
V = reservoir volume (m^3)
T_o = initial reservoir temperature (°C)
T_a = application abandonment temperature (°C).

The relative ease of thermal energy extraction from hydrothermal resources has been accompanied by a relatively low thermal extraction efficiency. For example, as noted in Table 1 (from Ramey, Kruger, and Raghaven, 1973), for the high-quality steam-dominated reservoir, a large fluid (steam) extraction fraction (80%) results in only a small extraction (6%) of thermal energy, due to the essentially isothermal extraction of steam without heat transfer from the reservoir rock. In contrast, the greater mass of fluid extracted from a liquid-dominated reservoir is accompanied by a greater thermal energy extraction fraction due to in-reservoir boiling by heat transfer from the rock upon pressure reduction in the reservoir.

(2) Hot Dry Rock Reservoirs

For hot dry rock (HDR) resources, the dimensions of the reservoir may be considered to be those bounding the rock volume of mean initial temperature for which circulation paths exist (or can be stimulated) to provide surface area for heat transfer. The available heat content, HC, of a HDR reservoir, analogous to the total oil in-place in a petroleum reservoir or mineral in a mining deposit, is given by

Table 1
Energy Recovery from Hydrothermal Resources*

	Steam Reservoir		Liquid Reservoir	
	Rock	Fluid	Rock	Fluid
Reservoir Mass (Tg)	450	0.663	450	15.0
Abandonment Content	--	0.134	--	0.16
Production (Tg)				
as steam	--	0.429	--	3.7
as water	--	0	--	11.1
Available Energy (PJ)	57.4	1.84	57.4	8.04
Recovery (%)				
of fluid mass	--	79.7	--	98.9
of available energy	--	6.3	--	43.0

*based on a reservoir of 280°C initial temperature, 10% porosity, 2×10^8 m^3 volume, 1900 kJ/kg production enthalpy, and abandonment pressure of 0.8 MPa (170°C) Adapted from Ramey, Kruger, and Raghaven (1973).

$$HC = (\rho V)\, C_v\, (T_o - T_a) \qquad (2)$$

where ρ = rock density (kg/m^3)
V = reservoir volume (m^3)
C_v = specific heat (J/kg-C)
T_o = initial formation temperature (°C)
T_a = abandonment fluid temperature (°C)

The commercial quality of a geothermal resource can be evaluated by the potential for an adequate, sustainable thermal extraction rate over a minimum lifetime (usually a given amortization period) until the abandonment temperature is reached. The thermal extraction rate depends on two sets of conditions: (1) the heat transfer properties of the formation and (2) the hydraulic properties of the fluid flow regime. The former is determined by the rock-type fracture network within the formation volume which controls the rate of heat conduction to the rock-block surfaces for heat transfer to the circulating fluid. The latter is determined by the connected fracture porosity and permeability distributions which control the fluid flowrate.

The rate of heat extraction may be described by a single index, the number of heat transfer units (N_{tu}) which is the ratio of two time parameters for the thermal and hydraulic properties. The thermal index is the mean-sized rock-block time constant, τ, a measure of the rate with which heat from inside the rock blocks can be conducted to the block surfaces for heat transfer. The hydraulic index is the mean residence time, t_r, a measure of how long the surrounding fluid is in contact with the rock blocks. thus, $N_{tu} = t_r/\tau$. For a given available heat content and a given abandonment temperature, the range of attainable thermal extraction rates is governed by the sustainable production flowrate at acceptable pressure for the application and the sustainable heat transfer rate to the initial in-place and recharge heat-carrier fluids.

The total energy extracted, HE, is given by the production history to time of abandonment,

$$HE = \int_{t_a}^{t_o} Q(t)\, \Delta h(T_f - T_i)\, dt \qquad (3)$$

where Q = production flowrate, as a function of pressure, (kg/s)
Δh = enthalpy of the produced fluid (kJ/kg)
T_f = produced fluid temperature (°C)
T_i = injection fluid temperature (°C).

$\Delta h(T_f - T_i)$ is the increase in enthalpy of the produced fluid above the enthalpy of the injected fluid. For an amortization period in which the temperature difference $(T_o - T_a)$ is small compared to the temperature difference $(T_o - T_i)$, the heat extracted can be approximated from the mean parameter values as

$$HE = \bar{Q}\ \overline{\Delta h}\ t \qquad (4)$$

The thermal energy fraction produced is the ratio FP = HE/HC. The fraction produced is visualized in Figure 1. The area under the cooldown curve is proportional to the energy extracted. The rectangular area encompassing the cooldown curve, from T_o to T_a and t_o to t_a, is proportional to the heat content. For a given set of thermal properties, the shape (and area) of the cooldown curve depends on the production flowrate, Q. For large Q (small mean residence time, t_r), N_{Fo} is small and after the heat close to the rock block surfaces is extracted, the fluid temperature falls rapidly. In contrast, for small Q (large t_r), N_{Fo} is large and the fluid sweeps the rock volume at rapid thermal equilibrium until the heat content above T_a is exhausted. An optimum flowrate is needed to balance the needs for maximum thermal power output and maximum thermal extraction efficiency over the lifetime of the resource.

B. Basic Properties of Geothermal Reservoirs

Common to all types of geothermal reservoirs are: (1) location (depth), size, and dimensions; (2) structure (stress and fracture networks); (3) thermal conditions (temperature, its gradient and distribution, and heat content); and (4) fluid conditions (storage, transmissivity). For analysis of the governing heat and mass processes, descriptions of a geothermal reservoir include rock properties, fluid properties, rock-fluid properties, distribution functions, and boundary conditions.

1. Rock Properties

Rock properties include geological, mineral, thermal, and structural aspects; the geological, mineral (chemical) properties (as reviewed in Volume 1) determine the character of the thermal and structural (mechanical) properties of the reservoir. The major mechanical properties include pressure, rock type, grain density, matrix and fracture porosity, fracture spacing, and absolute permeability along the principal axes. For single-phase reservoirs, compressibility and expansivity are important parameters. The major rock thermal properties include temperature, specific heat, thermal conductivity, and thermal diffusivity. The specific heat affects the heat content of the formation, the thermal conductivity and the thermal diffusivity influence the rate of heat transfer from the bulk rock to the circulating fluid.

2. Fluid Properties

Geothermal fluids vary markedly in physical and chemical composition. The heat-carrier fluid can be single or two phase water and contain multicomponent liquids and gases. The major fluid properties are temperature, pressure, phase mass fractions, and the fluid equation of state (e.g., for two-phase fluid (steam and water), for two-phase fluid and CO_2, for two-phase fluid and air, etc.). The thermophysical properties of density, specific enthalpy, viscosity, and saturated vapor pressure are calculated from steam tables on the basis of pressure and temperature values.

The rock/fluid properties that affect the amount of fluid and its ability to flow in the reservoir are the total and connected porosities, the relative permeabilities of the phases, and capillary pressure functions. Fluid storage is also dependent on the compressibility of the rock and the composition of the fluid phases.

An example of these basic properties for the Mutnovsky geothermal reservoir (Kiryukhin, 1993) is given in Table 2.

Two other aspects of a reservoir need consideration. One is the distribution of property values from one point of the reservoir to another and the other is the set of boundary conditions around the reservoir. Where possible, it is important to know the distribution of basic properties within the reservoir volume as a 3-D function of space coordinates. In other cases, the distribution of basic properties can be defined as important lumped parameters of the reservoir, such as heat and mass content, which are useful in evaluation of geothermal resources.

Boundary conditions include convection of hot fluid flows from a distant magmatic heat source, as well as discharge conditions on the surface: e.g., steam jets and thermal water springs, and cold water recharge into the reservoir.

II. Modeling of Geothermal Reservoirs

A. Diagnostics and Production Modeling of the HTHR (Dachny HTHR of the Mutnovsky hydrothermal system).

The main objective in the diagnostics of a HTHR is to identify distributions of primary parameters (temperatures, pressures (phase conditions), rock and reservoir properties) within the reservoir volume, to make estimates of mass and heat inflows and outflows. The most effective methods are : three- dimensional mapping of the geological structure,

Table 2
Basic Properties of the Mutnovsky Geothermal Reservoir*

1.Rock properties:

Rock Type	Density (kg/m^3)	Matr/Frac Porosity	Fracture Spacing (m)	Heat Conduct (W/mC)	Specific Heat (J/kgC)	Permeab (mD)
Quaternary ignimbrites pliocene lavas & rhyolitic tuffs	2100	0.20 0.01	25-60	2.05	1000	9.1
Miocene sandstones	2300	0.08 0.003 -0.0003	200	2.10	1000	4.5
Intrusive contact zone	2400	0.03		2.10	1000	3.2
Diorites	2700	0.02		2.10	1000	0.3

2.Fluid properties:

Chemistry of fluid	Dominant Gas	Mass Fraction of Gas (ppm)	Fluid Type (EOS)	Temp. (C)	Pressure (MPa)	Steam Satur.
M1.5 Cl70SO$_4$20/Na90	CO2	200	eos1 (water+steam)	240-305	3.0-10.2	0.03-0.20

*from Kiryukhin (1993).

temperature, pressure and permeability, (2) interpretation of tracer tests and reservoir fluid chemistry, and (3) flow test data analysis. It is assumed that the petrophysical parameters of various lithologic units have been determined on the basis of core and geophysical data. These methods when applied to the HTHR yield the distribution in the field of lithologies, temperatures, phases, and pressures, as well as the characteristics of the high temperature fluid circulation (natural state initial and boundary conditions for the associated heat transfer problem) (Kiryukhin, 1993). The methods are illustrated with the Dachny HTHR of the Mutnovsky hydrothermal system as an example.

To check the 3-D heat and mass transfer processes rectangular model of the Dachny reservoir from a physical point of view (e.g., mass and energy conservation) it is necessary to assure that the model is able to maintain stable (stationary) conditions (i.e., without undergoing changes in pressures, temperatures, and saturations) and to compute fluid and heat outputs that agree with known measured values. The input parameters (permeability distribution and boundary conditions) to the 3-D rectangular model were adjusted accordingly to improve the match between calculated and observed pressure and temperature values. Another useful criteria to verify the model is flow-test matching, which may yield more correct estimations of local permeability around the test wells and geometry of fracture spacing. For this purpose, the TOUGH2 computer codes developed by Pruess at LBL with wellbore simulators DEBIT (Kiryukhin and Sugrobov, 1987) and HOLA (Aunzo et al, 1991) were used.

On the basis of calibration studies using the above methods, the following natural state conditions were identified within the Dachny reservoir (Kiryukhin, 1991,1993):

1. The modeled spatial distributions of temperature in different layers of the model are shown in Fig.2.

2. The modeled spatial pressure distributions are shown in Fig.3.

3. The modeled steam saturations are shown in Fig.4. Steam saturation in Layer 2 reaches 0.15 and there is no steam below Layer 3, where steam saturations are 0.04.

4. Fluid flow distributions are shown in Fig.5. It is noted that for each of the model cubic elements, only the main flow direction was shown. The main flow was selected as the flow with the greatest absolute value among all flows through the sides of each cubic element in the 3-D rectangular model for water and steam separately. These main flows are shown in Fig.5 if the value of flow is greater than 1 kg/s for water and 0.1 kg/s for steam correspondingly. The flow patterns show complex convection cells with two main upflow zones (Main + North-Eastern and North-Eastern 2 with a total mass rate of 54 kg/s) and one main downflow zone (Condensate with a total mass rate of 16 kg/s). Significant horizontal flows with meridional mass flow component of northerly direction observed in Layers 3 and 4, these flows turned in a western direction in the northern part of the reservoir and discharges in the NE part of the reservoir with a rate of 37 kg/s. Separation patterns were observed in Layer 2, reflecting a dividing of flow to steam (upflows) and water (downflows) nearly of steam discharge areas (Dachny and Verkhne Mutnovsky sites, the total mass steam discharge was about 1 kg/s) when the pressure became near saturation pressure.

5. The "Double-porosity" model is the most appropriate for the 55-month long test (1983-88) with flow-test matches (for wells 26, 016, 1, 01, and 24) in the model. Hence, a fracture porosity of 0.01 (lithologic unit 1) to 0.003 - 0.0003 (lithologic unit 2) and three fracture sets of 25-60 m spacing (lithologic unit 1) to 200 m spacing (lithologic unit 2) were assigned. The fractures were considered to be the main permeable zones of the model as opposed to the relatively impermeable matrix media (k in microdarcies). The GMINC approach (Pruess, 1983) was used to develop the mesh for the double-porosity model (two interaction continuum in each grid element were used).

Modeling the behavior of wells 26, 016, 1, 01, and 24 with additional load of wells 013, 014, 037, 048, 055 ,049 ,045 , and 022 during the 20 year exploitation period is very useful to predict the possible response of the reservoir during the operation of proposed 80 MWe electric power-plant (Perveev, 1992), which is under step by step development to achieve 80 MWe (4 modules of 20 MWe each) by 1996-1998. The study was performed using a previously improved natural state model of the system, to which was added wells: 1, 01, 24, 016, and 26 with prescribed productivity indexes and wells 013, 014, 037, 048, 055, 049, 045, and 022, having corresponding constant flowrates rates of 35, 8, 30, 65, 30, 30, 35 and 25 kg/s (in accordance with the development plan for 80 MWe production at the Mutnovsky geothermal field (Perveev, 1992). Thus, the total flowrate of the "constant rate" wells was specified as 258 kg/s. The temperature, pressure, and saturation data measured at the end of the 55 month long (1983-88) flow test were assumed to be the initial conditions for the modeling study.

It is not clearly known how the boundary conditions (that were proved as appropriate for the natural state model) will change in response to exploitation and what reinjection program will be realized, so 4 different scenarios of possible changes in boundary conditions and reinjection rates were assumed:

1. No changes in boundary conditions. No reinjection.
2. Steam discharge areas (Dachny, Verkhne-Mutnovsky) will transfer to water recharge areas. No reinjection.
3. Steam discharge areas (Dachny, Verkhne-Mutnovsky) will transfer to water recharge areas, reinjection in well 027 with 100 kg/s flowrate and 420 kJ/kg enthalpy.
4. Steam discharge areas (Dachny, Verkhne-Mutnovsky) will transfer to water recharge areas and cold water inflow from surrounding rocks. No reinjection.

These four assumed scenarios are described further.

Exploitation scenario #1.

The computed total flow and steam discharge for all wells is shown in Fig.6. The steam discharge increased from 128.4 kg/s to 186.0 kg/s due to pressure depletion to saturation and boiling processes in the reservoir. On the other side, this process induces a large pressure depletion in the reservoir, particularly in well 048 (element A388), and this well is not able to produce steam after 200 months of modeling time (145 months of exploitation). Moreover, for an assumed pressure drop of 1.0 MPa between the well and the reservoir, it becomes clear that wells 013 and 014 are not able to supply steam with pressure of 0.6 MPa to the power plant. For an "average" exploitation well of radius 0.122 m to a depth of 1100 m and radius 0.084 m below, at least two "average" exploitation wells will be necessary in well 045 (element A424) to maintain a flowrate of 35 kg/s. Thus, the total computed steam discharge of all wells (excluding wells 013 and 014) may be really 143.0 kg/s, or 71.5 MWe for a specific steam consumption of 2 kg/s per MWe.

Exploitation scenario #2.

The second possible scenario of exploitation will be realized if there will be a change of the boundary conditions in the steam discharge areas (A142, Dachny, A1A9, V.Mutnovsky), e.g., the discharge area will transfer to a recharge area, with specified pressure (P=0.1 MPa) and temperatures (T=20 C). This case is very common in world experience of geothermal field exploitation under heavy load. The computed total flow and steam discharge for all wells is shown in Fig.6. The steam discharge increased from 128.4 kg/s to 181.4 kg/s due to boiling processes in the reservoir. On the other hand, this process induces a large pressure depletion in the reservoir, particularly in well 048 (element A388), and this well is not able to produce steam after 205 months of modeling time (150 months of exploitation). For an assumed pressure drop of 1.0 MPa between the well and the reservoir, it becomes clear that well 013 alone is not able to supply 35.0 kg/s of steam with pressure of 0.6 MPa to the power plant. At least six "average " exploitation wells will be necessary to maintain a flow of 35 kg/s in well 013 (element A455) and two of them to maintain 35 kg/s in the well 045 (element A424). Thus, the total computed steam discharge of all wells may be really 146.4 kg/s (excluding well 013), that is 73.2 MWe.

Exploitation scenario #3.

The effect of reinjection on the exploitation characteristics of the system was studied in the modeling of injection of liquid with enthalpy of 420 kJ/kg into well 027 at a rate of 100 kg/s. The computed total flow and steam discharge for all wells is shown in Fig.6. The steam discharge increased from 128.4 kg/s to 169.7 kg/s due to boiling processes in the reservoir and this reduces the ability of well 048 (element A388) to produce steam after 237 months of modeling time (182 months of exploitation). For an assumed pressure drop of 1.0 MPa between the well and the reservoir, at least two "average" exploitation wells will be necessary to maintain the specified rate (35 kg/s) in wells 013 and 045. Thus, the total computed steam discharge of all wells may be 169.7 kg/s, that is 84.9 MWe.

Exploitation scenarios #4 and #5 .

Another possible scenario of exploitation may include cold water inflow from the ambient rocks. In our model, these would be rocks of Domain 1, with an artificially low permeability of $1x10^{-19}$ m^2. Real rocks surrounding geothermal reservoir have higher permeabilities (at least one order with Domain 2, with 6-9 mD), but they are separated from the geothermal reservoir with the low permeability boundary, which may be destroyed if cooling during heavy load exploitation takes place and closed fractures are opened due to matrix thermal compression. Thus, if a heavy load triggers the erasure of impermeable boundaries, cold water inflow from Domain 1 with real permeability will take place. In this variant, the geothermal reservoir boundaries were erased through switch on 2 mD (#4) and 10 mD (#5) permeability in Domain 1. The computed total flow and steam discharge for all wells is shown in Fig.6. The steam discharge decreased from 128.4 kg/s to 112.0 kg/s (#4) and to 87.9 kg/s (#5) due to recharge processes in the reservoir. For an assumed 1.0 MPa pressure drop between the well and the reservoir, at least four "average" exploitation wells will be necessary to maintain the specified rate (65 kg/s) in well 048 (element A388)(#4), and there is no need for additional exploitation wells for variant #5. Thus, the total computed steam discharge of all wells may be 112.0 kg/s, that is 56.0 MWe (#4) and 87.9 kg/s, that is 44 MWe (#5).

The spatial distributions of computed temperatures, pressures and saturations in Layer 3 of the model at the end of 20 year period of exploitation are shown in Fig.7 (#4). The exploitation results in average pressure decline to 3.0-3.5 MPa, temperature decline to 220 - 240 C, and saturation increase up to 0.20 - 0.40. Table 3 summarizes the recovery characteristics for the different exploitation scenarios for the Mutnovsky HTHR.

Table 3

Energy Recovery from Mutnovsky HTHR*

	Variant No.				
	#1	#2	#3	#4	#5
Recovery, %					
of fluid mass	9.2	7.7	6.2	3.5	-2.8
of total energy	2.7	2.3	2.1	1.9	1.5

* for a reservoir volume of 5.0×10^{10} m^3
and initial fluid mass of 3.65×10^{13} kg.

B. Hot Dry Rock Reservoirs

As noted in the Introduction, the two key parameters (generally unknown) for HDR geothermal resources are the rock volume of the reservoir and the optimal rate of heat extraction. The volume of the reservoir constitutes the geometry (and heat content above the abandonment temperature) of the rock formation accessible for heat transfer to the production fluid. The rate of heat extraction is influenced by both the circulation flowrate and the rock-block size distribution which determines the rate of heat conduction to the rock-block surfaces. The optimal rate of heat extraction should be a balance between maximum economic power level and maximum thermal extraction efficiency and resource longevity. The parameters of reservoir volume and mean fracture size are the two key parameters in the Stanford Geothermal Program 1-D Linear Heat Sweep Model (Hunsbedt, Lam, and Kruger, 1983), which was developed to assess the potential for heat extraction from geothermal resources.

A primary constraint to commercial development of HDR resources is the ability to design accurately the stimulation of fracture permeability over an adequate reservoir volume for heat extraction by artificial fluid circulation. It is also important to develop reliable means to evaluate the potential for commercial heat extraction at an early stage in the development of prospective sites. Several experimental projects are underway in many countries to expand the technology for efficient thermal energy extraction from a variety of fractured reservoirs.

Experimental verification of heat extraction estimates are made in the form of long-term constant flowrate reservoir testing. Long term signifies a sufficient circulation period to estimate the two key parameters of total accessible heat content and optimum extraction rate for sustainable deliverability at sufficient power level and longevity for maximum extraction efficiency. These need to be evaluated with sufficient confidence for investment and management decisions.

(a) The SGP 1-D Heat Sweep Model

The SGP 1-D Heat Sweep Model was developed in three phases based on a physical model of a fractured rock hydrothermal reservoir to estimate heat extraction with limited geologic and thermodynamic data. The first phase involved lumped-parameter analysis (Hunsbedt, Kruger, and London, 1978) using three non-isothermal production methods: (1) pressure reduction with in-place boiling; (2) reservoir sweep with injection of colder water; and (3) steam drive with pressurized fluid production. The results indicated that reservoir sweep with cold water injection could effectively enhance energy extraction.

The second phase was the development of a heat transfer model for fractured rock of irregular shapes and arbitrary size distribution. Heat extraction from irregular-shaped rock to cooler surrounding water was described by Kuo, Kruger, and Brigham (1977) in terms of heat transfer from a sphere of equivalent thermal radius, for which the heat transfer equations can be solved analytically (Carslaw and Jaeger, 1973). For rock blocks with length to width aspect ratios as large as 8:1, the equivalent radius for heat transfer can be given by the product of the radius of a sphere of equal volume and a sphericity factor given by the surface to volume ratio. The model for heat extraction from a single rock was extended to a distribution of rock-block sizes by Hunsbedt, et al (1979). The distribution can be approximated as a mean spherical rock with effective thermal radius for heat transfer by the ratio of the distribution of rock surface areas and volumes.

The third phase was an experimental verification of the model to predict heat extraction from a rock loading of regular geometric shaped rock blocks of known thermal properties in the physical model. The results were reported by Hunsbedt, et al (1979); a description of the 1-D linear heat sweep model was given by Hunsbedt, Lam, and Kruger (1983); and comparison of the results by the model to analysis by the MULKOM geothermal reservoir simulator of Pruess (1983) was given in Lam, et al (1988). The model was subsequently improved to provide for radial and doublet flow (Lam, 1990) and for non-uniform initial temperature distribution (Lam and Kruger, 1989).

The 1-D heat sweep model was initiated in 1978 by Hunsbedt who showed that the difference in temperature between a rock block at mean temperature, T_r, and the surrounding fluid at temperature, T_f, in a reservoir undergoing linear thermal drawdown is given by

$$T_r - T_f = \mu\tau[1-e^{-t/\tau}] \qquad (5)$$

where μ = cooldown rate (°C/s)
τ = time constant of the rock block (s)

The time constant for heat conduction to the rock surface was shown by Hunsbedt to be approximated by

$$\tau = R_e^2/3\alpha_r\,(0.2 + 1/N_{Bi}) \qquad (6)$$

where R_e = equivalent sphere radius (m)
α_r = thermal diffusivity of the rock (m^2/s)
N_{Bi} = Biot number of the rock

The governing equations describing heat transfer from the equivalent spherical rock blocks to the circulating fluid under uniform heat sweep are given in Hunsbedt, et al (1983). The solution of the equations for a prescribed linear sweep boundary and initial conditions is obtained by conversion to Laplace transform equations and numerical inversion with the Stehfest (1970) algorithm.

The model has also been developed continuously through application to several hydrothermal and petrothermal geothermal resources. A summary of applications in hydrothermal reservoirs for various objectives is listed in Table 4 with references for application details.

Table 4
Application of the SGP 1-D LHSM to Hydrothermal Reservoirs

Geothermal Field, Country	Application	Ref
Cerro Prieto, Mexico	Matching of cooldown for 3 inflows	[1]
La Primavera, Mexico	Cooldown predictions in new field	[2]
Los Azufres, Mexico	Cooldown predictions in 3 zones	[3]
Los Humeros, Mexico	Cooldown predictions for new wells	[4]
Wairakei, New Zealand	Prediction for reinjection test	[5]
Mutnovsky, Russia	Cooldown analysis of tracer response	[6]

[1] Kruger, et al (1985)
[2] Kruger, et al (1988)
[3] Molinar, et al (1987)
[4] Aragon and Kruger (1987)
[5] Kruger (1989)
[6] Kiryukhin and Kruger (1990)

(2) Applications to HDR Geothermal Resources

The SGP 1-D LHS model has been applied to many of the world's experimental HDR resources for various objectives, ranging from pre-development estimates of heat extraction potential to matching of observed cooldown histories. Summary descriptions of the joint studies are given in chronological order.

(a) Preproduction Estimate of Cooldown during the Long-Term Flow Test at Fenton Hill, NM with LANL

A comparison of two heat extraction models for HDR simulation was made by Robinson and Kruger (1988) for the planned Phase II long-term thermal drawdown experiment at Fenton Hill, NM being conducted by the Los Alamos National Laboratory (LANL). The LANL tracer-based model (Robinson and Jones, 1987) uses an observed tracer response curve to obtain the degree of flow nonuniformity and the total fluid volume. The reservoir volume is determined by the choice of mean fracture porosity. Comparison of the simulated cooldowns were made for a wide range of flowrates, MFS, reservoir thickness, and fracture porosity. Results of the simulations to an abandonment temperature of 150°C were in agreement for similar values of reservoir volume. It was concluded that better means to estimate reservoir volume for heat extraction estimation were needed.

The joint study was continued to simulate temperature decline prior to the start of the long-term flow test (LTFT) in 1992. Robinson and Kruger (1992) evaluated the potential for early observed cooldown under the production strategy requested by industrial advisors to maintain a constant production rate for electrical utility needs at a flowrate smaller than the critical flowrate for induced microseismicity. For more sensitive comparison of the two heat extraction models, a better definition of reservoir volume was examined. Table 5 lists the several methods used to estimate the Fenton Hill Phase II reservoir. In Kruger (1990), an initial estimate of 117×10^6 m^3 as the envelope of all observed seismic events proved to be much too large for heat extraction volume. Subsequent estimates are given in Table 3. One key method is by tracer testing. The larger value for reservoir volume was calculated for porosity of 10^{-4} estimated from fracture size and aperture distribution. The smaller volume for porosity obtained from a tracer test gives a volume in agreement with the minimum seismic-derived volume.

Table 5
Estimates of Fenton Hill HDR Reservoir Volume*

Method	Test Conditions	Volume ($10^6 m^3$)	Basis	Ref
Swept	interwell	2.9	geometry of flow	
volume	dipole	6.3	around well pair	[1]
Microseismic	minimum	6.45	envelope of	
events	1σ estimate	16	seismic	
	S-wave velocity	28	hypocenters	[1]
Tracer	porosity = 10^{-4}	22	measured tracer vol.	
tests	porosity = 0.003	6.6	and est'd porosity	[2]
Pressure	bulk modulus	16	hydraulic stressing	
tests	= 55 MPa		of reservoir	[3]

[1] Robinson and Fehler (1991) [2] Dash, et al (1989) [3] Brown (1991)
* From Robinson and Kruger (1992).

Figure 8 shows a comparison of the "best" estimates of cooldown for the planned Fenton Hill LTFT. The LANL model was based on a reservoir volume of $16x10^6$ m^3 (the hydro-mechanical volume from pressure testing) and a MFS of 20 m (from tracer tests), in contrast to the SGP model for a reservoir volume of $6.45x10^6$ m^3 (minimum microseismic) and MFS of 40 m (from prior estimates). The two results seem to have narrowed the range in estimates of reservoir volume in Table 5 by about a factor of four. Both models predicted that cooldown would not be observed during the first two years of the LTFT production period. Verification of the estimates awaits the experimental cooldown data.

Currently, the test has been suspended after three periods of production at different pumping capacities. Hourly production data are available for the first four-month period at steady flowrate. To obtain an estimate of the fraction of heat extracted, the integral of flowrate and increased circulation fluid enthalpy is being compiled and an analysis of heat extracted is underway.

(b) Match of the Observed Cooldown and Evaluation of a Deeper Reservoir at the Rosemanowes Site in Cornwall,England with CSMA

The second joint study of HDR simulation was made with the Camborne School of Mines Associates (CSMA) following the 3-year long-term circulation test in the shallow (2-km) reservoir in the Carnmenellis granite. A description of the test was reported by Parker (1989). Evaluation of the heat extraction by Nicol and Robinson (1990) noted that in addition to the thermal data, additional data from tracer tests, well logs, and seismic monitoring were necessary. They noted that the volume of the reservoir, estimated from the location of microseismic events was 5 x 10^6 m^3, with considerable uncertainty in the estimate. In an evaluation of the potential for estimating HDR reservoir volume based on microseismicity data by Kruger (1990), an analysis of the cooldown data was attempted. Figure 9 shows the match of the observed cooldown curve based on fitted reservoir volume and mean fracture spacing. The match parameters from sensitivity analysis yielded a reservoir volume of 3.25 ($\pm$ 0.25) x 10^6 m^3 and a MFS of 50 ($\pm$5) m.

CSMA prepared a design for a prototype deep (6-km) hydrofractured HDR reservoir where the rock temperature was estimated to be sufficient for generation of electricity. The CSMA design (Corlett, 1991) was reviewed by RTZ Consultants (1991) and the uncertainties in parameters for estimating the potential for thermal energy recovery included: (1) the volume of fractured rock accessible to the circulating heat-carrier fluid; (2) the mean fracture spacing of the rock blocks for heat transfer; and (3) the mean flowrate through the interconnected fracture porosity. An analysis of the potential for heat extraction covering a reasonable range of these parameters under the RTZC design specifications was reported by Kruger, Hicks, and Willis-Richards (1992). Table 6 shows the cooldown times to an abandonment temperature of 160°C for a reservoir volume of $200x10^6$ m^3 for MFS from 25 to 200 m and flowrate from 50 to 100 kg/s. The data show a production period greater than the specified amortization period and potential for management decision to either increase power generation capacity for the specified period or increase total energy recovery over a longer lifetime. The results indicated a good potential for energy extraction from the Cornwall granites with a heat content of 10^{20} J within the 200°C isotherm at 6-km depth.

Table 6
Cooldown Simulations for a 6-km HDR Reservoir at Rosemanowes*

MFS (m)	Time (years) to T(f) = 160°C for Flowrate (kg/s) 50	75	100
25	64	41	31
50	60	38	28
100	49	29	19
200	25	10	3

* from Kruger, Hicks, and Willis-Richards (1992).

(c) Comparative Estimates of Cooldown in Russian HDR Projects with the SPMI Numerical and Analytic Models

The first HDR simulation with the SGP 1-D model was reported by Dyadkin and Kruger (1987) for a hypothetical reservoir consisting of equally-spaced parallel hydrofractures spaced for comparison with the 2-D model developed by the Mining Thermophysics Research Laboratory of the Leningrad (now Saint Petersburg) Mining Institute. The simulations were made with two very different models of heat transfer; one based for water circulating through connected planar hydrofractures and the other based on uniform flow through a collection spherical rocks of equivalent thermal radius. The flow geometry for the two models are shown in Figure 10. The results of the two models were in good agreement and provided confidence in the potential for estimating heat extraction in new fields where little production data are available.

Table 7
Comparison of Russkie Komarovtsy Cooldown Simulations*

Bottom-Hole Fluid Temperature (°C) after 10 years of production

Flowrate (kg/s/frac)	SPMI Models Num	SPMI Models Anal	SGP MFS (m) 354	SGP MFS (m) 160	SGP MFS (m) 50
5.5	123	–	106	124	124
11.0	120	–	83	120	124
14.0	118	114	–	115	124
16.0	113	–	–	110	124
20.0	111	–	–	104	124
25.0	108	107	–	97	123
50.0–	87	103	–	72	108

* adapted from Kruger, et al (1991).

The study was extended to the plans in the former Soviet Union to develop technology for economic heat extraction from low-temperature geothermal resources located throughout the USSR. Dyadkin (1987) described the search for candidate sites with selection of Russkie Komarovtsy (Ukraine) and Cholpon Ata (Kirgizia) as the sites selected for further study. Dyadkin and Kruger (1990) reported the SPMI design to create a large three- parallel hydrofracture reservoir in the Russkie Komarovtsy granodiorite formation. Comparison of thermal drawdown estimates by the SPMI numerical and analytic models and the SGP model were given by Kruger, et al (1991) and the results are reproduced in Table 7. The values for the SPMI analytical model agreed well with the SPMI numerical model for flowrates of 14 and 25 kg/s, but differed somewhat for 50 kg/s. The SGP model with only the short-circuiting major hydrofractures (MFS = 354 m ; τ=89y) showed a very rapid temperature cooldown . For well-fractured rock blocks, much smaller than those corresponding to a few major fractures (i.e., MFS = 50 m), there is no temperature decline for ten years at flowrates up to about 25 kg/s per fracture and a large potential for sustained production at 50 kg/sec for almost 10 years. The SGP model matches the SPMI models for a MFS of about 160 m (τ=18.1y), between the major hydrofractures and a well-fractured reservoir; the calculated values are in agreement at flowrates to about 20 kg/s, the SGP model shows a somewhat faster decline thereafter.

Further studies of the SGP-SPMI project are concentrated on the Tirniauz HDR experiment in the Caucuses of Russia. A description of the first hydrofracturing in granitic rock at this resource was summarized by Kruger (1992) based on the Russian manuscripts of Slyusarev, et al (1991) and Khakhaev, et al (1991). Estimates of potential heat extraction from the Tirniauz reservoir based on the reservoir design for the next hydrofracturing experiment and data from the first hydrofracturing experience have been made.

(d) Analysis of the Observed Cooldowns in the 90-Day Multiwell Circulation Test at Hijiori, Japan

The first circulation test in a HDR reservoir with multiple production wells was carried out in the Hijiori reservoir in Japan. A description of the test was given by Yamaguchi, et al (1992). The test was made with accumulation of extensive diagnostic data and frequent downhole logs to describe the flow geometries and downhole temperature history. The measurements identified a number of entry zones into each well and allowed an analysis of the observed cooldowns. Kruger and Yamaguchi (1993) reported an analysis of the thermal drawdown based on allocating the constant injection flowrate among the multiple entry zones of the three production wells, adjusted for observed water loss. The conceptual model for radial sweep flow to the individual zonal sectors is shown in Figure 11. The simulations indicated that the zonal sector volumes were too small to account for the observed cooldowns. An example is shown in Figure 12 where a match of observed cooldown in zone 4 of well HDR-1 requires a volume about 3.5 times the zonal sector volume. The analysis of this relatively short circulation test was made difficult by the large flow excursions at the start of the test to increase permeability and the successive shutting in of two wells during the test for two weeks to observe the behavior of the third well individually.

III. Discussion

A. High Temperature Hydrothermal Reservoirs

Based on natural-state and flow-tests simulation studies carried out with the computer code TOUGH2 (Pruess, 1991) and 3-D mapping methods (Kiryukhin, 1993), the 3-D natural state distribution of temperatures, pressures and fluid phases, and the circulation characteristics of the high-temperature fluid and the permeabilities, may be deduced as appropriate initial and boundary conditions in HTHR. This information may be used for modeling various exploitation scenarios, as a basis of confidence of investment and management decisions.

Four exploitation scenarios of the Dachny HTHR as an example with wells scheduled for production under 80 MWe load and with different boundary conditions changing during exploitation were studied: (1) Natural state boundary conditions maintained, (2) Turn on steam discharge areas to recharge areas, (3) Case (2) with reinjection, (4) Cold water inflow from ambient rocks. These studies show that the total computed steam discharge of all wells scheduled for production under 80 MWe is from 87.9 kg/s to 169.7 kg/s (44.0-84.9 MWe), depending on what boundary conditions and exploitation regime will really take place during the 20 years exploitation period.

It is worth continuing modeling studies and flow tests in the Mutnovsky geothermal field before large scale exploitation will begin and concentrating on the following problems: (a) 1-year interference flow tests from wells 048, 049, 055, 013, 037. and from wells 022 and 045 (all wells should be equipped with James tanks for accurate discharge-enthalpy estimations) identify local permeability and fracture porosity parameters around these wells and determine whether there is any meteoric water inflow into the reservoir (tritium and geochemistry data are important with no drilling at this time at the field), (b) tracer tests between reinjection and production wells to understand characteristics of field where reinjected water will penetrate main reservoir, (c) flow tests matches and modeling exploitation with improved model parameters. If these works (a), (b), (c) will not be made, it will be very difficult to guarantee projected 80 MWe power plant future exploitation.

B. Hot Dry Rock Reservoirs

The long-term successful development of geothermal energy as an important contribution to world energy supplies depends on improved technology for efficient heat extraction from a variety of subsurface concentrations of thermal energy deposited in accessible volumes of rock formations over a range of useful temperatures and containing a range of in-place heat-carrier fluid, from HDR (none) to hydrothermal (abundant) systems.

It is important to establish reliable means to evaluate the potential for thermal energy extraction at an early_stage in the development of prospective resources for commercial utilization. The key parameters are temperature, reservoir volume, and mean fracture spacing for estimating total accessible heat content and optimum energy extraction rate for sustainable deliverability at sufficient power level and longevity for maximum extraction efficiency. These need to be evaluated with sufficient confidence for investment and management decisions.

Experiments to establish such reliable means are available in the form of long-term constant flowrate reservoir testing. Long term signifies a period sufficient to estimate the available heat content above the application minimum temperature and the range of extraction rate - lifetime relations for optimum reservoir management.

The experiences obtained for the several HDR studies summarized in this paper indicate that long-term constant flowrate tests will provide the confidences needed for HDR technology development.

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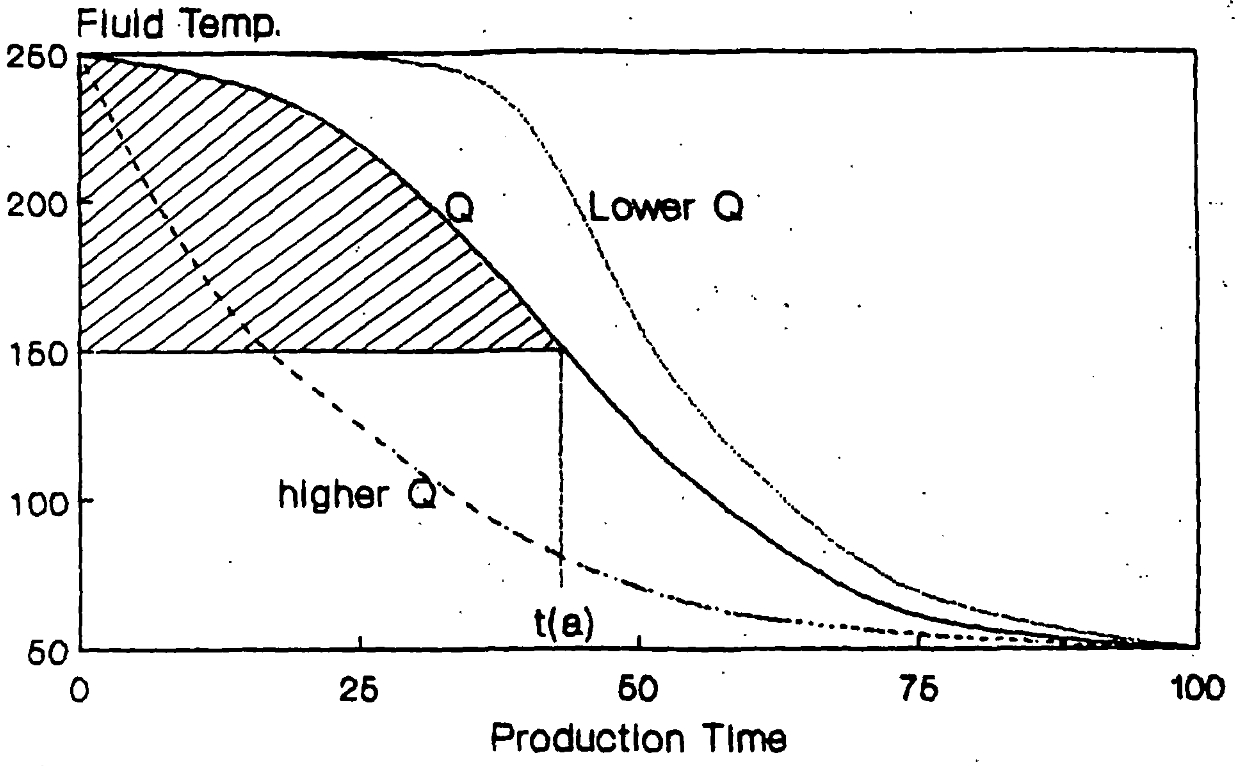


Fig. 1 Relationship of fraction produced (shaded area) above a given abandonment temperature to the production flowrate.

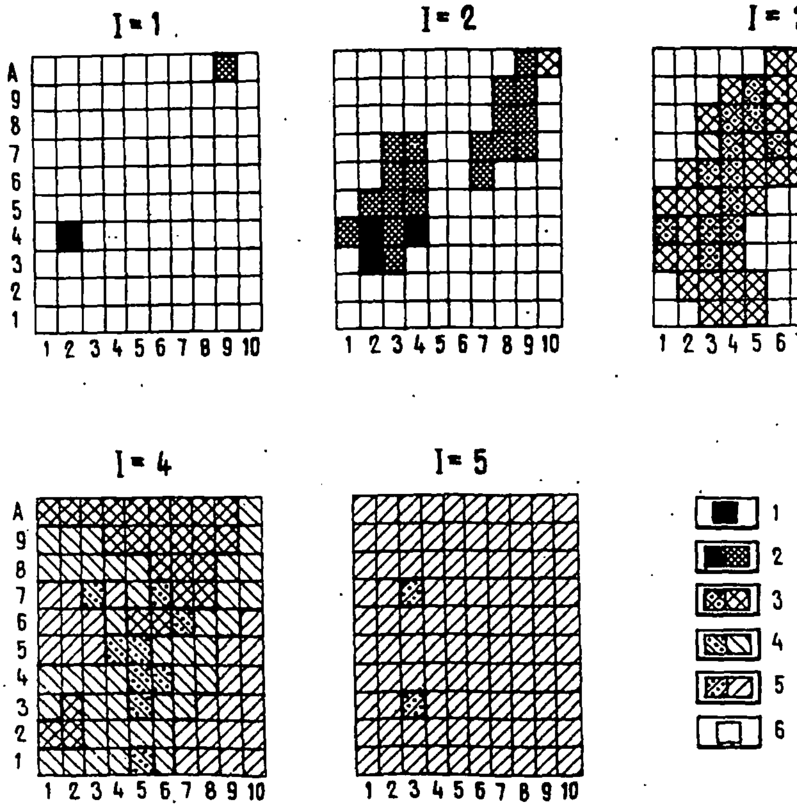


Fig.2. Basic petrophysical-permeability domain distribution.
1- Domain 6, 2- Domain 2, 3- Domain 3,
4- Domain 4, 5- Domain 5, 6- Domain 1.

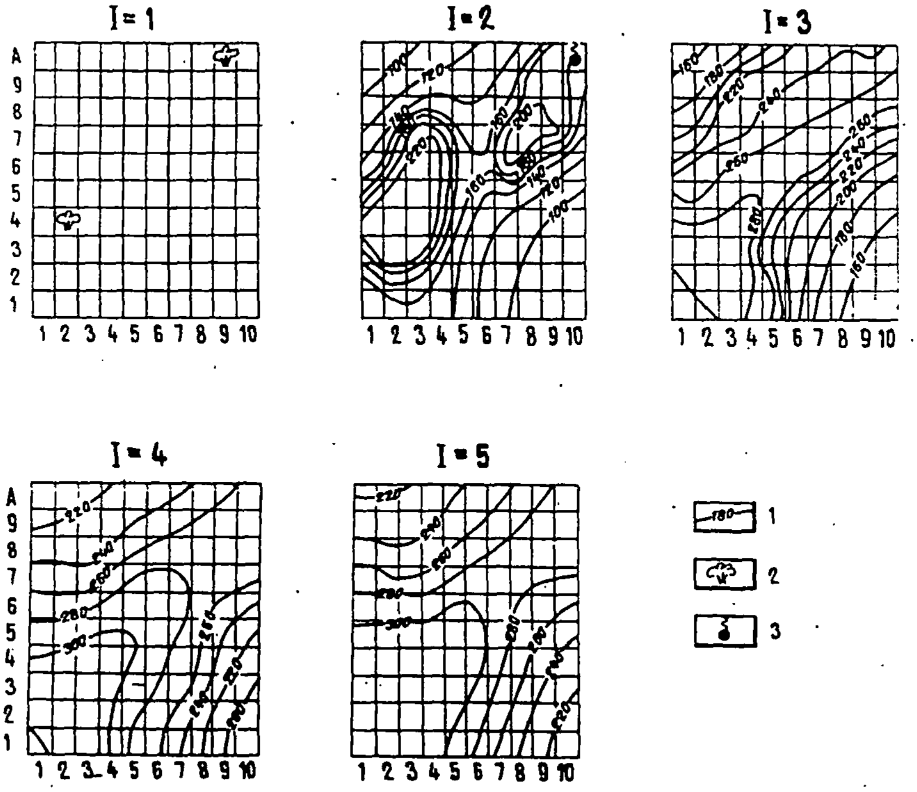


Fig.2 Modeling of the natural state of the Dachny+Verkhne-Mutnovsky reservoir. Distribution of stationary temperature within model layers 1-5 for run #062.

1- temperatures, C,
2- steam discharge inactive elements,
3- water discharge inactive elements.

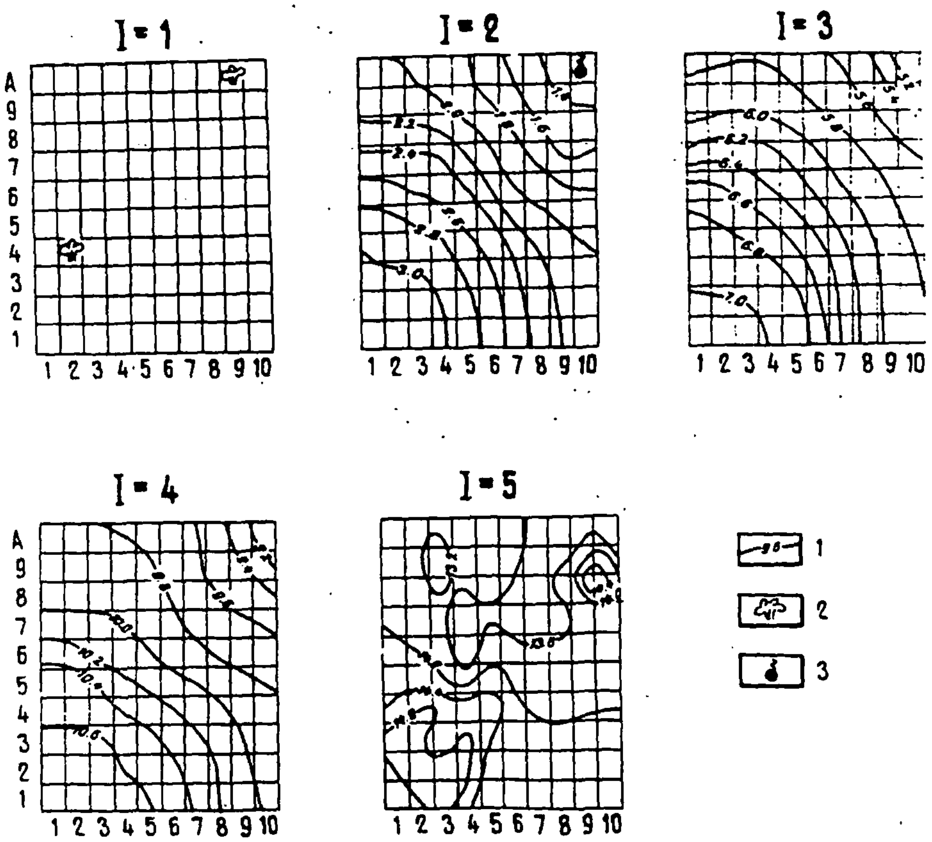


Fig.3 Modeling of the natural state of the Dachny+Verkhne-Mutnovsky reservoir. Distribution of stationary pressure (MPa) within model layers 1-5 for run #062.

1- pressures, MPa,
2- steam discharge inactive elements,
3- water discharge inactive elements.

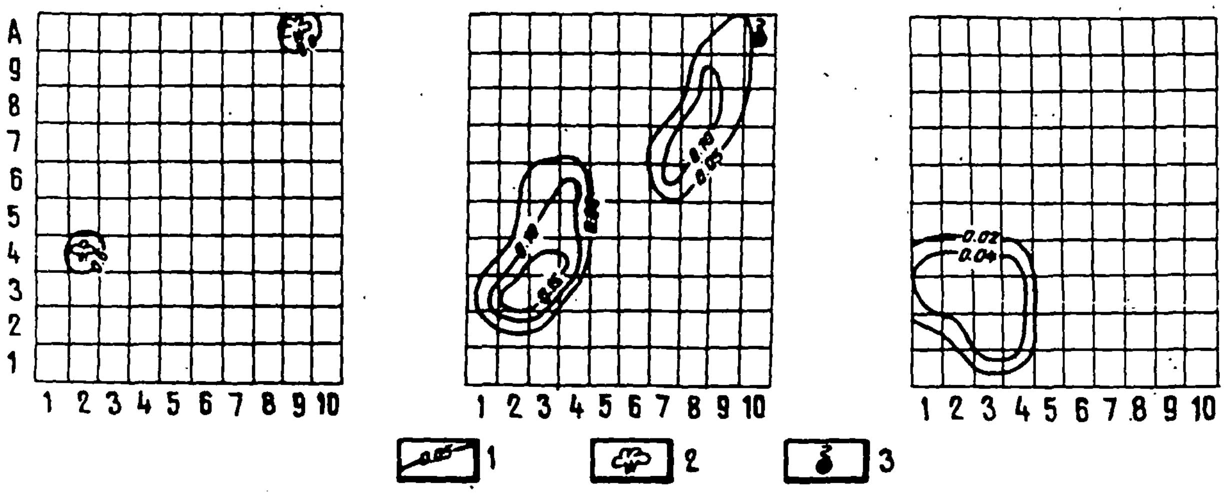


Fig.4 Modeling of the natural state of the Dachny+Verkhne-Mutnovsky reservoir. Distribution of stationary saturation within model layers 1-3 for run #062.

1- saturations,
2- steam discharge inactive elements,
3- water discharge inactive elements.

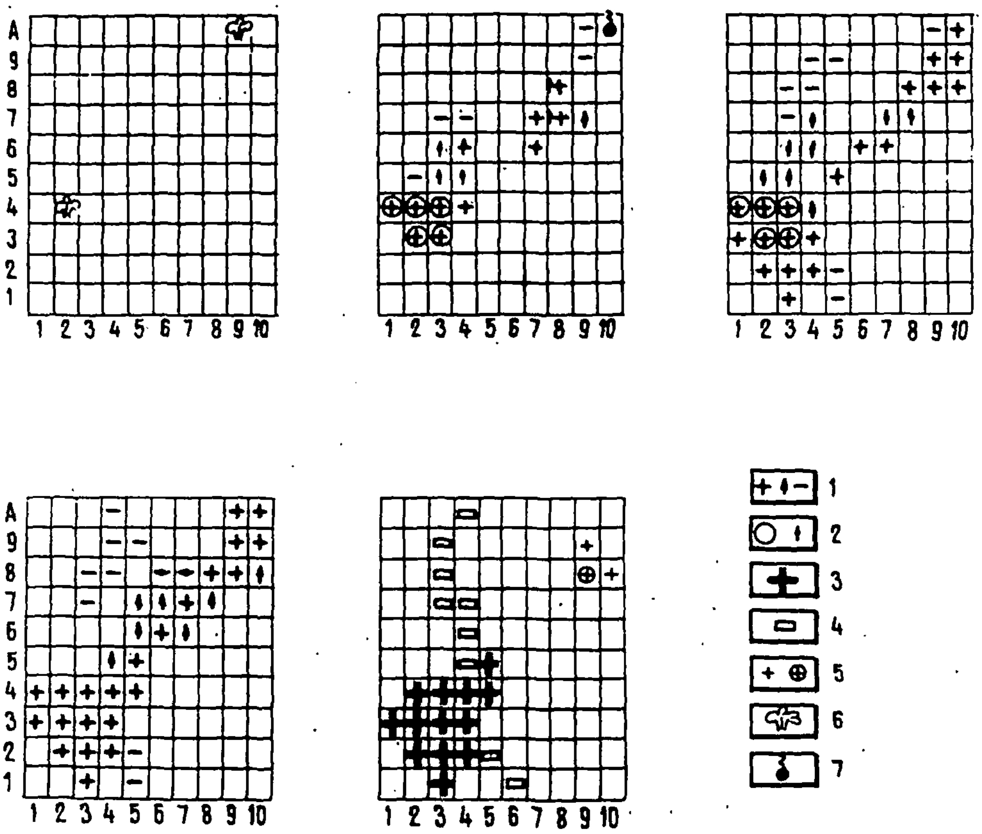


Fig.5 Modeling of the natural state of the Dachny+Verkhne-Mutnovsky reservoir. Distribution of flows within model layers 1-5 for run #062.

1-water flows: upward, horizontal, downward,
2-steam flows: upward, horizontal, downward,
3-sources (Main + North-Eastern upflow),
4-sinks (Condensate downflow),
5-sources (North-Eastern 2 upflow).
6-steam discharge inactive elements,
7-water discharge inactive element.

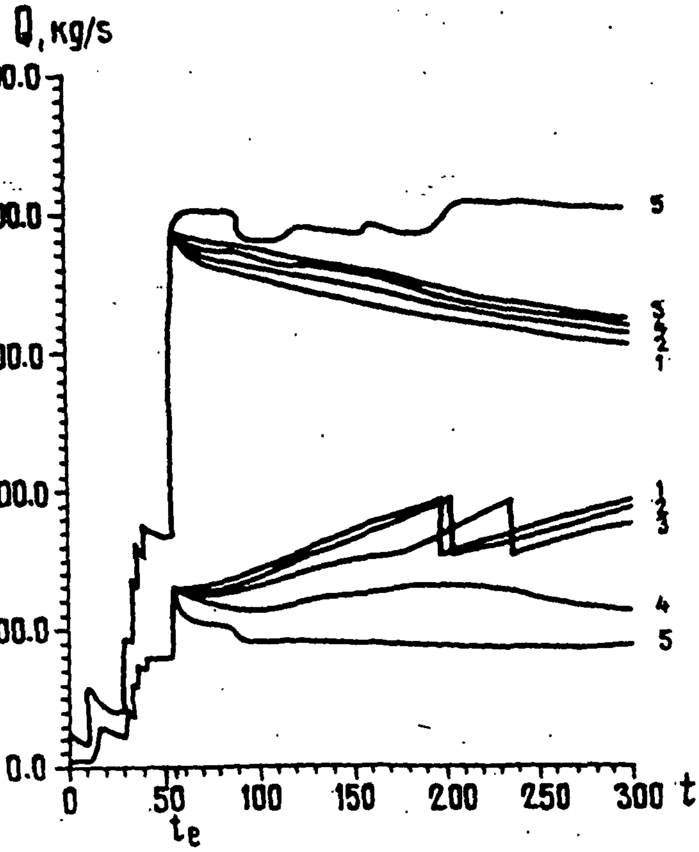
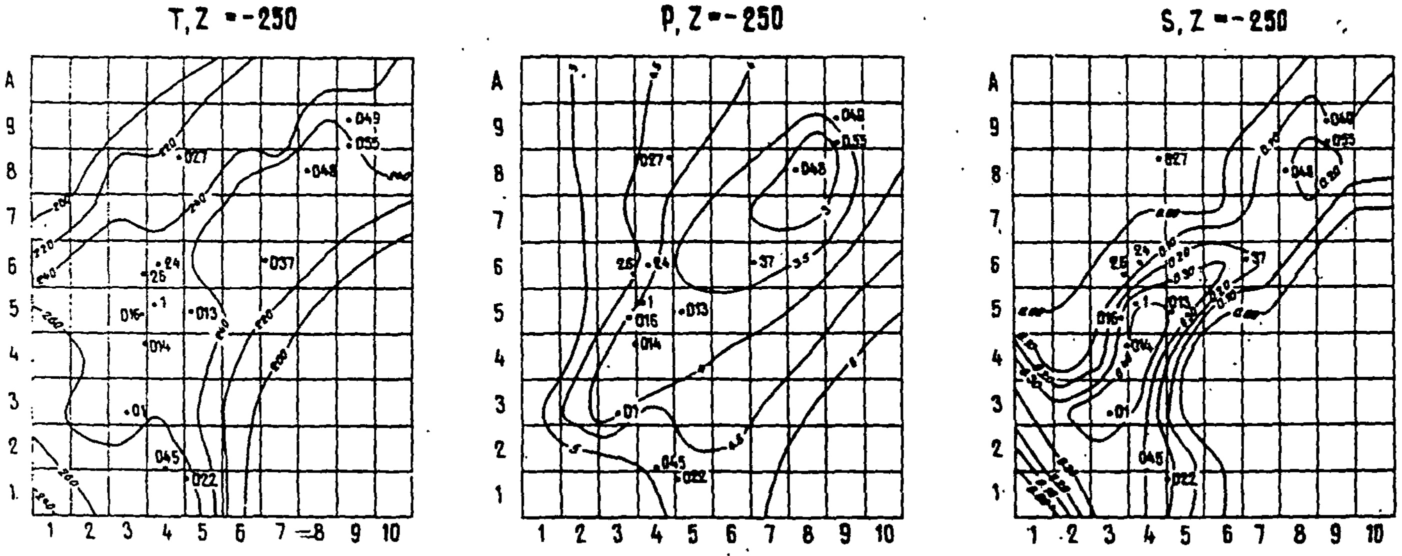


Fig.6 Wells 1,01,24,26,016, 013,014,037,048,055,049,055 and 022.
Computed total production for 1983-88 flow tests and 20 year exploitation period for different exploitation scenarios.

1 - total steam-water discharge (upper graph)
2 - total steam discharge (lower graph)

Exploitation scenarios: #1,#2,#3,#4,#5.


T, Z =-250

P, Z =-250

S, Z =-250

Fig.7 Computed temperature, pressure and steam saturation distribution in Layer 3 (fractures) of the model (at -250 masl) at the end of 20 years of exploitation.
Exploitation scenario #4.

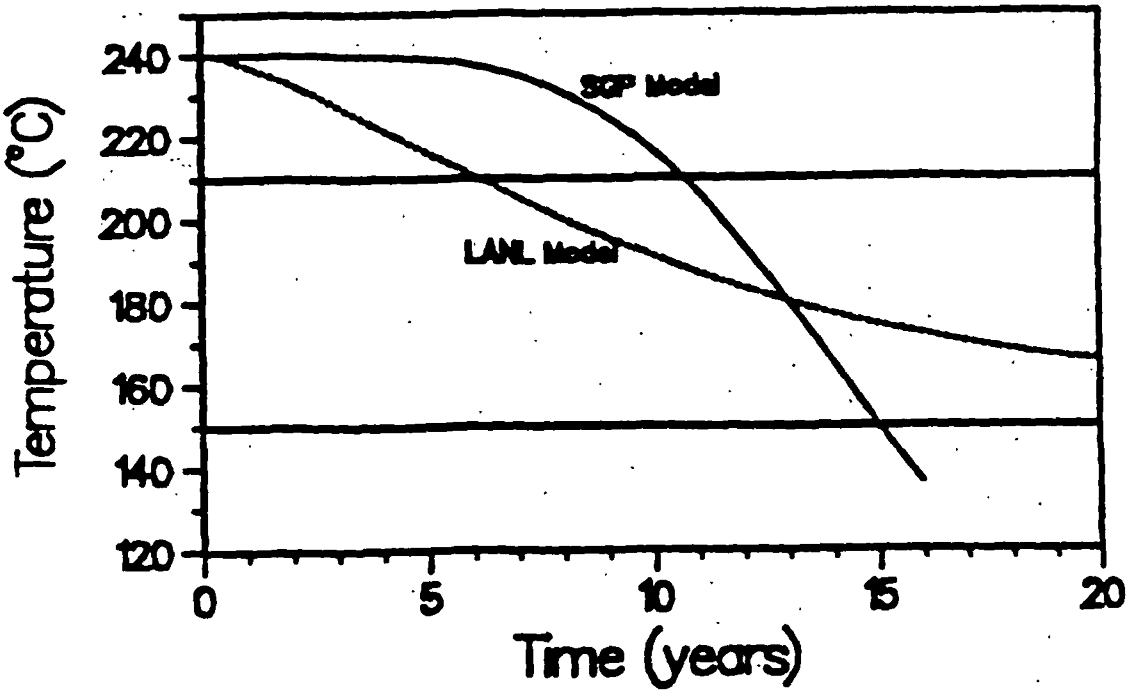


Fig.8 Simulated cooldowns for the Fenton Hill Long-Term Flow Test; (a) by the LANL model with V_r = 16x10^6 m^3 and MFS = 20 m, and (b) by the SGP model with V_r = 6.5x10^6 m^3 and MFS = 40 m. From Robinson and Kruger (1992).

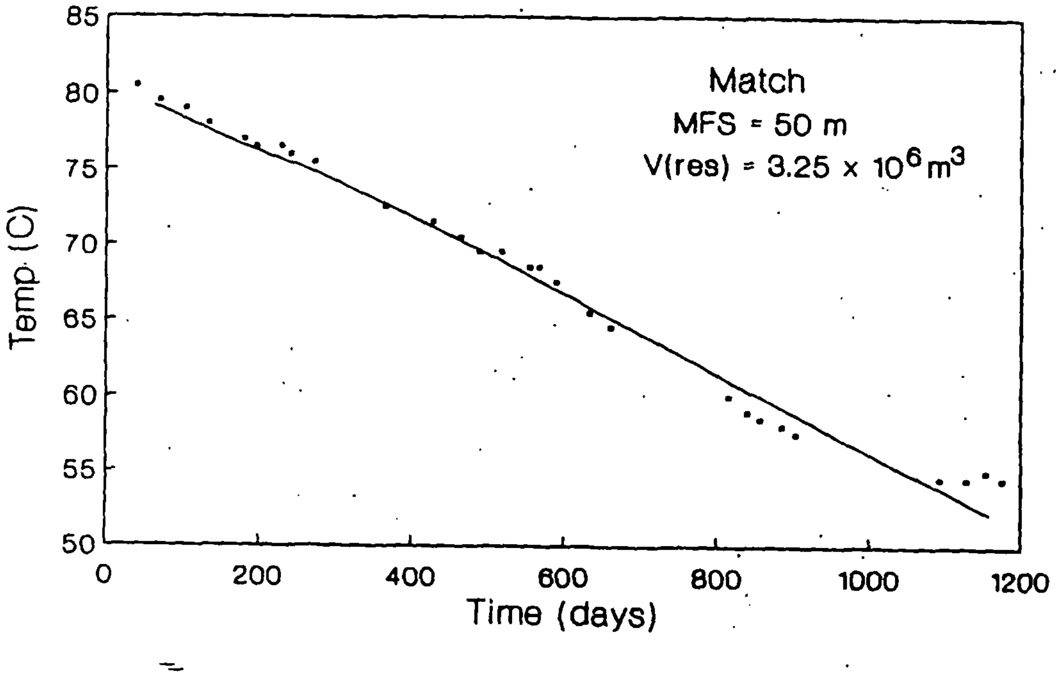


Fig.9 Match of observed cooldown at Rosemanowes with simulated cooldown based on fitted reservoir volume and mean fracture spacing. From Kruger (1990).

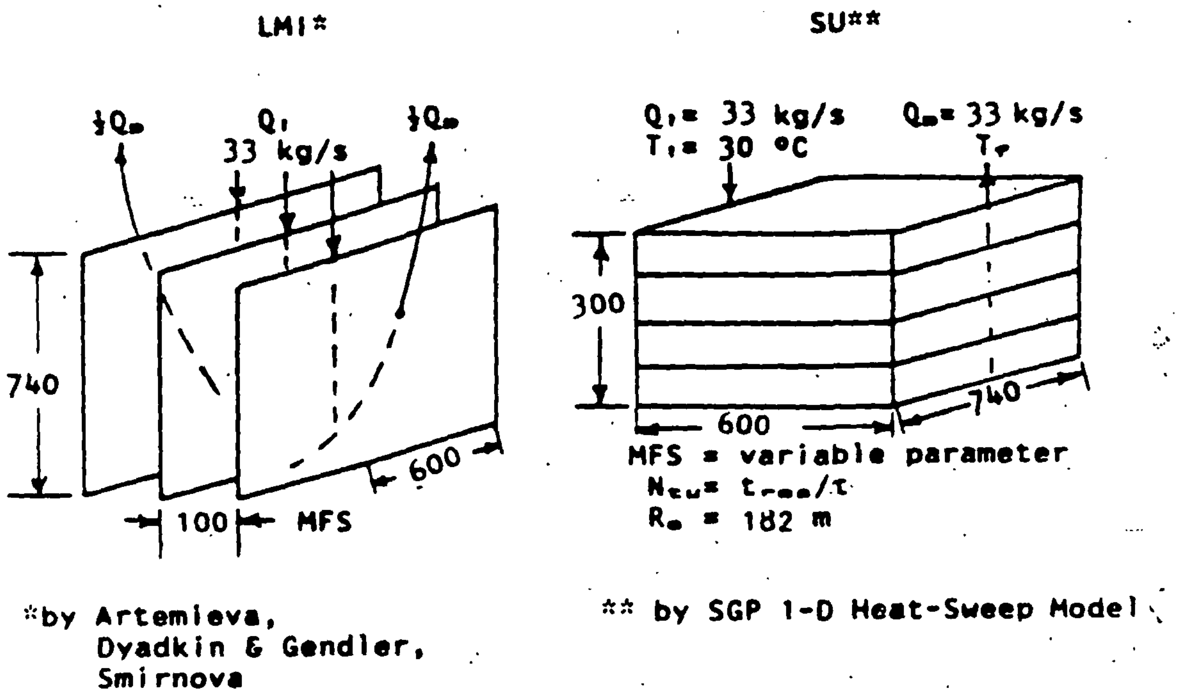


Fig.10 Comparison of the flow geometries for (a) the SPMI parallel fracture model and (b) the SGP 1-D uniform flow model. From Dyadkin and Kruger (1987).

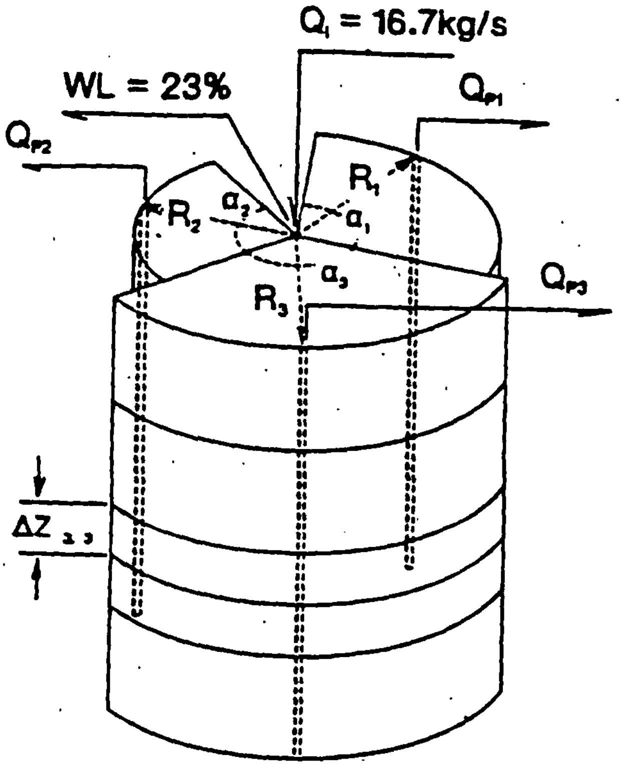


Fig.11 Conceptual model of the Hijiori zonal flow distribution with radial flow through individual zonal sectors. From Kruger and Yamaguchi (1993).

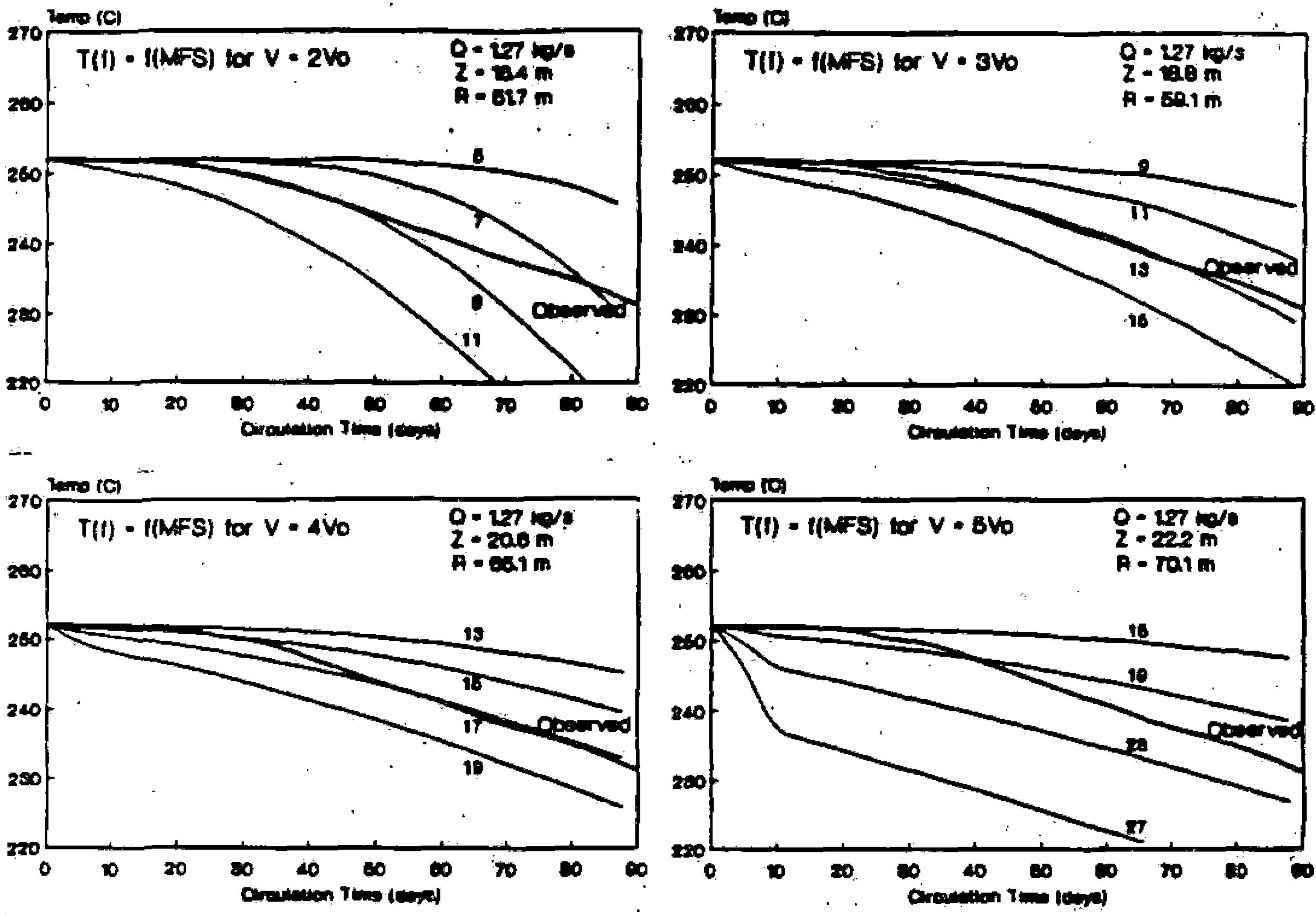


Fig.12 Simulated cooldowns for production well HDR-1 zone 4 for the progression of zonal sector volume from 2Vo to 5Vo. From Kruger and Yamaguchi (1993).

Telefax (Four Pages)

TO: Dr. Vladimir I. Kononov,
Laboratory of Geoenergetics and Hydrochemistry,
Geological Institute, Russian Academy of Sciences,
Pyzhervsky per. 7, Moscow, 109017, Russia.
FAX No: 001-7-95-231-81-06

FROM: Wilfred A. Elders,
Beppu Geophysical Research Laboratory, Kyoto University,
Noguchibaru, Beppu, 870, Japan
FAX: 81-977-22-0965 18 November 1993

Dear Dr. Kononov,

I am becoming increasingly concerned that I have had no answer to my letter concerning Volume 1 of the geothermal monograph which I sent to you by airmail in September. It is imperative that we reach a decision about the contents of volume one immediately if we are to proceed further. I attach a copy of that letter for your attention and would appreciate ackowledgement that it was received.

Yours sincerely,

W.A. Elders

W.A.Elders

c.c.		
c.c.	Paul Kruger, Stanford University	0011 415 725 8662
	Denis Nielson, UURI	0011 801 584 4453
	David Blackwell, SMU	0011 214 768 4289
	Phillip Wright, UURI	0011 801 584 4453 ←
	Donald Campbell, Mesquite Inc.,	0011 714 525 2852

BEPPU GEOPHYSICAL RESEARCH LABORATORY
KYOTO UNIVERSITY
NOGUCHIBARU, BEPPU 874, JAPAN
TEL. 0977-22-0713, TELEFAX 0977-22-0965

Dr. Vladimir I. Kononov,
Russian Academy of Sciences,
Geological Institute,
Pyzhevsky per., 7
109017, Moscow,
Russia.

16 September 1993

International Monograph on Geothermal Resources

Dear Dr. Kononov,

I must apologize for the delay in following up our discussions in St. Petersburg. As I mentioned when we met there, I will be a visiting scientist at this address in Japan until 31 March 1994, when I will return to the University of California in the U.S.A. None-the-less I intend to continue my role as the American editor of Volume One of the monograph, keeping in touch with my colleagues in the U.S.A. by airmail, telefax and electronic mail (email). In addition to the address and telephone numbers listed above, if case you are able to use it, my email address in Japan is G53444@JPNKUPC.BITNET.

In St. Petersburg you and Dr.Polyak gave me a hand written revised table of contents for Volume One as follows:-

Volume A. "Terrestrial Heat and Resources of Geothermal Energy".
(eds. W.A. Elders and V.I. Kononov)

Chapter 1. "Geoenergetic Budget and Terrestrial Heat Losses", by B.C. Polyak (already written in Russian)
Chapter 2. "Background Geotemperature Field and its Anomalies", by D. Blackwell (U.S.A.) and A.A. Smyslov (Russia).
Chapter 3. "Nature of Geothermal Systems", by D. L. Neilson (already written in English).
Chapter 4. "Exploration of Hydrothermal Resources (geological, geophysical, and geochemical methods)", by V.I. Kononov (Russia) and P.M Wright (U.S.A.)
Chapter 5. "Evaluation of Hydrothermal Resources", by A.A. Sphak (already written in Russian) and Donald Campbell (U.S.A.).

Professor Kruger and I have had a several exchanges of views concerning these suggested revisions to the content of Volume One. His most recent instructions to me, received today by email, are that we should retain the table of contents as originally agreed and only modify the contents as might become necessary when all the manuscripts are received from both the Russian and American authors, hopefully before the end of November. At that point he suggests that we could harmonize the different approaches used by the co-authors of the chapters and modify the table of contents accordingly.

The original table of contents given to me by Dr. Kruger was as follows:-

Volume One: "Resources".
Editors: Patrick Muffler (U.S.A.) and V.I. Kononov (Russia)

Chapter 1.1: "The nature of geothermal energy", by Dennis Neilson (U.S.A.) and Boris G. Polyak (Russia).
Chapter 1.2: "Heat flow distribution and geothermal anomalies", by David D. Blackwell (U.S.A.) and Yakov B. Smirnov (Russia).
Chapter 1.3 "Resource base and resource types", by Patrick Muffler (U.S.A.) and Anotaly A. Sphak (Russia).
Chapter 1.4: "Exploration geosciences (geology, geophysics, geochemistry)", by Philip M. Wright (U.S.A.) and Vladimir I. Kononov (Russia).
Chapter 1.5: "Prospect Evaluation", by Norman Goldstein (U.S.A.) and Anna B. Vainblatt (Russia).

If we are to keep the original subjects of the chapters unchanged, as suggested by Professor Kruger, the only changes would be to make the substitutions of authors which we discussed in St. Petersburg. These changes from our side would be (1) in addition to my assuming the role of the American editor of Volume 1, I would also become the American author of Chapter 1.3, on "Resource Base and Resource Type", and (2) Donald Campbell would become the American author of Chapter 1.5, on "Prospect Evaluation". From your side, I assume that, as you mentioned in St. Petersburg, there would be the following changes, (1) A.A. Smyslov would become the Russian author of Chapter 1.2, instead of Y. B. Smirnov, and (2) Dr. Vainblatt's paper would be moved to Volume 2 and A.A. Sphak would become the author of Chapter 1.5.

As for other changes, I can see the logic of separating Dr. Polyak's chapter from that of Dr. Neilson as they take very different approaches. Dr. Polyak's paper is about the heat budget of the Earth, whereas Dr. Neilson's is about geothermal systems which have economic potential, i.e. about geothermal resources. Also I see no problem about putting Dr. Neilson's paper after the chapter by Blackwell and Smyslov, as their material is global in scope. However the biggest problem with the revised contents you suggested in St. Petersburg is that it leaves hanging the question of who would be the Russian author of Chapter 1.3 on "Resource Base and Resource Types". Dr. Kruger tells me that he has not had Dr. Sphak's text translated yet as it is much too long to be included in the volume as written.

Unfortunately Dr. Sphak was not in St. Petersburg and so, before you gave me your suggestions for the revised table of contents for Volume 1 on 25 June, I had already given a draft version of the material I was intending to include in my part of Chapter 1.3 to Dr. Grebenshikova Titania Borisova to carry to Dr. Sphak in Moscow. I also gave her my address here in Japan to give to him. However I have heard nothing from him yet.

I would appreciate hearing from you as soon as possible about your views on how we could adhere to Professor Kruger's plan, of keeping the chapter topics as they were originally, or at least until we have all the manuscripts in hand. Although I wrote to the American authors in July telling them about what happened in St. Petersburg, and, among other things, about the proposed November deadline, I need to remind them again soon of what we expect from them and when. We need to clear up the confusion about the agreed table of contents and list of authors before we can proceed further with writing and editing the volume.

Yours sincerely,

Wilfred A. Elders

Wilfred A. Elders,

Visiting Professor,
Kyoto University

FROM: WILFRED A. ELDERS
BEPPU GEOPHYSICAL RESEARCH LABORATORY,
KYOTO UNIVERSITY,
NOGUCHIBARU,
BEPPU 874, JAPAN.
TELEPHONE No. 89 977 33 0713
FAX NO 81-977-22-0965

23 July 1993

TO:		
	Paul Kruger, Satanford University	0011 415 725 8662
	Dennis Neilson, UURI	0011 801 584 4453
	David Blackwell, SMU	0011 214 768 4289
	Phillip Wright, UURI,	0011 801 584 4453
	Donald Campbell, Mesquite, Inc.	0011 714 525 2852

Volume 1 Russian American Monograph.

Dear Paul/Dennis/Dave/Mike/Don,

(Sorry Paul. "Satanford" was I typo but I decided to share it with you because even editors stumble. This is being written with an old Japanese version of Microsoft Word, on an old Macintosh Classic with a Japanese keyboard and Japanese commands and menus, by an old British/American professor.) Greetings from the Tsuyuu season in Japan where the humidity and heat make me think about the dry heat of southern California. Just kidding! As I am in Japan until 31 March, 1994, I will be experiencing the humidity and the cold all too soon. As well as using the above address and FAX number you can reach me by E-mail where my address is :-

G53444@jpnkudpc.bitnet

I'll try to bring you up to date on St. Petersburg. The simplest way to for you to understand what happened there would be for you to read my DOE trip report, a copy of which I will put in the mail for you. As far as the monograph is concerned, I am ambivalent about what happened. Some things were decided, but there are still some loose ends. The important news is:-

(1) We decided to continue with the monograph in the expectation that it would be published, although no firm date or plan for publication emerged. (2) Authors are asked to submit all copy before 30 November 1993. (3) Paul Kruger will arrange Russian English translations through Sandia National Lab. (Send Russian texts to him ASAP). (3) We can have separate versions of Chapters from Russian and American authors where integration is difficult. (4) There will be some changes in the content and authorship of Volume 1.

After you review the situation, I would appreciate your input about your own chapter and how it relates to the overall volume. As all of us have written extensively on geothermal topics, I expect that we can be adaptable and modify material we have already written, where appropriate, and so we can move expeditiously.

On a following page is a copy of the Table of Contents for Volume 1, as given to me by Paul Kruger last Fall. On 11 June 1993 Norman Goldstein informed me he had decided to drop out of the project. I am delighted to say that Don Campbell and Sue Petty of Mesquite, Inc, agreed to take over his assignment at short notice. Norm's reason was that he is no longer involved in geothermal work. In any case Norm 's work was mainly in exploration geophysics, which is rather different from Prospect Evaluation. However Don and Sue are very active professionally in well testing, reservoir assessment and economic evaluation, after the intitial discovery wells are tested successfully. In my opinion, prospect evaluation, particularly economic analysis, is an area in which Russian experience is relatively lacking in view of the undeveloped state of their geothermal industry.

When I left for St. Petersburg the score for Volume 1 appeared to be Russian authors 5::American authors 1. Five Russian manuscripts had been in the U.S.A. for some time. I had one from Shpak for Chapter 1.3 and Goldstein sent me one from Vainblat which I passed on to Don Campbell. As for the English Chapters only Chapter 1.1 was complete. Dennis earned bonus points from the editors as, not only did he get Polyak's chapter translated, but he sent his own text to Polyak at the end of April. My feeling about that these two versions of Chapter 1 was that they were very different. Dennis was writing about geothermal fields and Polyak was writing about sources and sinks of heat in the interior of the Earth. This brings home an essential problem. Are we writing a text book for students of the Physics of the Earth or is it a manual for Geothermal Developers? My preference would be closer to the latter than the former. However the contents and authorships of the chapters were decided by General Editors Kruger and Dyadkin long before I got involved. I do not advocate changing horses in mid-stream - but I like to know which horse I am on.

Status of GEOTHERMAL ENERGY
Joint Soviet-American Monograph
in Three Volumes
1992
(28 September 92)

Volume 1 Resources

Volume Editors
V. Kononov, Council for Geothermal Research RAS
W. Elders, University of California-Riverside

Chapter Authors

1.1 Nature of Geothermal Energy
USSR: Boris G. Polyak (Geol.Inst, AS)
USA: Dennis Neilson (UURI)

1.2 Heat Flow Distribution and Geothermal Anomalies
USSR: Yakov B. Smirnov (Geol.Inst, AS)
USA: David D. Blackwell (SMU)

1.3 Resource Base and Resource by Type
USSR: Anotaly A. Shpak (AURIH&EG)
USA: Wilfred Elders (UC-R)

1.4 Exploration Geosciences (geology,geophysics,geochemistry)
USSR: Vladimir I. Kononov (Geol.Inst, AS)
USA: Phillip M. Wright (UURI)

1.5 Prospect Evaluation
USSR: Anna B. Vainblat (LMI)
USA: ~~Norman E. Goldstein (LBL)~~

June 1993 Goldstein declined to continue
and so the USA author of Chapter 1.4 was changed to
Donald Campbell and Sue Petty of Mesquite, Inc.

I took to St. Petersburg:
, for Chapter 1.1, Dennis' manuscript;
for Chapter 1.2, Dave's list of topics and an outline of a paper he had written as text for "The Heat Flow Map of North America" published by the Geological Society of America;
for Chapter 1.3, my list of topics and a manuscript of a paper I had written for a GRC Short Course which covered most of the material;
for Chapter 1.4, Mike's list of topics and his outline of a chapter he had written on Geothermal Exploration for the Handbook on Direct Use Applications published by the Geoheat Center; and
for Chapter 1.5, a detailed outline by Don & Sue describing methods of prospect evaluation and case histories from their experience.

In St. Petersburg I had brief meetings with Kononov (co-editor and author of Chapter 1.4), Polyak (Chapter 1.1) and Vainblat (Chapter 1.5). Unfortunately Smirnov (1.2) and Shpak (1.3) were not there. I gave my manuscript for Chapter 1.3 to a colleague of Dr. Shpak to deliver to him, with a hand-written note. (My laptop and printer were on their way to Japan and have'nt arrived yet.) Polyak took an active role in the discussions, as he is more fluent in English than Kononov (and also more assertive). I spoke to Vainblat first briefly with Paul Kruger making introductions and translating and, then later at more length, when I discovered she spoke some German. I showed her Don and Sue's chapter outline.

At our first meeting on 23 June Polyak gave me a revised version of his Russian text for Chapter 1.1, which is shorter than the previous one. I will send it to Paul for translation. I mentioned the differences in approach between Neilson and Polyak towards geothermal resources. Kononov also went over the proposed outline of Chapter 1.5 which Don & Sue had given me and seemed pleased with it. However Kononov recommended the following changes from the earlier scheme. (1) The Russian author of Chapter 1.2 would now be A.A. Smyslov (rather than Smirnov). (2) The order of Chapters 1.3 and 1.4 would be reversed. Vainblat's paper would be moved to Volume 2 and Shpak's paper would be divided into two parts, the first going into Chapter 1.4 and the second going into Chapter 1.5. I told him that we should take that up with the General Editors.

The meeting of all the editors took place on the afternoon of the last day and was very largely taken up with general issues about the monograph. Only in the last few minutes was there a chance to talk about Volume 1 with Kononov, again with Polyak in attendance. They showed me the version of a new table of contents transcribed verbatim here. (Theirs was hand-written in Russian and English by Polyak).

"Volume A. Terrestial Heat and Resources of Geothermal Energy.
eds W.A.Elders and V.I.Kononov.

Ch I. Problems of Geoenergetic Budget and Terrestial Heat Losses.
B. G. Polyak (Russia) Ready in Russian.
Ch II. Background Geotemperature Field and its Anomalies.
D. Blackwell (USA) and A.A. Smyslov (Russia)
Ch.III. Nature of Geothermal Sytems.
D.L. Neilson (USA) Ready in English/Semi-ready
Ch. IV Exploration of Hydrothermal Resources - Geochemical, Geophysical and Geochemical Methods .
V.I. Kononov (Russia) and P.M. Wright (USA) Ready in Russian
Ch. V. Evaluation of Hydrothermal Resources.
A.A. Shpak (Russia) Don Campbell (USA)

When I mentioned that my contribution was not included in this version, Polyak simply crossed out "Campbell" and wrote my name underneath. I had just begun ask about the reasons behind their suggestions when General Editor Dyadkin. terminated the meeting at 5.00 p.m., telling us that our transportation to the dormitory was waiting. As I walked out of the room protesting at the unfinished business, Dr. Boguslavskiy, co-editor of Volume 2 handed me another manuscript in Russian about Hot Dry Rock and John Lund told me it was to be included in Volume 1. Paul Kruger's advice to me was to take it and to sort it out later. Subsequently I tried to give it to Paul but he suggested that I take the new Russian manuscript with me to Japan. Unfortunately Russian - English dictionaries are hard to find here and it I am very slow using a Russian-Japanese and then a Japanese-English dictionary. I am sending it back to you, Paul.

Where do we go from here?

Sincerely,

Wilf

Wilfred Elders

UNCLASSIFIED TRIP REPORT- FOREIGN TRAVEL
SUMMARY

A. Name of Traveler:-

Wilfred A. Elders,
Professor of Geology,
Institute of Geophysics & Planetary Physics,
University of California,
Riverside, CA 92521, U.S.A.
{Sandia Division 6111 (Contractor) Geothermal
Contract Number DE AC04 76DP00789}

(Until 31 March 1994,
temporarily assigned to :-
Beppu Geophysical
Research Laboratory,
Kyoto University,
Noguchibaru, Beppu,
874, JAPAN.

B. Date of Report:- 14 July 1993

C. Trip Number:- 9303154

D. Changes Made to Originally Approved Trip:- None.

E. Destinations:
St. Petersburg Mining Institute (SPMI),
St. Petersburg, Russia.

F. Dates of Trip:-19 June 1993 (Depart U.S.A)--28 June 1993 (Depart Russia)

G. Succint Statement of Trip Purpose:-
(1) To attend an International Symposium on Geothermal Energy.
(2) To expedite editing a monograph on Geothermal Energy.

H. Abstract:-

At the suggestion of the Director of the Geothermal Division of DOE, I attended an international syposium sponsored by the Russian Geothermal Association (RGA) and the SPMI. The main purpose was to meet with Russian co-editors and authors in order to expedite production of the joint Russian-American Monograph on "Geothermal Energy". This aim was achieved to some extent and some progress was made on this issue, although more time could profitably have been spent on it. That was not possible due to the way the symposium was scheduled. However the editors did develop a timetable and may have a firmer basis for future collaboration, although problems of communication undoubtedly remain, given the language barrier and the current economic crisis in Russia. Secondary objectives which were more fully achieved included participation in the symposium, learning about geothermal resources in Russia and other countries, and presenting a paper about work previously carried out with colleagues in Mexico. General impressions during this trip include (1) there is a genuine enthusiasm for international collaboration on the part of some Russian colleagues, (2) Russia has a large untapped potential for geothermal development, particularly for direct use applications, and (3) although the scientists and engineers involved are well-trained, many lack hands-on experience of practical geothermal development. Russia today faces serious political and economic problems, exacerbated in the field of energy by loss of oil-fields in former territories of the USSR, and environmental problems in its nuclear power industry. One way in which the U.S.A. could help mitigate this situation would be in training and technology transfer in alternative energy. The U.S Department of Energy should give serious consideration to what role it might play in this international arena. If problems of financing could be solved, this might create opportunities for involvement of U.S. industry in development of geothermal resources within the Russian Federation.

SECTION 2

Statement of Purpose of Activities:-

The reason for the trip to Saint Petersburg, Russia, to participate in the International Symposium on "Problems of Geothermal Energy", held by the Russian Geothermal Association (RGA) and the St. Petersburg Mining Institute (SPMI), was to further the production of a bi-national Russian-American Monograph on Geothermal Energy. It was anticipated that all of the co-editors of the monograph and many of the co-authors, especially those from Russia, would be present, thus facilitating discussions. These face-to-face meetings were deemed an essential step in producing the monograph, which previously had been delayed by problems of communication. A secondary objective was to participate in the symposium, learn about geothermal developments and practices in Russia, and other countries, and to report upon work concerning the economics of geothermal direct use applications in Mexico, recently completed by myself, together with Mexican colleagues.

Background to the Foreign Travel: At the request of Dr. Paul Kruger of Stanford University, California, U.S.A., (DOE contract number SNL-AA-9446), I became a co-editor of Volume One of a joint Russian-American monograph. This is the first of three volumes, each under the supervision of a Russian and an American editor, with chapters each written jointly by Russian and American authors. The plan for editorial responsibilities is:-

Chief Editors:	Yuri D. Dyakin,	St. Petersburg Mining Institute.
	Paul Kruger,	Stanford University, CA.

Volume editors:

Vol. 1	Vladimir I. Kononov, Geol. Inst., Acad. of Sciences, Moscow Wilfred A. Elders, IGPP, Univ. of California, Riverside, CA.
Vol. 2	Emil I. Boguslavskiy, Geothermal Program, SPMI, Russia. Hugh Murphy, Los Alamos National Laboratory, NM.
Vol. 3	Boris M. Kozlov, Gosplan, Russia. John Lund, Oregon Institute of Technology, OR.

At the time of his invitation to me, he made it clear that, up to that point, all of the editors and authors were to serve without remuneration, or even funds to cover the expenses of writing and illustration, communications, translation, and editing of the texts for which they had agreed to be responsible. Nor was there, at that time, a commitment from a publisher.

However, Professor Kruger communicated a contagious enthusiasm for the project as a worthwhile contribution to the literature on geothermal resources, and asserted his optimism that it would have a successful conclusion. In February 1993, Professor Kruger's enthusiasm was supported by a renewed invitation from Dr. John Mock, Director of the Geothermal Division of the U.S. DOE. This invitation was reassuring on a number of points. It indicated the willingness of the Geothermal Division to seek authorization for support for (1) publication of the monograph, (2) a meeting of the editors at the RGA-SPMI symposium in St. Petersburg, (3) translation of Russian and English texts (see Section 3 - Appendix 1). This encouraging development was followed by a formal request from Dr. James C. Dunn for me to travel to St. Petersburg with expenses to be reimbursed by Sandia National Laboratory (see Section 3 - Appendix 2). This report is an outcome of accepting that invitation.

Relationship to U.S./DOE Interests:-

I have received no briefing on DOE's interests and can therefore only speculate on that issue. The following homily (as do any subsequent remarks) represents my personal opinions, and not those of DOE, nor of its contractors in Sandia National Laboratory and Stanford University. At the outset, the idea of a joint Russian-American monograph on geothermal resources seemed strange. In terms of its installed generating capacity, the U.S.A. is the world's leader in utlilizing geothermal resources, whereas Russia has only 11 MWe of installed geothermal electrical generation, or about 0.3% of the U.S. capacity. Thus, at first sight, a bi-national monograph comparing and contrasting the experience and technology of geothermal developments of the U.S.A. with that in the Philippines, Mexico, Italy, New Zealand, Iceland, or any of several other countries with a more highly developed geothermal industry, appeared to me to be more likely to have a substantive content and the possibility of a wider readership.

On the other hand, the Russian Federation faces severe political and economic problems, but its vast territory has a diverse and enormous energy resource potential. Since the end of the Second World War, world politics had been dominated by the cold war. In that arena, the weapons program of the U.S. Atomic Energy Commission, and its successors, ERDA and DOE, played a pivotal role in the strategy of the U.S.A. The recent dramatic break-up of the communist bloc now demands reassessment of the U.S strategic position and opens the opportunity for the DOE to examine possible new roles to forward U.S. interests internationally. One possible role, consistent with advancing

U.S. interests, would be the application of DOE expertise in alternative energy in selected countries abroad.

The Group of Seven industrialized nations has just guaranteed US $ 3 billion to stabilise the rouble and assist in the transition to a market economy in Russia. At the same time the energy situation in the Federation has been eroded by the loss of oil-fields due the break-up of the USSR, and by safety and environmental problems in its nuclear power industry. Because electrical generation and direct use from geothermal sources can be developed rapidly in flexible modular increments, geothermal resources lend themselves to development by decentralized or private agencies. Could the DOE be a catalyst in bringing about U.S. involvement in this industry in the Russian Federation? The joint U.S.-Russian monograph on geothermal energy could be a small step in that direction.

Summary of Activities, Emphazing Findings, Problems, and Decisions:-

(1) Itinerary:-

My Full Itinernary appears in Section 3, Appendix 4. Note that, because my obligation to Kyoto University required me to arrive in Japan on 1 July 1993, I left St. Petersburg for Japan without first returning to the U.S.A. **Findings:** Several airlines offer "Round the World" fares at advantageous rates. **Problems:** The choice of routing is limited by the airline(s) concerned so that travel may not be by the most direct route. **Decisions:** The decision was made to accept a lower fare and a longer route.

(2) Symposium:-

A summary of the overall program of the symposium appears in Section 3 - Appendix 3 of this report, where it will be seen that there were "Plenary Sessions" on the mornings of Monday through Friday, and three parallel "Specialist Sessions" on Tuesday, Wednesday and Friday afternoons. The program devoted Monday afternoon to a tour of the historic St. Petersburg Mining Institute and Friday afternoon tour of Puskin's Palace. The overall program took place as listed in Section 3 - Appendix 3. The "Specialist Sessions" were as follows:-

Tuesday 22 June 1993

Section A. Session 1.	High-temperature geothermal fields*
Section B. Session 1.	Wells, reinjection, hydrofracturing
Section C. Session 1.	Geothermal power plants and equipment

Wednesday 23 June 1993

Section A. Session 2.	Thermal water of sedimentary basins*
Section B. Session 2.	Heat-mass transfer, hydrochemical processes
Section C. Session 2.	Direct uses of geothermal fluids

Thursday 24 June 1993

Section A. Session 3.	Evaluation and mapping of geothermal resources
Section B. Session 3.	Geothermal energy and fuel optimization and accumulation
Section C. Session 3.	Environmental optimization, new projects*

In addition to attending the morning plenary sessions, I also participated in the specialist sessions indicated by an asterisk in the list above, and presented a paper in Section C, Session 3.

Findings: This first international symposium to be hosted by the Russsian Geothermal Association was only partially successful, and it is to be hoped that the RGA will profit from the experience gained in organizing any future international meetings. St. Petersburg is a beautiful city, and a wonderful setting for any kind of meeting. However, although its location is convenient to participants from Europe and western Russia, it is far away from any geothermal features or installations and so no field trips were arranged. Presumably the meeting was held in this location because of the established program of geothermal research at the St. Petersburg Mining Institute, an historic setting (founded in 1773) with neo-classic architecture and superb mineral collections. Our gracious Russian hosts were exceptionally hospitable and anxious that we should enjoy our visit. Yet, in terms of international participation, meeting organization, and facilities, the symposium was disappointing.

Not all of these defficiencies could be charged to the organizers. The symposium had been postponed from last summer, apparently because of perceived conflicts with another international geothermal symposium being held in Iceland, sponsored by the International Geothermal Association. However participation by the IGA at St. Petersburg in June 1993 was conspicuously absent. Although the printed program listed several keynote speakers from the IGA, they were not present.

We heard reviews of the status of geothermal developments in Russia, Mexico, Chile, El Salvador and other countries of Central America and the Carribean, Germany, Japan, Macedonia, India, and the U.S.A. However national status reports announced in the printed program from the EEC, Italy, the Philippines, New Zealand, Iceland, France, Turkey, Hungary, Romania, and Kenya were not presented, and some national reviews were given by substitute speakers at short notice. For example, this occurred with the status report for the U.S.A. which, in the absence of Dr. John Mock of DOE, was given by Dr. Paul Kruger.

The status report for Russia, given by Dr. V.I. Kononov, indicated the considerable potential for development of geothermal resources in the 68 Governmental Regions and 21 Autonomous Teritories of the Russian Federation. He reported that 14 regional centers for geothermal resource investigations have recently been formed, each with several branches. His report was an up-date of information published last year (Kononov, V.I., 1992. "Utilization of Geothermal Energy in Russia.", Geothermics, Vol. 21, No 5/6, pp.617-622). The potential high enthalpy geothermal resources of Russia occur in the belt of Recent volcanism of Kamchatka and the Kurile Islands and also in the Caucasus region of Cenozoic tectonic activity In these regions the Geothermal Resource Centers are attached to the State Company Gasprom. In other regions with potential low-enthalpy resources, the Centers are in departments of the Geological Committee (Survey?) or in research and educational institutions, such as the SPMI. At the concluding banquet of the Symposium, Dr. Gustavo Cuellar, Inter-regional Geothermal Advisor in the Department of Economic & Social Development of the United Nations announced that he would recommend that a UN Geothermal Institute should be set up at the St. Petersburg Mining Institute, to serve Eastern Europe and Russia.

The only geothermal power plant currently operating in Russia is at Pauzhetskaya at the south end of the Kamchatka Peninsula. It produces 11 MWe from a water-dominated reservoir where temperatures of up to 210 °C are encountered at only 300-500 m depth. There are nine production wells, connected to the power station, 11 injection wells and 13 observation wells. Well depths vary between 300 and 1100 m and one well discharges at about 100 tonnes/hr. I am not clear how many of these 33 wells were exploration wells or why the production and installed capacity is so low. Perhaps further development is hindered by unfavorable economics, or by the remoteness of the site from large population centers. Further north in Kamchatka, in the Mutnovsky geothermal system, 70 km south of the city of Petropavlovsk-Kamchatka, 58 wells (28 of them production wells) have been drilled and temperatures of 250-310 °C found at 900-2100 m depth. The first 70 MWe stage of a geothermal power station in the Mutnovsky field will be operational in 1995 and its capacity is expected to rise to 210 MWe by the year 2000. A 100 MWe plant is planned for a vapor dominated resource at Koshelevskaya also in South Kamchatka.

At the present time only about 100,000 people in the Russian Federation, mostly in North Caucasus, but also in West Siberia, and Kamchatka, are now using geothermal waters for district heating. Similarly industrial use of geothermal energy is as yet not highly developed. However according to several presentations at the symposium, regions potentially containing low enthalpy geothermal resources appear to be quite widespread in Russia. In addition to the volcanic Kamchatka and the Kurile Islands region, the most likely prospects are in the Caucasus fold belt and the Baikalian Rift with Cenozoic tectonic activity, and in the sedimentary aquifers of the Scythian and West-Siberian Paleozoic platforms. The latter basin has an area of 3 million km^2 where groundwater temperatures reach 100 to 120 ^{o}C at about 3,000 m. It is estimated that the total hydrothermal resource of water between 35 to 75 ^{o}C in this aquifer amounts to 180 m^3/s for 25 years (Kononov, 1992; oral report, 1993).

Although drilling costs would be high, the volume of hot water is enormous, and given the Russian energy picture, the economics of its utilization should be seriously considered. Among the presentations at the symposium was the concept of upgrading the thermal water from these deep aquifers in hybrid systems using boilers fired by natural gas. Aquifer systems where this could be considered are widespread in Russia.

During the meeting there were several presentations by Russian scientists concerning studies of Hot Dry Rock (HDR) geothermal energy, including one by Dr. Yu. D. Dyadkin. However, as far as I was able to understand, the presentations on the Russian HDR program appeared to be mostly theoretical. Although much was undoubtedly lost in translation, I was not aware that reports of actual engineering experience, field data or hard economic analyses were presented. However, in some contexts in St. Petersberg, the term "HDR" geothermal energy is a misnomer. It could more properly be referred to as "Artificial Circulation System" geothermal energy, but then any production or injection well is artificial. A foreign sceptic at the symposium facetiously referred to it (in a private comment) as "TDR" or *Tepid Damp Rock* geothermal energy. This sceptism arose over mention of a new SPMI project to drill wells for a HDR geothermal resource to supply hot water to the City of St. Petersburg. The proposal is to drill and artificially fracture boreholes 3000 m deep where a temperature of 110 ^{o}C is expected. To the foreign sceptic, the low temperature gradients in the Proterozoic granites and gneisses of the Fennoscandian shield, which underlie the region of St. Petersberg, would appear to be an unlikely geothermal resource. A superficial review of costs reported for HDR projects in the U.S.A., U.K., and Japan, would seem to suggest that, for the SPMI project to be economically successful, extremely low drilling costs and power outputs requiring extremely high flow rates would be necessary. One option for St. Petersberg, which I did not hear discussed, would be an analysis of the economics of ground source heat pumps to upgrade the use of natural gas for space heating and cooling. If the appropriate cost figures for Russia were available, a "back of the envelope analysis" for the City of St. Petersburg pitting a U.S. expert on the economics of HDR versus a U.S. expert on the economics of heat pumps could be an interesting tutorial in market economics.

Problems: The make up of the technical program was in a state of flux throughout the meeting, with papers being cancelled and moved and others being substituted as the program was abbreviated. Consequently it was difficult to be sure if and when a particular paper would be given. This made it impossible to plan on moving between concurrent Specialist Sessions. The organizers seemed to have expected a foreign attendance larger than was actually present. The printed program scheduled about 100 papers to be given in Russian and about 40 to be given in English, the two working languages of the meeting. More than 15 of the English papers were not given. The list of attendees provided contained 181 names, with about 95 attendees from Russia and 8 or 9 more from countries of eastern Europe. Out of the remaining number, at least 35 of the people listed are known to me but were not present. This was consistent with the attendance at the sessions. About 80 people (including a number of accompanying members) were present at the first Plenary Session, about 65 at the second, and about 60 at the third and 38 at the fourth. About 30 people were present in Specialist Session A1, 20 in Session A2 and only 17 in Session C3, out of whom I was one of the two foreigners present. A Japanese colleague commented that to him the meeting seemed more like a domestic meeting rather than an international symposium. However, from personal experience, I know domestic meetings of the Japanese Geothermal Research Association are better organized.

There were no facilities for simultaneous translation, but a series of what appeared to be amateur interpreters strove to bridge the language barrier by serial translation. Unfortunately some of the Russian speakers made no effort to pause for the translation, and there were times when I could not understand. The situation for non-Russian-speaking participants for whom English is a second language must have been worse. Projection facilities were provided and used by all of the English speakers but by too few of the Russian speakers. Some of the Russian speakers illustrated their oral presentations with tiny posters covered with dense script.

Possibly the most frustrating aspect of this international symposium was the poor communications before the meeting. It was difficult to get details of the program or to find out if reservations for accommodation and submitted abstracts were accepted. Mail went unanswered and telefax communication was very tenuous. These communication problems may be partly responsible for the reduced attendence from abroad. In former times I participated in four international meetings in the USSR, two in Moscow, one in Jaroslavl, and one in Irkutsk. These meetings were conducted in a well-organized and professional manner. Thus my experiences in St. Petersburg came as a surprise and a disappointment.

Decisions: I decided to enjoy the symposium by being patient and persistent and to participate as fully as possible.

(3) Editing the Monograph:-

In St. Petersburg the three American co-editors and two of the Russian co-editors discussed the monograph with the chief editors. It was agreed to continue our work and assume that the monograph will be published in the U.S.A. The problem of finding the resources to publish the Russian version remains to be solved. It was further agreed that all remaining first drafts of chapters should be compiled by 30 November 1993, and at that time the volume editors should start completing their task of revision. Dr. Kruger announced that he would arrange translations from Russian to English using DOE funding at Sandia. In addition I met with Dr. V.I. Kononov, my co-editor of Volume 1 and with Dr. E.M. Boguslavskiy, the co-editor with Dr. J. Lund of Volume 2., and had discussions with two of the Russian authors of chapters submitted to Volume 1.

Findings: Although some progress was made in terms of putting the Russian-American Monograph on a more solid footing, the meeting was unsatisfactory in terms of what still needs to be done. More could perhaps have been achieved if more time had been specifically set aside for discussion of the monograph, and if an agenda for such discussion had been mutually agreed upon ahead of time. Although there was brief discussion at three levels, embracing general policy and scheduling, and between volume editor to volume editor, and editor to author, there was no opportunity for feed-back between these levels, and there was insufficient time to consult and to respond to a rapidly changing situation.

Problems: With one exception, all of the problems remain of those mentioned at the beginning of my involvement in this project. As mentioned above, Dr. Kruger, in October 1992, explained, "All of the editors and authors were to serve without remuneration, or even funds to cover the expenses of writing and illustration, communications, translation, and editing of the texts for which they had agreed to be responsible. Nor was there, at that time, a commitment from a publisher". The exception is that a mechanism for translation from Russian to English is now being put in place.

For me the major problem is, "If, when, and where will the monograph be published?" Dr. Kruger and I differ on priorities. He believes that we should complete the text before discussing publication. I believe that an essential step in publishing a technical book is a preliminary survey of the likely worldwide readership. This is necessary in order to begin discussions with potential publishers about publishing and marketing, and can be done when a concept, a table of contents, and one or more specimen chapters are available for publishers to review. At this stage, even an informal expression of interest by a publisher would be reassuring to the authors, this one included, and would encourage their timely participation. These busy people need to know the probability of these volumes being published and need a credible plan and timetable for doing so. There were also problems with the plan espoused by the chief editors that the Russian and American authors of each chapter would together co-ordinate their texts. It was not clear to me how specialists in the two countries, with different interests and experiences and different languages, are to achieve this in practice.

I was looking forward to St. Petersburg for enlightenment on these topics. However in St. Petersburg there was a very full program of sessions and social events arranged and the chief editors of the monograph, both of whom were on the program committee of the symposium, had not scheduled meetings with the co-editors and authors. This oversight was disturbing as it seemed to imply either that the chief editors had an unwarranted complacency about the status of the monograph, or that they gave it a low priority.

Decisions:- On my own initiative I sought out my co-editor Dr. V.I. Kononov, who is also a co-author of Chapter 1.4, and met with two other authors from Volume 1, Dr. B.G. Polyak (Chapter 1.1) and Dr. A.B. Vainblatt (Chapter 1.4). These discussions were held in the interstices of the schedule of the Symposium, without the benefit of an interpreter. Fortunately Drs. Kononov and Polyak speak some English and Dr. Vainblatt speaks some German. During these brief meetings changes to the format, content, and authorship of Volume One were discussed. I was impressed with the earnest and sincere attitude of these scientists towards the monograph and also their willingness to compromise. Because of circumstances which will be discussed in detail below, there was not time to finalise these discussions and I believe it possible, and even likely, that we left with different ideas of what had been agreed. Another unfortunate circumstance was that other Russian co-authors of chapters in Volume 1, Dr. Y. B. Smirnov and Dr. Anatoly Shpak, were not in St. Petersburg. Dr Shpak is to co-author Chapter 1.3 with me and I therefore sought out one of his colleagues from Dr. Shpak's institute in Moscow and gave her a letter and my English manuscript for the chapter to carry to him.

Early in the meeting I approached Chief Editor Dr. Dyadkin to ask when an editors' meeting would take place, but he did not scheduled it. By noon on Friday time was running out, for although I had purposely arranged my schedule to be remain in St. Petersburg on Saturday and Sunday in case that time was needed for meetings concerning the monograph, other editors and authors involved were leaving. I therefore repeated the request to Dr. Dyakin urging that the meeting be held that afternoon. He refused, saying that an excursion to Puskin's Palace was scheduled for that time. This reluctance on the part of the Russian chief editor to meet for discussion of the monograph was (and remains) the most disturbing aspect of my association with this enterprise. I have no explanation for his reluctance.

I therefore urged Dr. Kruger to take up the issue of holding a meeting with our Russian colleagues that afternoon and Drs. Lund and Murphy concurred in the request. The outcome was that a rather tense, but on the whole cooperative, discussion took place between the chief editors and all of the co-editors except Dr. Boris M. Kozlar (Volume 3) between 14.30 and 17.00 on 25 June 1933. The meeting was serially interpreted, with occasional failures when people interrupted or spoke without waiting for the translator.

Chief Editor Dyadkin began the meeting, stating that the situation in Russia was very difficult. As far as the monograph is concerned, in addition to the problem of translations, the major problem of finding the financial support for publishing the Russian version would be very difficult. He offered the following alternatives, (1) not to proceed further with the monograph, (2) to follow the plan already agreed, however long it took, (3) to seek new authors for the chapters not yet written, or (4) to issue the monograph in English with only those articles finished by 30 November of this year, while he continued to seek funding from the RGA and the Russian Academy of Sciences for the Russian version. He also suggested that if alternatives 3 or 4 were to be chosen, there could be different chapters in Russian and English where integration was lacking.

Chief Editor Kruger responded that work had been going on for two years, a great deal had been accomplished and many manuscripts written. He stated his preference following the original plan of 26 Russian and 26 American authors working together, and then the editors organizing what the authors submitted. He referred to the problem of communication as being the most difficult. Co-editor Boguslavskiy commented that where the integration of the chapters,had been successful, they could be published under the names of both authors, whereas chapters lacking integration could be published under separate authorship.

After general discussion, the American editors and broke off to caucus, where we found that there was a strong consensus that (1) because so much effort had been expended at this stage, we should proceed with the monograph and try to be optimistic that it would receive timely publication, and (2) we should accept individual, i.e. non-integrated chapters where necessary. When the joint meeting resumed, Chief Editor Kruger reported our agreed position. He also restated his philosophy of separating the problems of writing and editing the monograph from the problems of publishing it. His preference was to concentrate on the former problems at that time and face publication problems in the future. He further announced that he had financial support in the U.S.A. for Russsian-English translation at Sandia National Laboratory, thus Russian authors should submit texts in Russian. Chief Editor Dyadkin, in response to a question, stated that English-Russian translation could be handled in Russia. There appeared to be no objections to the cut-off date of 30 November 1993 for the receipt of manuscripts.

The meeting ended in some confusion as far as I was concerned. It was decided to devote the remaining few minutes of the meeting to individual discussions by the co-editors about the individual volumes. At that point Drs. Kononov and Polyak presented me with a revised plan for Volume One, different from any previous version I had seen, even in our interactions earlier in the week. Before I was able to respond properly to their suggestions, it was announced the Americans should leave as it was 17.00 and a car was waiting to take us to the SPMI dormitory. The meeting was terminated over my protests. As I was leaving the room a Russian manuscript on HDR was handed to me and I was told that it was to go into Volume One. This paper had not appeared on any variant of the Table of Contents for Volume One, as far as I am aware. I decided that this was an issue for the chief editors to mediate.

Overall Impressions: In writing this report I have treated the account of the editors meeting in great detail, because, in terms of the reason why the DOE sent the American editors to St. Petersburg, it was the most important event of the week. However the meeting was less than satisfactory. It came too late, was too short, and was the kind of confusing meeting from which participants leave with different perceptions of the implications of what transpired. The version given above is based on my personal perceptions and detailed notes.

My general impression is that there is a genuine enthusiasm for international collaboration in geothermics on the part of some Russian colleagues. I would be happy to work on the monograph, or other projects, with the likes of Dr. Kononov and Dr. Boguslavskiy.

Russia has a vast and largely untapped potential for geothermal development, for electric power production in the far east, but more particularly for direct use applications over much broader areas. Although the scientists and engineers involved in geothermal resources in Russia appear to be well-trained, in view of the rather undeveloped state of their geothermal industry, most must lack hands-on experience of practical geothermal development. This is most particularly true with respect to making economic analyses in an open market economy.

(4) Description of Traveler's Role:-

In October 1992 I was invited by Dr. Paul Kruger to assume the co-editorship of Volume One of a joint Russian-American monograph on geothermal energy, and to co-author one of its chapters. Professor Kruger further explained that I was the third U.S. person asked to be the co-editor of Volume One, as previously there had been delays and difficulties in editing and writing that volume. Two years earlier Dr. Patrick Muffler, of the USGS, had agreed to edit Volume One, but subsequently withdrew, apparently frustrated by lack of progress. The assignment was then assumed by Dr. Grant Heiken of Los Alamos National Laboratory, NM. In July of 1992, he followed Dr. Muffler's example and resigned as editor of Volume One. Dr. Kruger also requested that I should assume responsibilty for co-authoring a chapter in Volume One on the geothermal resource base which was to have been written by Dr. Muffler.

With some misgivings I agreed to participate. Among these misgivings were (a) I had only a superficial knowledge of the situation of geothermal energy in Russia and had had no previous contacts with any of the Russian co-editors or authors, but I knew that Russia's geothermal industry was miniscule compared to that of the U.S.A., and (b) Russian is not among the five languages I can read.

As indicated above, the traveler's role in St. Petersburg was to co-ordinate with Russian and American co-editors the production of the monograph and to consult with a Russian co-author about a chapter to be written jointly by us.

(5) Recommendations for Follow-up Activities:-

(1) Communicate with Dr. Kononov about my latest understanding of the content and authorship of Volume One to clarify the hasty discussions in Russia, and also keep Dr. Kruger informed. (2) Report back on the St. Peterburg meeting to the American authors of the chapters of Volume One, urge them to be prepared to meet the 30 November deadline, and try to clarify the make-up of the individual chapters. (3) Arrange to send Russian manuscripts for Volume One to Dr. Kruger for immediate translation. (4) Urge Dr. Kruger to make an initial economic analysis of possible publication costs and potential readership, and to contact likely publishers. (5) Recommend that the U.S Department of Energy should give serious consideration to opportunities for international training and technology transfer in geothermal resources, especially within the Russian Federation. Today the Russian federation faces serious political and economic problems, exacerbated in the field of energy by loss of oil-fields and power plants in former territories of the USSR, and safety and environmental problems in its nuclear power industry. One way in which the U.S.A. could help mitigate this situation would be in training and technology transfer in renewable energy and geothermal resources. The U.S Department of Energy should give serious consideration to what role it might play in this international arena. If problems of financing could be solved, this could create opportunities for involvement of U.S. industry in development of geothermal resources within the Russian Federation.

(5) Information about the General energy Posture of the Country Visited:-

The increasing interest in geothermal energy can be understood in the context of the current gloomy economic and energy picture of the Russian Federation. According to Dr. Kononov, the energy supply of Russia has recently rapidly deteriorated and the total energy consumption by the Russian economy is expected to diminish by **20-25%** (Kononov, 1992, and oral communication 1993). In 1990 the electrical generation amounted to 1.7 million GWh/yr distributed between about 74.5% from hydrocarbon fuels, 13% from hydroelectric, and 12.5% from nuclear power plants. Since the break-up of the USSR some power plants and oil fields now lie outside Russian territory, the extraction of petroleum has declined 35%, the cost of coal has increased sharply, and the realisation that most of the nuclear plants require upgrading has become apparent. An increasing share of the energy supply will come from natural gas, however even so the energy supply will decrease markedly.

Geothermal resources could play a role in mitigating this situation, but as yet they have been relatively little developed. The potential contribution from geothermal resources could be significant in the vast and diverse territory of Russia, but serious efforts must be made to make credible economic analyses of the projects being discussed. A possible analogy might be that the situation in Russia today with respect to geothermal development ressembles that in the U.S.A twenty years ago, when the "energy crisis" dominated long term planning and large claims were being made for the future role of alternative energy, some of which have not survived the realities of technology and the marketplace. The Russian Federation could benefit from our experience.

(6) Security Related Concerns:- None.

SECTION 3

Appendices:-

Department of Energy
Washington, DC 20585

CE122

FEB 12 1993

Dr. Wilford Elders
Department of Earth Sciences
University of California Riverside
Riverside, CA 92521

Dear Wilf:

I would like to express my appreciation for your willingness to serve as an editor on the Russian-American Geothermal Monograph. From comments I heard at the Stanford Geothermal Workshop, it appears that the effort may have lost some of its early zest and momentum. I would like to encourage all participants in this significant venture to work with me in producing a timely product which will serve as a definitive reference for years to come.

I would like to encourage each of the editors of the three volumes of the monograph to ensure that communications between the American and Russian co-authors are accelerated to meet the schedule for completing the first drafts of their sections, and to prepare a summary paper of the compiled drafts for presentation in June at the plenary sessions at the Russian Geothermal Association International Symposium.

Although the DOE Geothermal Budget has been extremely tight these past few years, I feel that the Stanford University - St. Petersburg Mining Institute non-government cooperative program is very useful for geothermal energy development, and I will try to support publication of the Monograph as much as possible. I will also try to obtain authorization for the Editors to participate as invited speakers for the Plenary Sessions of the RGA Symposium and provide some support for translations to ease the difficulty of meshing the English and Russian Sections into the Chapters.

I look forward to working with you in the preparation of a very successful Monograph.

With best wishes,

Ted

John E. Mock, Director
Geothermal Division
Conservation and Renewable Energy

Sandia National Laboratories

Albuquerque, New Mexico 87185

April 21, 1993

Dr. Wilfred A. Elders
Institute of Geophysics and
Planetary Physics
University of California
Riverside, CA 92521

Dear Dr. Elders:

We would like to have you attend the Russian Geothermal Association Symposium on Geothermal Energy which is being held by the St. Petersburg Mining Institute in St. Petersburg from June 20 to 27, 1993. This will enable you to meet with the two other U.S. editors and the Russian co-editors of the Russian-American Monograph.

Sandia National Laboratories will reimburse you for reasonable actual travel and living expenses incurred between Riverside, California, and St. Petersburg, Russia, and during your stay in St. Petersburg. We request you use airline accommodations which are less than first-class, if available.

We will need to have you submit a trip report within thirty days of the conclusion of the symposium.

Sincerely,

James C. Dunn, 6111

Approved: ______________________
R. W. Lynch

Date: APR 21 ______________________

SECTION 3 - APPENDIX 3

Russian Academy of Sciences(RAS). Academy of Natural Sciences(RANS)
State Committee on Higher Education RF
Ministry of Environment and Natural Resources RF
International Bureau on Mining Thermophysics of WMC

Saint-Petersburg State Mining Institute - Technical Universit
Russian Geothermal Association

INTERNATIONAL SYMPOSIUM

PROBLEMS OF GEOTHERMAL ENERGY

21-27 June 1993

Russia Saint-Petersburg

Honour Chairman doct. Jim Combs, President of IGA

GENERAL TABLE OF SYMPOSIUM SESSIONS

Monday 21 June	8.00	Registration
	10.00 - 13.00	Plenary Session 1. Symposium opening
	13.00 - 14.00	Lunch
	14.00 - 18.00	Visit to the Mining Museum. Bus-Excursions.
	19.00	Welcoming Supper
Teusday 22 June	10.00	Plenary Session 2
	13.00 - 14.00	Lunch
	14.00 - 18.00	Parallel Sessions of Sections A-1,B-1,C-1
Wendesday 23 June	10.00	Plenary Session 3.
	13.00 - 14.00	Lunch
	14.00 - 18.00	Parallel Sessions of Sections A-2,B-2,C-2
Thursday 24 June	10.00	Plenary Session 4
	13.00 - 14.00	Lunch
	14.00 - 18.00	Parallel Sessions of Sections A-3,B-3,C-3
Fraiday 25 June	10.00	Final Plenary Session
	12.00 - 18.00	Lunch
	13.00 - 16.00	Bus Excursion to the famous Museums and Suburban Palaces of Saint Petersburg
	19.00	Farewell Supper
Saturday, Sunday 26,27 June		Excursions by Cultural Programme Participans and Guests Departure

Time Regulations :

Plenary session :

Scientific Report 20 min
Country Report 15 min

Session of Section
Report 15 min
Communication 10 min
Discussion 5 min

SECTION 3.

Appendix 4:- Full Itinerary of Traveler

Date	Travel or Location	Activity
19 JUN- 9.15A	Riverside CA-Ontario CA	departure/private car
19 JUN-11.25A	Ontario CA-Dallas Fort Worth TX	flight
19 JUN- 5.15P	Dallas FW - Frankfurt	overnight flight
20 JUN-12.10P	Frankfurt - St. Petersburg	flight
20 JUN- 6.10P	St. Petersburg	arrival
21 JUN	St. Petersburg	symposium
22 JUN	St. Petersburg	symposium
23 JUN	St. Petersburg	symposium
24 JUN	St. Petersburg	symposium
25 JUN	St. Petersburg	symposium/monograph
26 JUN	St. Petersburg	social program
27 JUN	St. Petersburg	social program
28 JUN- 7.50A	St. Petersburg-Frankfurt	departure
28 JUN- 2.31P	Frankfurt-Zurich	train
29 JUN	ETH-Zurich	technical discussion
29 JUN- 8.45P	Zurich-Singapore	overnight flight
30 JUN-11.00P	Singapore-Narita/Tokyo	overnight flight
01 JUL- 6.40A	Tokyo/transfer to Haneda	arrival/bus
01 JUL- 6.50P	Haneda-Oita	flight
01 JUL- 8.45P	Oita-Beppu	private car/arrival

Appendix 5:- List of Persons Contacted.

There were about 80 people at the SPMI symposium in St. Petersburg. The program listed more than 180 names but as many of them were not there I have not appended that list. However I can supply it if necessary. The Russians with whom I had most contact are the authors and editors of the monograph named on page 2 of the main text.

Appendix 6:- Bibliographic Listing of Literature Acquired.

1. Abstracts of Papers, International Symposium on "Problems of Geothermal Energy", St. Petersburg, June 1993, Russian Geothermal Association (in Russian & English).
2. Geothermal Bulletin, Quarterly Nos. 7-8, Russian Geothermal Association, St. Petersburg, 1993. (in Russian but has English program).
3. <u>Geothermics</u>, Volume 1, Academy of Sciences, NAUKA, Moscow, 1991 (in Russian)

FYI -
DLN

NATURE OF GEOTHERMAL SYSTEMS

Dennis L. Nielson
University of Utah Research Institute
Salt Lake City, Utah U. S. A.

INTRODUCTION

World-wide, naturally convecting high-temperature geothermal systems are presently the source of approximately 6000 MW of electrical generating capacity. Utilization of this resource is relatively recent compared with other sources, and, coupled with a large resource base, the amount of electricity generated is projected to increase in the future. Geothermal systems have interested scientists, for a long period of time, as the sources for much of the world's reserves of base and precious metals. Indeed, much of our knowledge of the internal geometry and water-rock interaction processes of active systems comes from the study of fossil hydrothermal convection systems. Although deeply buried regional aquifers and geopressured zones could be included in this discussion, it will concentrate instead on hydrothermal convective circulation systems that transport heat from a thermal source or are driven by deep circulation along fault zones.

This paper will investigate some of the more important physical aspects of hydrothermal convection systems. Elder (1965), Henley and Ellis (1983) and Norton (1984) provide reviews of the character of hydrothermal systems. Elder (1965) summarizes the critical elements of a geothermal system: heat source, recharge system, recirculation system, and discharge system. These features are diagrammatically shown on Figure 1. Studies of natural systems show that a magmatic heat source is also often also a source of volatiles and fluids. The recirculation system, or convective reservoir volume, is the focus of most studies of high-temperature systems. Convective circulation is most often hosted by permeable pathways provided by faults and fractures, and driven by temperature-induced buoyancy differences. Recharge takes place along fractures as well as through the matrix of suroundirg rocks. Discharge can be to the surface to form hot springs and fumaroles, as a lateral plume in the subsurface (Goff et al., 1988), or, as is often the case, a combination of both.

The discussion here will focus on magmatic geothermal heat sources and permeability/porosity relationships. Since the recharge, discharge and recirculation systems all depend on rock permeability, the formation and destruction of permeability and porosity will be presented in a generic context, as processes generally applicable to different components of the hydrothermal convective system.

HEAT SOURCE

Although deep circulation of fluids in zones of thin crust and high heat flow supports geothermal systems in many parts of the world, most notably the Basin & Range province of the western United States (Wright et al., 1989), the heat sources for most high-temperature hydrothermal systems are shallow igneous intrusions.

Smith and Shaw (1975) proposed that volcanic rocks could be used as regional guides to high-temperature geothermal systems. They calculated the heat contents of plutons from estimates of the pluton volume and radiometric ages of associated volcanic activity. The available energy was postulated to depend directly on the heat provided by the magma chamber. Smith and Shaw adopted the premise that magmas contribute little heat to the upper crust unless they form chambers. They assumed conductive cooling but recognized that hydrothermal convection would speed cooling while continued magmatic input would extend system life.

Magmas of different chemical compositions exhibit unique physical behaviors that influence the geometry of the plutons they form. Viscosity is one important, composition-dependent parameter in the movement of magma. In general, silicic melts are more viscous than mafic melts as a result of polymerization of SiO_4^{-4} tetrahedra. All melts show increasing viscosity as temperature decreases, but the viscosity of rhyolite increases faster with decreasing temperature than does the viscosity of basalt. Viscosity of silicic melts also decreases with increasing water content. Loss of fluid as a result of reduction in confining pressure may be sufficient to stop an ascending melt.

Because of both viscosity and crystallization relationships, basaltic melts tend to flow to the surface through relatively narrow conduits while granitic melts tend to crystallize before reaching the surface. Silicic melts may form plutons of considerable dimension and heat content. Figure 2 shows phase diagrams for the basalt and granite systems. Consider a liquid basalt on the saturated liquidus at a depth of about 12 Km, equivalent to about 4 Kb pressure. This melt will be starting to crystallize. If it is intruded into the upper crust with little heat loss to the wall rocks, it will reach the surface before it intersects the solidus curve and becomes completely crystallized. The effect of water in the basalt is shown by liquidus curves for 0, 2, and 4 percent H_2O (Figure 2a). Lower water content favors the ascent of the melt to the surface prior to crystallizing. The granite system (Figure 2b) behaves somewhat differently. If a melt at 4 Kb along the saturated liquidus ascends to the surface without losing heat, it will intersect the solidus curve at somewhat less than 2 Kb pressure.

The surface eruption of a granitic melt is favored by either an initial temperature above the liquidus temperature or a lower water content.

An overall conceptualization of magmatic systems was presented by Hildreth (1981). To summarize his thinking, magmatic systems are considered to be fundamentally basaltic since the heat of the system is derived from basalts originating in the mantle. Rocks of granitic composition are subsequently formed through either the process of fractional crystallization or fusion of pre-existing crustal material. Smith and Shaw (1975), Lachenbruch et al. (1976) and Hildreth (1981) all postulated that major silicic volcanic centers require continued thermal input from mantle-derived basaltic liquids to sustain high temperature convective hydrothermal circulation. Basaltic liquids will not ascend through granitic liquids because of their higher density. Therefore, basalts are thought to pond at the base of a volume of granitic melt and transfer heat to the granitic melt through conduction. On the surface, this phenomina results in a "shadow zone" where basalts surround but do not occur over a felsic volcanic center until the felsic melt has crystallized.

Models given by Hildreth (1981) relate different styles of magmatism to various amounts of thermal input and crustal extension. Systems that produce magmas of intermediate composition occur in non-extensional areas, with andesitic stratovolcanos such as those in the Cascades representing an early stage of development. Hydrothermal systems associated with mature mafic to intermediate volcanos occur at Mt. Lassen, California (Sorey and Ingebritsen, 1984), Crater Lake, Oregon (Blackwell and Steele, 1987), Medicine Lake, California and Newberry, Oregon (Sammel, 1981). On a world-wide basis, these magmatic systems support the majority of high-temperature convective systems. High basaltic flux from the mantle in areas of extension appears to produce large amounts of rhyolitic melt, leading to explosive eruptions and the formation of calderas. The best known examples in the U. S., all of which support high-temperature geothermal convection, are Long Valley, California (Sorey et al., 1978), Valles caldera, New Mexico (Hulen and Nielson, 1986), and Yellowstone caldera, Wyoming (Keith et al., 1978). Rhyolitic dome fields occur in areas of crustal extension and modest amounts of heat input. Examples of dome-field related hydrothermal systems are Roosevelt Hot Springs, Utah (Ross et al., 1982) and Coso Hot Springs, California (Bacon et al., 1980).

A determining factor in the efficiency of heat transfer from a magma body to an associated hydrothermal system is the depth at which the magma body resides. If the pluton is below a level where extensive fracturing can take place, heat transfer from the magma will be principally by conduction. At higher levels of the crust where fracturing is possible, heat transfer will occur mainly through convection of hydrothermal fluids.

Samples of the plutonic heat source for most high-temperature geothermal systems are rarely available for study. The most comprehensive data on the evolution of hydrothermal systems associated with pluton emplacement are in the literature on porphyry copper ore bodies. These plutons are normally intermediate to silicic in composition and emplaced at high levels in the crust.

Burnham (1979) presents a model for the emplacement of melts and associated hydrothermal processes developed by the expulsion of fluids from the magma. His model is for a granodiorite, with an initial content of 3% H_2O, intruded into a subvolcanic environment. Crystallization from the outer margins of the stock forms a carapace that becomes H_2O-saturated as the pluton cools.

Then, as crystallization proceeds, fluids are generated through the process of resurgent boiling, increasing the fluid pressure in the carapace. When pressures exceed the least effective principal stress plus the tensile strength of the rock, fractures are propagated, breccias formed, and heat and "magmatic" fluids are transferred to the wall rocks. The generation of fluids from the magma ceases when the pluton has crystallized. However, strong temperature gradients remain, and evidence (Taylor, 1974; Beane, 1983) shows that more dilute fluids, representing meteoric sources, form convective systems that, through time, penetrate into the pluton.

Since magma is a liquid and will not support fracturing, it is generally thought that hydrothermal fluids derived from meteoric water do not come into contact with the igneous heat source until the pluton has crystallized. Instead, these fluids derive their heat through a zone of conductive heat transport that surrounds the pluton, These relationships were nicely demonstrated by Taylor and Foster (1979) in an oxygen and hydrogen isotopic study of the Skaergaard intrusive complex and its country rocks. They showed that meteoric fluids circulated around the pluton but only penetrated it following crystallization.

Although dikes are not uncommon in geothermal wells, in only a few instances have the plutonic heat sources for geothermal systems been intersected by drilling. The best example available is The Geysers steam system located in northern California (Thompson, 1989). Here a composite felsic pluton underlies and parallels the geometry of the geothermal system. The upper part of the pluton also serves as part of the geothermal reservoir (Thompson and Gunderson, 1989). Moore (1992) found that fluid inclusions from the Geysers showed decreasing temperature and salinity with distance from the pluton. The data are consistent with a collapse of an earlier high-temperature, high-salinity hydrothermal system which probably had a highproportion of magmatic fluids, and its replacement by more dilute, lower temperature fluids.

It is clear that fluids of different origins contribute to active hydrothermal circulation systems (White, 1974). Although most dilute fluids have been ascribed a meteoric origin, deep acid systems and high-salinity components of some systems are most certainly of magmatic origin (Hedenquist, 1992).

PERMEABILITY/POROSITY

The recharge, discharge and recirculation volumes of geothermal systems are controlled by porosity and permeability of host rocks. The following discussion presents information on the formation of porosity and permeability through rock alteration and different rock fracturing mechanisms.

Dual-Porosity Model

The dual-porosity model considers fluids in geothermal systems to be distributed in both fractures and matrix pore space. The model has been applied in geothermal studies to explain production characteristics of vapor-dominated geothermal systems (Truesdell and White, 1973; Pruess and Narasimhan, 1982). Fractures are narrow zones, generally considered to have permeability that is laterally continuous along strike. This permeability is non-penetrative, meaning that fracturing does not homogeneously effect the rock mass. Matrix porosity consists of isolated pores and pores that connect with fractures through passageways defined by low permeability. While fractures provide communication within the reservoir and are the source of production, the principal reservoir storage is in the matrix porosity.

Hot water-, or liquid-dominated systems, are defined as those in which liquid water is the dominant mobile phase (White et al., 1971; Donaldson and Grant, 1981). Pressure gradients with depth in these systems are defined by hydrostatic pressure. Water-saturated matrix pores are of little consequence in the behavior of such systems unless fluids in the fracture become depleted. As pointed out by Pruess and O'Sullivan (1992) the matrix pores surrounding a fracture must be liquid saturated in order for the fluid to move within the fracture. If the matrix is under-saturated, capillary forces will move fluid from the fracture to the pore space. Fractures in a water-dominated system constitute the principal reservoir fluid storage as well as the principal source of production. In order to balance the fluid flux, fractures also represent the principal conduits for fluid recharge.

Vapor-dominated geothermal systems (White et al., 1971) have steam as the pressure-controlling and most mobile phase. Pure end-member systems are relatively rare; the best known are The Geysers, California; Lardarello, Italy; and Kamojang, Indonesia. These systems produce steam at pressures and temperatures that are close to the maximum pressure and enthalpy of steam. The buffering of these production characteristics indicates the presence of a liquid phase. White et al.'s original paper suggested a deep, boiling water table, but drilling evidence suggests that liquid water is stored within the matrix pores and flashes to steam as pressure is lowered through production. Within a vapor-dominated system, the principal volume of reservoir storage is located within the rock matrix, and the fractures are low-pressure conduits for steam flow into which the matrix water flashes. Both in the natural state and as a consequence of production, hot water-dominated systems may develop vapor caps or zones within the system that are vapor-dominated or vapor-rich (Donaldson and Grant, 1981; Ingebritsen and Sorey, 1988).

Conductively heated rocks with low permeability are classified as Hot Dry Rock (HDR). Pressures in these systems are generally defined by the hydrostatic gradient. Blocks within and marginal to active hydrothermal systems also can be included in this classification.

Alteration

Rock alteration is an extremely important process in high-temperature geothermal systems. Study of mineralogy and zoning relationships provides valuable insight into system dynamics and evolution that are of great importance in the exploration and assessment. Numerous comprehensive summaries of hydrothermal alteration processes and the application of hydrothermal alteration mineralogy in exploration and development have been written, but will not be discussed here. The reader is referred to Browne (1978) for an overview of alteration mineralogy and its implications. Bird et al. (1984) have discussed calc-silicate formation in active geothermal systems. Hydrothermal layer silicates are the focus of an important paper by Steiner (1968). Alteration processes will be considered here in terms of enhancement or reduction in porosity and permeability of confining rocks of the geothermal system.

Processes that Enhance Porosity.

Alteration processes that enhance porosity are hydrothermal dissolution and metamorphic reactions that result in a volume decrease with respect to initial phases.

Studies of high-temperature geothermal systems and hydrothermal ore deposits suggest that the most important reaction in increasing porosity involves solution of calcite or other carbonate species (Hulen et al., 1991; McDowell and Elders, 1983; Kuehn and Rose, 1992). Figure 3 shows solubility of calcite as a function of temperature and PCO_2. The solubility is retrograde with respect to temperature, that is, calcite is more soluble in cooler fluids. The solubility also increases as the PCO_2 increases. Not shown on this diagram are the effects of pH on solubility. Carbonic, hydrochloric, sulphuric and boric acids are present in geothermal systems. Organic acids may be important at temperatures of around 100° C. Fournier (1985a) provides an excellent review of carbonate geochemistry in geothermal systems.

Dramatic examples of the magnitude of calcite dissolution can be found in the outflow plumes from high-temperature systems. The volume of calcite dissolution and reprecipitation as travertine is particularly pronounced when cooling fluids flow through fractures in carbonate-rich rocks. Good examples are the deposits at Mammoth Hot Springs in Yellowstone National Park (Bargar, 1978) and Soda Dam adjacent to the Valles caldera, New Mexico (Goff and Shevenell, 1987). Osterberg and Guilbert (1991) calculated that one cubic kilometer of carbonate had been removed by dissolution from the Chimney Creek gold deposit in Nevada.

In contrast with the behavior of carbonates in solution, silica will precipitate under cooling conditions and be dissolved as fluid temperature is increased. Petrographic evidence shows that solution and deposition of quartz are on-going processes within active systems. The volume of silica that can be dissolved from active systems is often high and certainly has an effect on the overall porosity of the system. One need only to consider the large volumes of siliceous sinter and silica-cemented gravels associated with upflow zones in Yellowstone National Park (White et al., 1975). Therefore, while systems, or parts of systems, are heating one expects porosity and permeability, especially along fractures, to increase as a result of silica solution.

Prograde metamorphic reactions often result in a decrease in volume of mineral phases, but this is a research topic that has not been well covered in the analysis of porosity in active systems. Certainly the reaction of carbonates to form calc-silicates, with the evolution of CO_2, results in a volume reduction of mineral products. Another common volume-reducing reaction is the transformation of smectite to mixed-layer illite-smectite and then to illite. Since these transformations are normally accompanied by an increase in depth and overburden pressure, it is likely that newly developed porosity is partially eliminated through compaction.

Processes that Reduce Porosity.

Most high-temperature hydrothermal fluids are saturated with respect to silica. The most prominent aspect of discussions on the geochemistry of silica in active hydrothermal systems center on precipitation of silica from solution and its importance in the sealing of geothermal pathways (Fournier, 1985b). In contrast to carbonates, the solubility of silica increases over the temperature range associated with most hydrothermal systems. Therefore, the normal means of precipitation is the simple cooling of fluids. The physical result of this precipitation is either wholesale replacement of the host rock (silicification) or the formation of quartz veins. At temperatures above 340° C there is a region of retrograde solubility where the solubility of quartz would decrease with heating. This raises the possibility that the maximum temperature attainable in hydrothermal solutions may be limited by precipitation of quartz (Fournier, 1985b).

Boiling of hydrothermal solutions results in a reduction of the partial pressure of CO_2 and the deposition of calcite. This is a common process at the top of geothermal systems and often leads to formation of calcite with a diagnostic bladed habit. Veins that show these textures can be effectively sealed by the process. It is probably one of the principal reactions in the formation of self-sealed caps that confine hydrothermal circulation.

Precipitation of clay minerals also reduces permeability in active geothermal systems. Illite, in particular, forms within fluid flow channels at temperatures of greater than 200° C. Its formation may be stimulated by hydrothermal or tectonic brecciation that provides starting material of fine grain size. Illite may also develop through changes in the chemistry of fluids, particularly increases in acidity.

Tectonic Brecciation

Faults and fractures provide the permeability necessary for the development of hot water- and vapor-dominated geothermal systems. It is generally assumed that active fracutring is required to overcome the effects of hydrothermal sealing. Therefore, a great deal of attention has been given to locating and characterizing fractures through geological and geophysical means. Faulting and associated fracturing can be best understood as a response to tectonic stress as shown in Figure 4.

Any applied stress may be resolved into three principal stress components. In the Basin and Range province of the United States and most volcanic environments, the stress orientation is similar to that shown in Figure 4a; the greatest principal stress is vertical, and the strike of faulting and fracturing is perpendicular to the least horizontal principal stress. Under these conditions, normal faults develop. The other tectonic environment where geothermal systems are commonly found are compressive regimes characterized by strike-slip faulting. The stress orientations responsible for this style of faulting are shown in Figure 4b. In this case, both the greatest and least principal stress directions are horizontal. Important geothermal districts such as the Imperial Valley and The Geysers in the United States are hosted by this type of regional environment.

Regional stress appears to fit a model where the applied stress is homogeneously distributed over large areas (Zoback and Zoback, 1980). However, a geothermal system, characterized by high heat flow, upwelling hot fluids, and perhaps an increase in fracturing, would theoretically represent an anomaly within the region.

In situ stress measurements and active seismic surveys indicate that the stress orientation in at least some geothermal fields is different from the regional stress. Walter and Weaver (1980) performed a detailed study of earthquakes from the Coso geothermal field in California. They noted a difference in the fault plane solutions of earthquakes in the geothermal system from those events located outside the system. They determined that strike slip movement on nearly vertical fault planes occurred everywhere except in the geothermal system. The regional motion is right lateral along NW striking planes and left lateral along the NE striking conjugate planes. This is consistent with the greatest principal stress oriented horizontally approximately NS and the least principal stress also oriented horizontally and in an EW direction. Within the geothermal system the fault plane solutions show predominantly normal movement with a small strike-slip component along NNE-trending planes. This implies that the least principal stress is horizontal and oriented WNW and that the greatest principal stress is vertical.

A change in stress orientation can also be documented in the

Roosevelt Hot Springs (RHS) geothermal system in Utah. This system is located within the transition zone between the Colorado Plateau and Basin & Range Provinces. In a nearby study of earthquakes, Arabasz and Julander (1986) have determined that the regional orientation of the least principal stress is 102 degrees, consistent with the EW extensional tectonics of the Basin & Range province. Geologic mapping of the area around RHS (Fig. 5) shows that Holocene normal faulting to the west of the geothermal system is north- to NNE-trending, consistent with the results of Arabasz and Julander.

However, much of the geothermal production at RHS is controlled by EW normal faults as exemplified by the Negro Mag fault (Fig. 5). Nielson et al. (1986) demonstrated that this fault is located along the axis of a complex graben. This structure would not form under the present regional stress orientation; it requires a least principal stress oriented approximately NS, at nearly a right angle to the regional orientation.

Pre-production seismicity from RHS is also shown in Figure 5. The earthquakes are clearly located along faults that are parallel to the Negro Mag fault. Analysis (G. Zandt, written communication) shows that the movement on the faults is predominantly normal with a strike-slip component. These data are consistent with the fault orientations discussed above and imply a roughly NS orientation of the least horizontal principal stress which is nearly perpendicular to the regional direction. It is also notable in Figure 5 that the earthquake swarms continue up to but do not cross the NNE-trending Opal Mound fault. The Opal Mound orientation is consistent with formation under the regional stress system. Sinter deposits and production wells along this fault also indicate that it contains geothermal fluids. Dry holes and a decrease in heat flow to the west suggest that the Opal Mound serves as the western boundary of the geothermal system. Data from well bore breakouts at RHS (Allison and Nielson, 1988c) also demonstrate that the horizontal least principal stress within the geothermal system is oriented approximately NS and not in the regional direction.

In conclusion, the data from both RHS and Coso geothermal fields demonstrate that there is a difference in the orientation of the stress within these geothermal systems from the regional stress environment. These observations require 1. different forces within the geothermal system and 2. mechanisms of structural decoupling of the geothermal system from the regional stress. At RHS, this decoupling apparently takes place along the Opal Mound fault to the west. Continuity of the local stresses in other directions is not known.

Faults and fractures are mechanical heterogeneities. Their strength is a function of the character of brecciation during fault movement and of mineral deposition along the features. It is not uncommon to find fractures that have been totally sealed by silica and are tougher than the host rock. However, fractures that exhibit high fluid to rock ratios are zones of weakness relative to the surrounding rock. As such, they serve as zones of stress release through faulting, and, by this mechanism, permeability is maintained rather than lost through the process of hydrothermal mineral deposition.

Allison and Nielson (1988a, b) have discovered that in many geothermal wells there is a dramatic change in stress orientation with depth. They have documented that, in some instances, this change takes place across faults. This, in addition to the data from RHS cited above, makes it clear that geothermal faults, due to their inherently weak nature, serve as zones of decoupling between different stress systems. In addition, Allison and Nielson found that there were often variations in stress orientation between wells within systems. The problem remaining is to explain the reason that stress may change orientation at the boundary of a geothermal system or within the system.

The evaluation of data from the Baca system (Nielson, 1989) shows that the stress due to temperature gradients is significant and in many cases may be the principal cause of stress variation within a geothermal system. In some instances, differences in fluid may also be important, but they were much less so in the example analyzed. Stress due to upper level volcanic processes may be important in some fields and promote a difference in orientation from the regional environment.

It has been shown that faults within a geothermal system have low strength due to the presence of hot fluids. Theoretically the regional stress is distorted by the presence of a geothermal system. This could be used as an exploration tool; however, there is not at present any evidence that this distortion process is measurable. The evidence from RHS does demonstrate, however, that the geothermal system is effectively decoupled from the regional stress along a single fault zone on one side of the field. This change in orientation should be considered in an effective exploration and development strategy.

One of the principal problems in exploration concerns the location and orientation of fractures that could provide geothermal production. Although determination of stress orientation will not locate fractures, it makes it possible to predict the orientation of fractures that are forming under the present-day stress system, or that will be kept open by the in situ stresses. This allows directional drilling programs to be designed such that wells cut across the fracture trend resulting in the maximum opportunity to intersect an open fracture.

It can be visualized that the geothermal fluid in a fracture exerts pressure against the fracture walls, helping to keep the fracture open. Removal of fluid from the fracture could result in a decrease in permeability. The solution to this problem would be injection along the structure to maintain fluid pressures, but care must be taken to avoid significant enthalpy decrease.

It is also evident from this analysis that the processes of production and injection will change the stress orientation in a reservoir as the temperatures are modified. This could have the effect of generating new permeability depending on the positions of the production and injection wells with respect to the stress system.

Hydrothermal Brecciation

Surface expressions of hydrothermal explosions (Muffler et al., 1971; Hedenquist and Henley, 1985) and their subsurface breccias (Grindley and Browne, 1976; Hulen and Nielson, 1988) are common features in geothermal fields. The breccias often show evidence of fluid flow such as rounding of fragments and flow foliation in comminuted open-space fillings. Identification of these breccias during drilling is often obscured by the lack of core. These are termed phreatic breccias by Sillitoe (1985) and are distinguished from magmatic-hydrothermal breccias that were described previously as resulting from resurgent boiling above plutonic bodies.

In general, breccias can form naturally through a variety of pressure release mechanisms that result in boiling at depth. They are developed within fault zones that contain geothermal fluids whose temperatures have exceeded the boiling point with depth curve. Phreatic explosions can also take place as a consequence of production.

Hulen and Nielson (1988) described hydrothermal breccias in the Jemez fault zone near the Valles caldera in New Mexico and proposed a model for their formation. The breccias consist of angular to rounded clasts, that average about 1.5 cm in diameter, in a rock-flour matrix. Both the rock flour and the clasts are intensely altered with the principal secondary phases being quartz and illite. Vapor- and two-phase liquid plus vapor fluid inclusions are present and allowed a determination of the thermal history leading up to formation of the breccias. Hydraulic rupture of the rock requires that the fluid pressure exceed the least principal stress plus the tensile strength of the rock. It was possible to estimate the pressures required to break the rock on the basis of nearby hydrofracture experiments. A boiling point with depth curve was then calculated at pressures required to brecciate the rock. This curve is shown in Figure 6 and exceeds the boiling point curve based on a hydrostatic pressure gradient. Fluid inclusion homogenization temperatures from the breccias are also plotted on Figure 6 and show that these data are compatible with temperatures that exceeded the boiling point curve but not the temperature required to fracture the rock. This degree of superheating could only take place where the rocks had been effectively sealed. This allowed fluid temperature to reach the point where the vapor pressure was sufficient to rupture the rock. The triggering event was probably an earthquake that instantly lowered the pressure resulting in flashing of fluids to steam and brecciation of the rock. Alternatively, the brecciation could have been initiated by the superheating of the rock. In either case, subsequent flashing of the contained water to steam both brecciated and altered the rock. Finely comminuted rock particles were easily and rapidly altered to illite, a process which decreased the porosity of the breccia soon after its formation.

Lithologic Controls

Lithologic variations are responsible for much of the fluid-flow heterogeneity seen in active geothermal systems. The differences are generally related to the ability of different lithologies to sustain open fractures.

There are strong lithologic controls on fracturing at The Geysers steam field. Sternfeld (1989) demonstrates that fractures are sustained through graywacke, but not through interbedded argillic horizons. These relationships are shown in Figure 7 where conjugate fractures are bounded by argillite below and by lithologic variations in the graywacke reservoir rock above.

Grindley and Browne (1976) have summarized some of the lithologic controls on fluid production that stem largely from the ability of different lithologies to support open fractures. They cite fractured andesites at Kawerau, New Zealand, rhyolitic pyroclastics at Wairakei, New Zealand, welded tuffs at Matsukawa, Japan, and scoreaceous contacts between basalts and hyaloclastites at Reykjanes in Iceland.

Impermeable lithologies are often as important to the hydrology of geothermal systems as the permeable rocks that comprise the reservoir volume. Hulen et al. (1989) have shown that a Paleozoic sedimentary sequence, consisting of shales, sandy shales, and carbonates, vertically separates hydrothermal convection systems in the Valles caldera of New Mexico. Figure 8 shows lithologic relationships in scientific corehole VC-2b. The section of the well above about 750 m is composed of Quaternary volcanic and volcanoclastic rocks erupted during the formation of the Valles caldera. These rocks have been intensely altered by hydrothermal fluids to assemblages of quartz-sericite at the top passing into chlorite-sericite in the lower portion of the section. Also fracturing is abundant through the volcanics. The sedimentary section shows a dramatic decrease in the intensity of alteration and fewer preserved fractures. Thermal gradients through this zone also suggest a conductive heat flow regime attesting to the lack of fluid circulation. Beneath the sediments is Precambrian granite where the intensity of alteration again increases and excellent examples of open veins are preserved in core. Water entries were found in this lower portion of the well, and fluid samples support the physical separation of this higher-temperature circulation system from the hydrothermal system in the volcanic section.

The above example points out also the ability of granitic rocks to serve as geothermal reservoirs. Crystalline rocks serve as some of the best reservoirs at Roosevelt Hot Springs, Utah (Nielson et al., 1986); Zunil, Guatemala (Adams et al., 1990); Coso, California (Bishop and Bird, 1987; Wright et al., 1985); and The Geysers, California (Thompson and Gunderson, 1989). This is largely due to the brittle nature of granite at temperature conditions of hydrothermal systems and low susceptibility to hydrothermal alteration.

Halfman et al. (1984) contrast the effects of different lithologies in the Cerro Prieto field on fluid flow. A thick shale unit, that is relatively impermeable, confines the flow of geothermal fluids to underlying sandstones. Where the shale unit is sandy, it allows the fluids to flow into higher sandstone units.

System Margins

The margins of geothermal convection systems respond differently under production, and this serves to illustrate some of the processes that are taking place. The typical model of a system has a cap and sides that are formed of hydrothermally altered rock with low permeability, typically termed a cap or "self-sealed" zone. Vapor-dominated systems require low-permeability margins; however, the different responses of water-dominated systems suggest that capping and sealing may or may not be present around all or parts of the convective system.

At Wairakei, mudstones have been suggested to act as a cap, but their existence is not relevant in the production response of the system. Because of the motion of the freewater surface, the field responds as if it were unconfined (Donaldson and Grant, 1981). Similar results were reported for Momotombo (Dykstra and Adams, 1977).

At Cerro Prieto, Elders et al. (1984) report "at the top of the reservoir detrital or authigenic clay minerals, like montmorillonite and kaolinite, are progressively replaced by pore-filling chlorite, illite, and especially calcite."

The development of a cap at the Salton Sea field has been studied in detail (Moore and Adams, 1988). They suggest that initially, the cap consisted of low permeability lacustrine and evaporite units. Subsequently, underlying deltaic sandstones were incorporated into the cap through the deposition of calcite and anhydrite that reduced their permeability.

Structural origins of system caps have also been proposed. Nielson and Moore (1979) showed how low-angle faulting at the Cove Fort-Sulphurdale geothermal systems in Utah could serve as effective cap on the high-temperature convective system.

SUMMARY

This paper has summarized some of the more important physical aspects in high-temperature hydrothermal convection systems. Shallow plutons provide heat, and in some cases, volatiles and fluids. Andesitic volcanos have the strongest association with magmatic fluids. Fluids and volatiles are contributed by the pluton up to the time that it is crystallized. Normally, the magmatic fluids mix with meteoric fluids, and, as crystallization proceeds, the meteoric component increases and then dominates. Silicic dome complexes and continental silicic calderas have either vented their fluids in pyroclastic eruptions or had low fluid contents to begin with because associated hydrothermal systems do not have large magmatic components.

High-temperature systems are favored by large plutons that are emplaced relatively close to the surface. In the U. S., they tend to be associated either with large caldera complexes or rhyolite dome fields. On a world-wide basis, mature andesitic volcanic complexes, underlain by shallow intrusions of dioritic composition, host significant active systems. Geologic models for such systems are based on those proposed for porphyry copper deposits.

Porosity and permeability control hydrothermal circulation as well as the recharge and discharge components of the system. The dual-porosity model provides a framework for understanding fluid-rock relationships. In most liquid-dominated reservoirs, fractures provide both reservoir storage and major fluid flow conduits. In vapor-dominated systems, reservoir storage is principally in the rock matrix, while the fractures again serve to connect the different portions of the reservoir. Fractures also govern recharge and discharge paths of the system.

The importance of fracturing in hydrothermal circulation results from the tendency of systems to seal themselves through the precipitation of alteration phases. This process dominates at system margins where temperature gradients are steep and silica is deposited as geothermal fluids cool. Within the system, recurrent fracturing is required to keep fluid-flow paths open. Mineral precipitation at system margins forms a confining cap in some systems, where lithologic changes serve the same role in others. Although much of the fracturing is of tectonic origin, hydrothermal brecciation is equally important in many systems.

Stress orientation within some liquid-dominated systems has been found to be different from the regional applied stress. This may result from the presence of a buried plutonic body or from differences in temperature.

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The preparation of this paper was supported by the University of Utah Research Institute. Jeffrey B. Hulen reviewed and significantly improved the manuscript.

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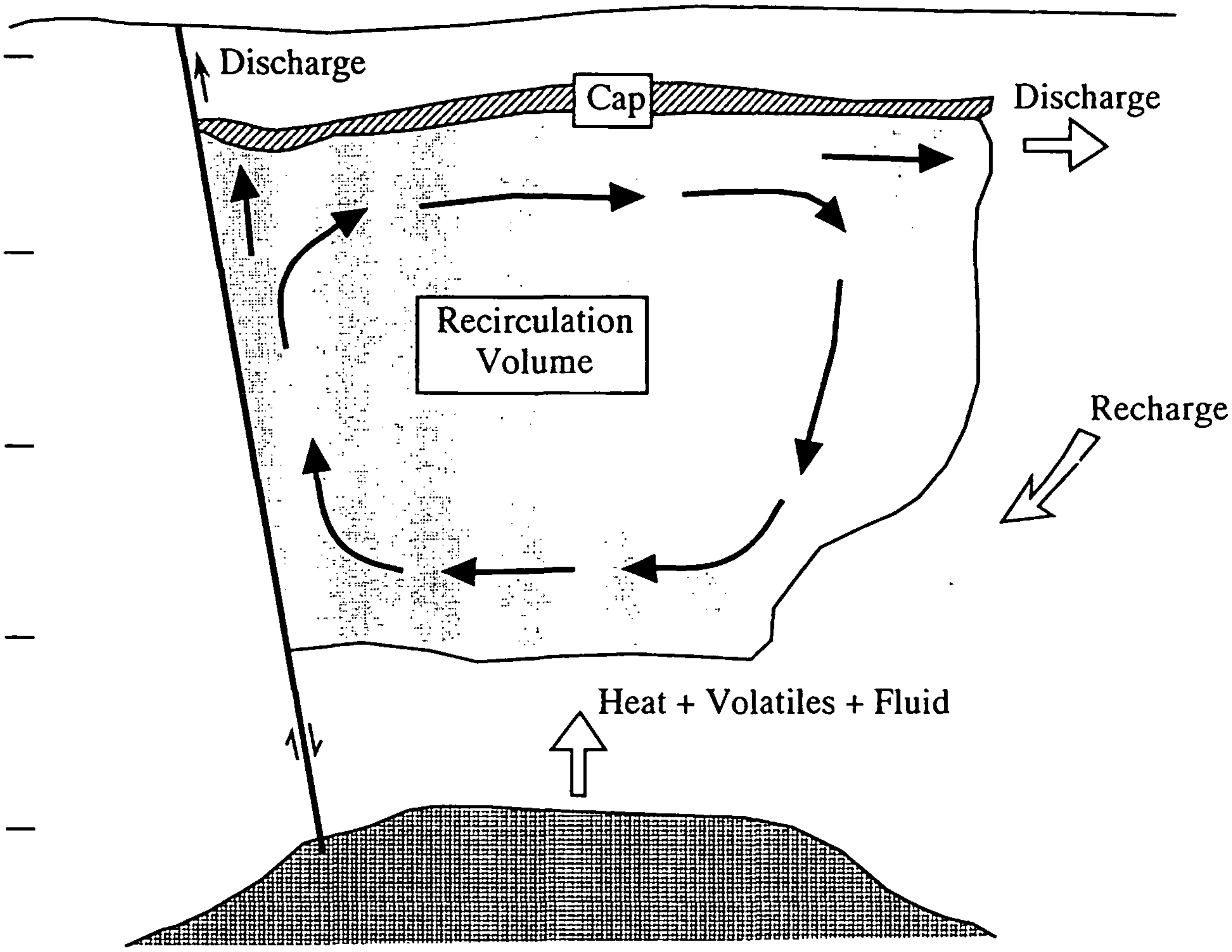


Figure 1. General model of a high-temperature hydrothermal convection system.

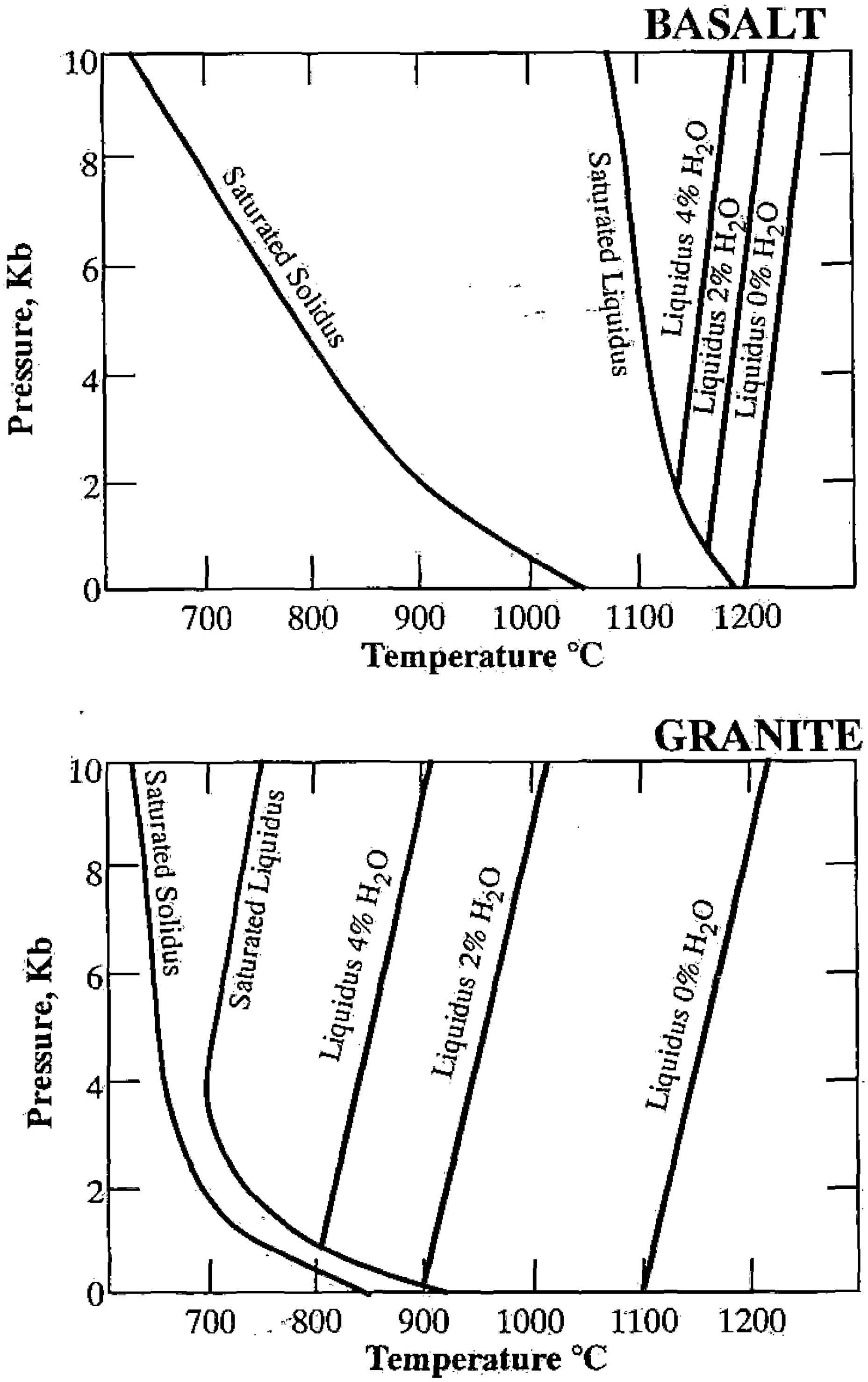


Figure 2. Phase relationships for rocks of basaltic composition (2a) and granitic composition (2b). (from Harris, Kennedy and Scarfe, 1970)

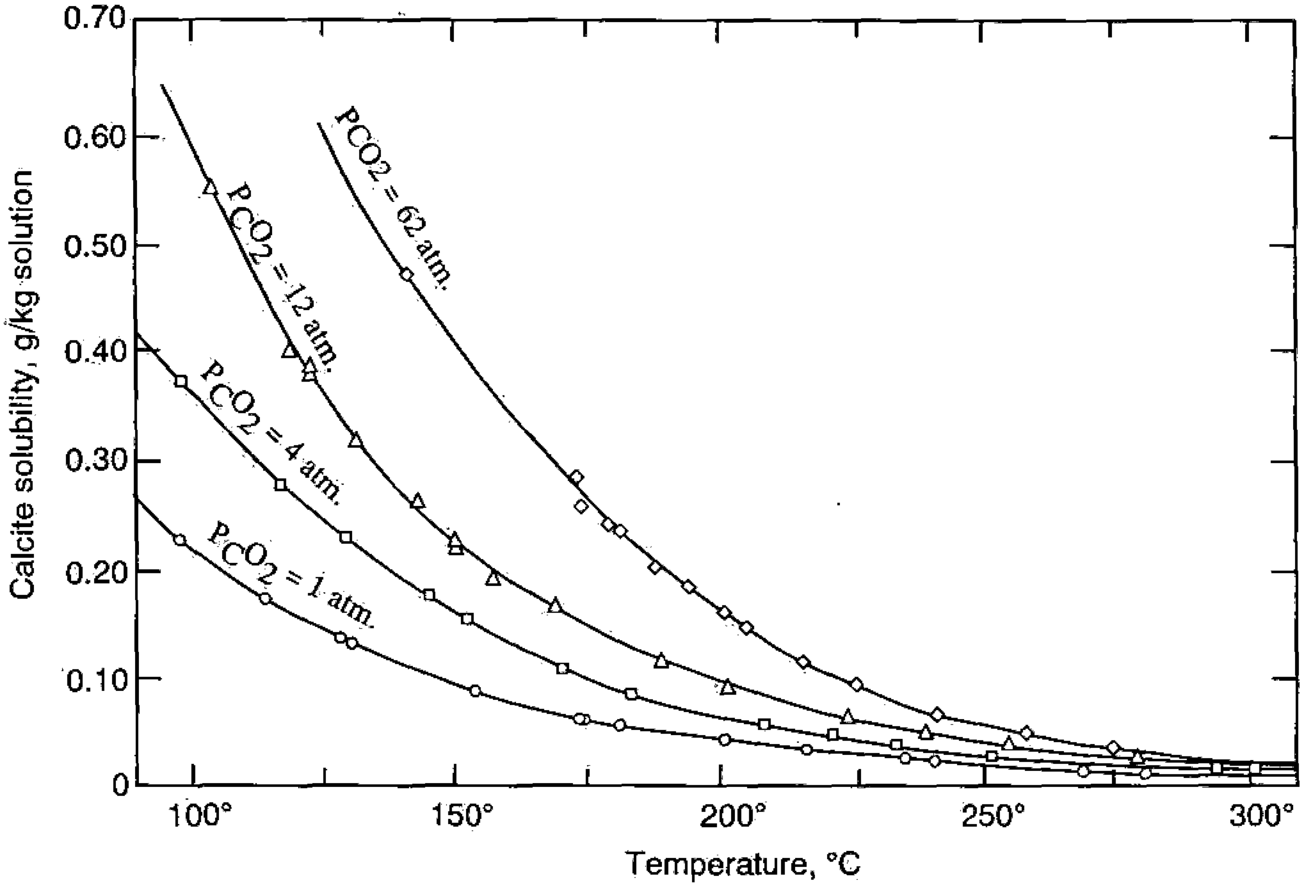
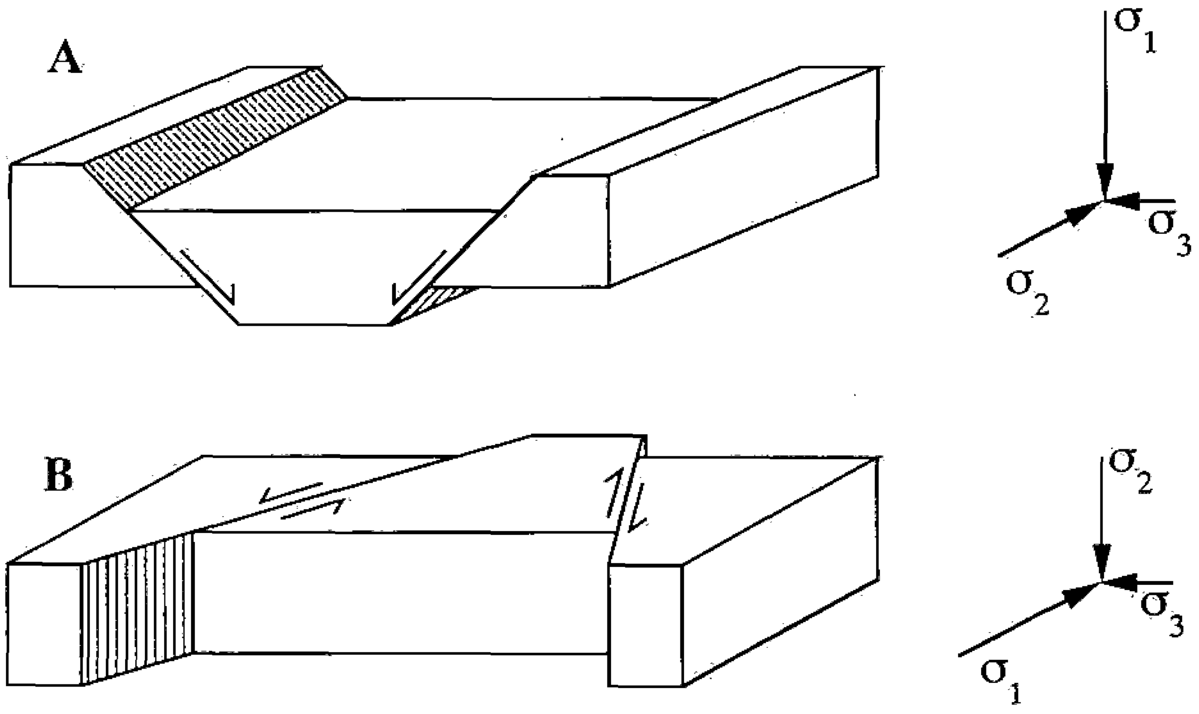


Figure 3. The solubility of calcite in water up to 300°C at various partial pressures of carbon dioxide. (from Ellis, 1959)



A: Normal fault
B: Strike-slip fault

Figure 4. Relationships between stress orientation and character of faulting.

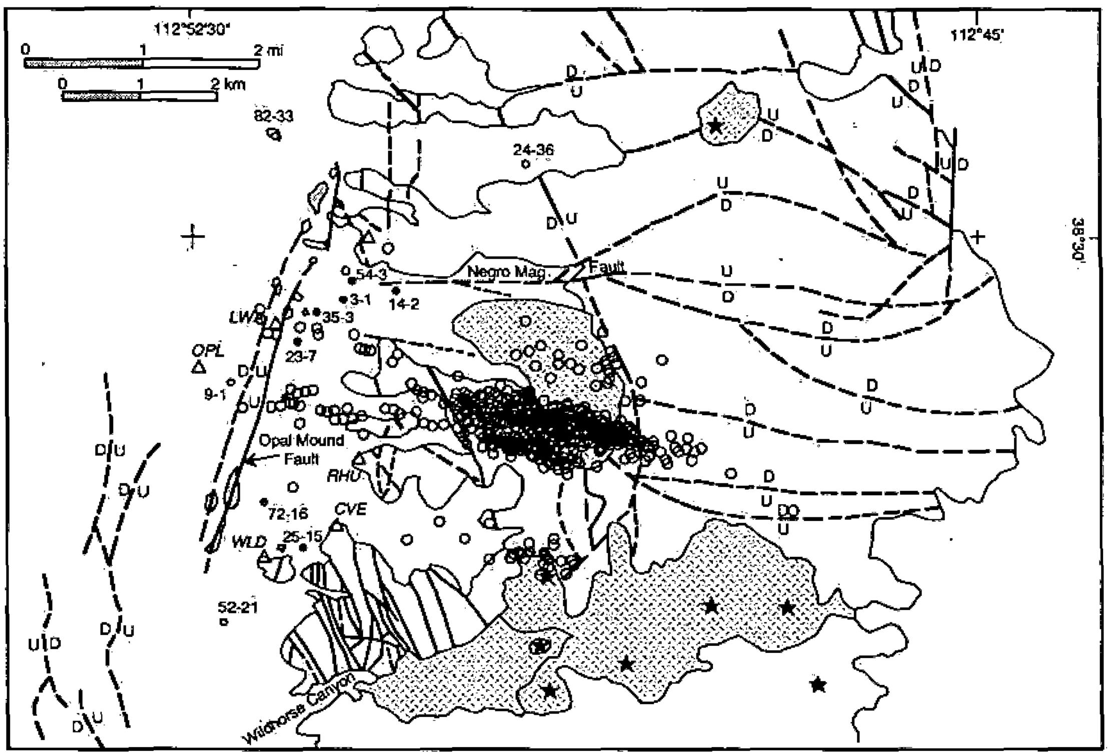


Figure 5. Geothermal wells, faults and earthquakes at the Roosevelt Hot Springs geothermal system, Utah. Pleistocene rhyolite is patterned; stars show the location of vent area.

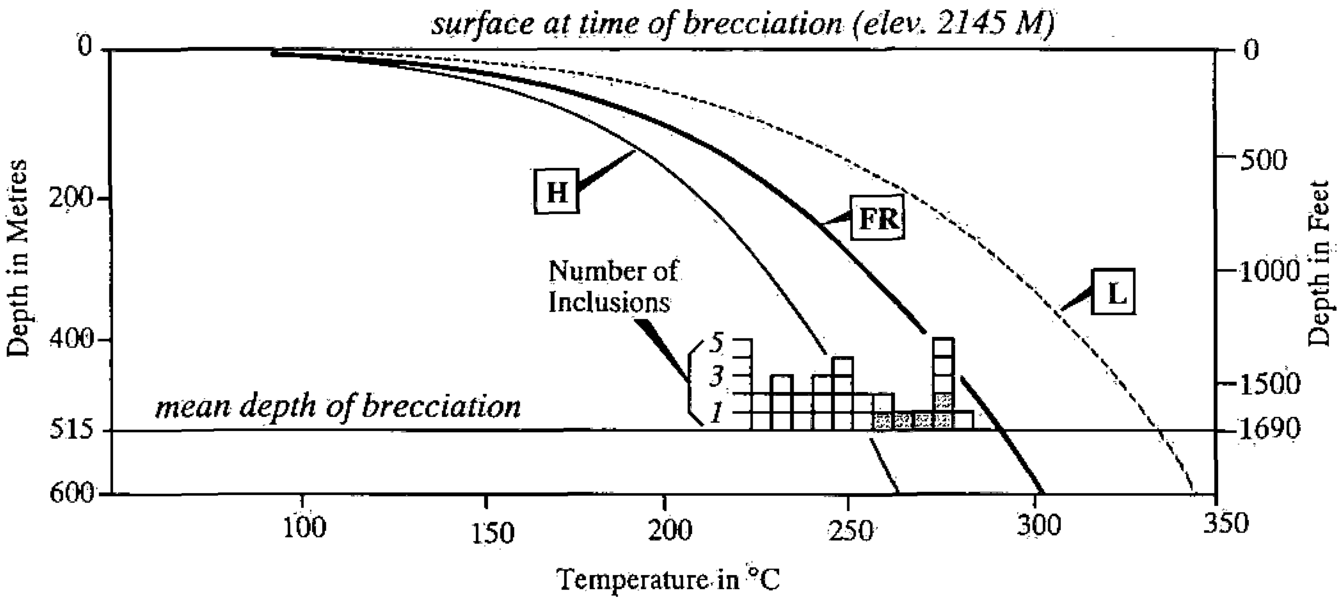


Figure 6. Boiling point curves for hydrostatic (H), lithostatic (L), and pressure required to fracture (FR) and homogenization temperatures for dilute, fluid inclusions in the VC-1 hydrothermal breccias. Crosshatching indicates primary inclusions.

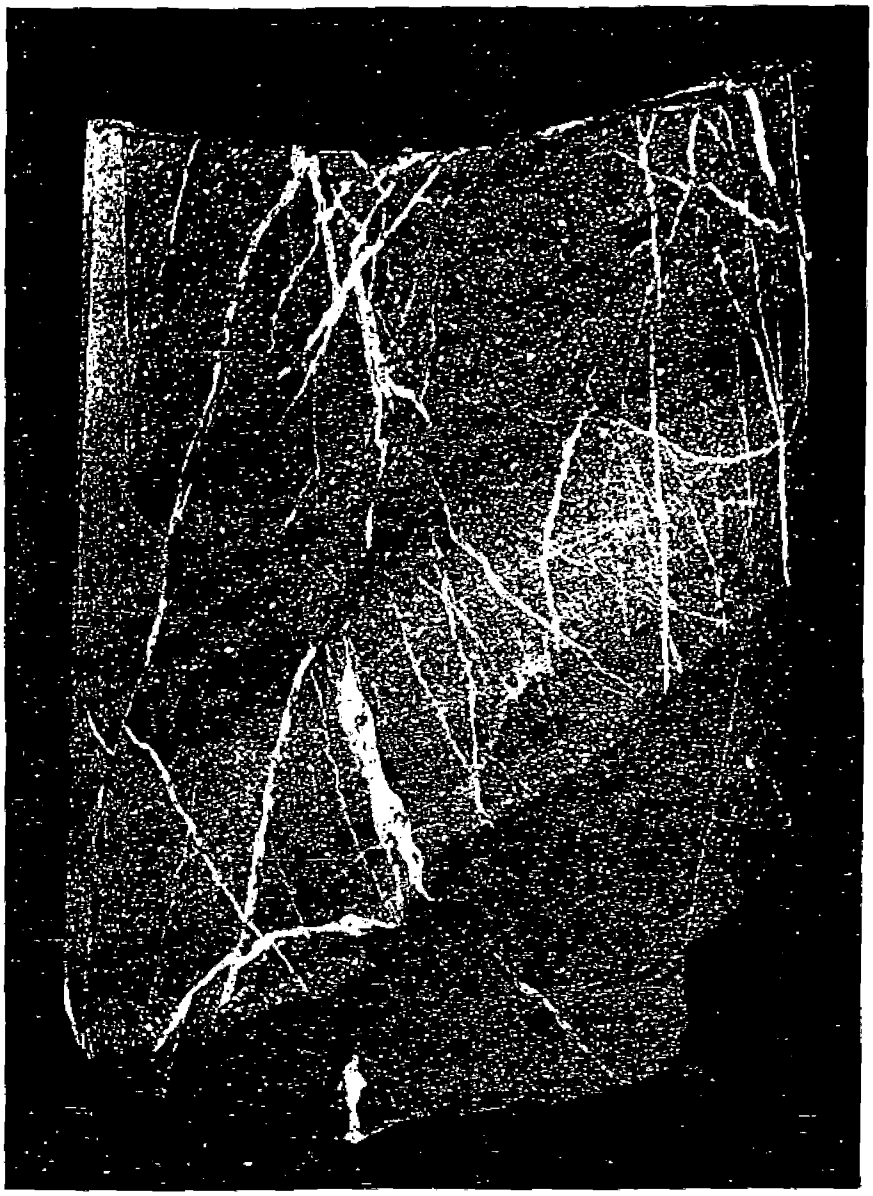
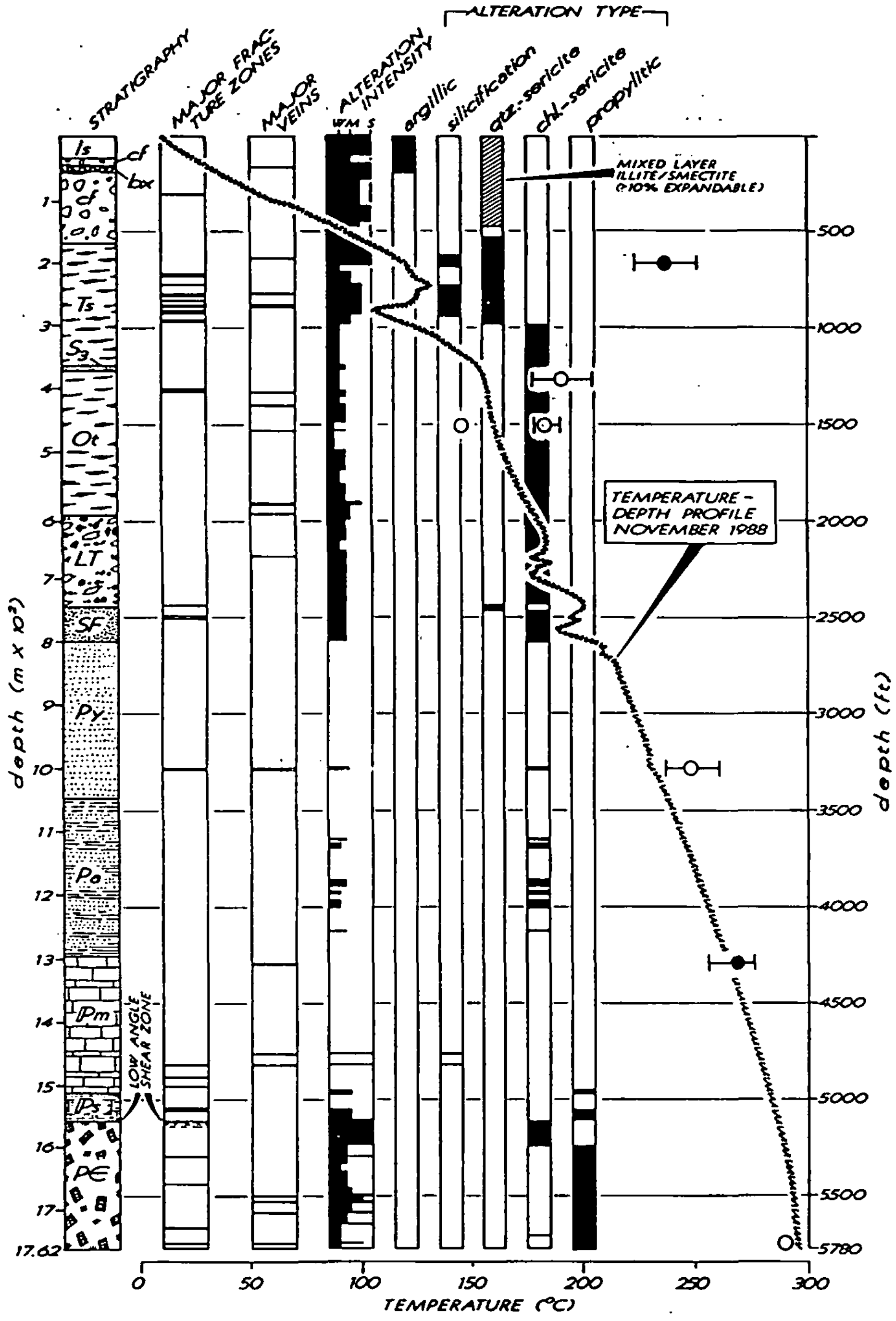


Figure 7. Photograph of core from well Prat. State 12 in The Geysers geothermal system, California. Note the lithologic control on fracture formation.



EXPLANATION

○ ● FLUID-INCLUSION HOMOGENIZATION TEMPERATURE (RANGE AND MEAN): CLOSED=PRIMARY, OPEN=SECONDARY

STRATIGRAPHIC DESIGNATIONS: ls—LANDSLIDE DEBRIS; cf—CALDERA-FILL DEBRIS-FLOW DEPOSITS AND VOLCANICLASTIC SANDSTONES; bx—HYDROTHERMAL BRECCIA AND DACITE PORPHYRY ZONE; Ts—TSHIREGE MEMBER, BANDELIER TUFF; S_1—S_3 CLASTIC DEPOSITS; Ot—OTOWI MEMBER, BANDELIER TUFF; LT—LOWER TUFFS; SF—SANDSTONE, SANTA FE GROUP; Py—PERMIAN YESO FORMATION; Po—PERMIAN ABO FORMATION; Pm—PENNSYLVANIAN MADERA LIMESTONE; Ps—PENNSYLVANIAN SANDIA FORMATION; P€—PRECAMBRIAN PORPHYRITIC QUARTZ MONZONITE.

Figure 8. Lithology and alteration in well VC-2b, Valles caldera, New Mexico (Hulen et al., 1989).

Russian-American Monograph on Geothermal Energy

To: Wilfred Elders, Hugh Murphy, John Lund
and American Co-Authors

Subject: NewsMemo No. 12 Date: 12 April 1993

In NewsMemo No. 11 of 30 September 1992, I summarized the status of our Russian-American Monograph and the discussions with the Russian editors on how to get going on initiating preparation of the Chapter drafts. The two major problems seemed to be (1) the means for communications between chapter co-authors for exchange of ideas and text drafts and (2) how to get the drafts in the respective languages translated. Since then things have improved somewhat: more pairs of authors have initiated communications and DOE is assisting us in making translation services available at Sandia. The first two Russian drafts (for 2.2 and 2.8) are now in the process of translation.

The second topic was preparations for the International Symposium in Saint Petersburg 21-27 June 1993. It is our understanding at this late date that all U.S. Co-Authors have been invited to send Abstracts for the program. It appears that only a few authors will be able to make the trip. We are hoping that DOE will be able to support at least the three volume editors so that they can present Status Reports of the Volumes on the respective topic days and meet with their Co-Editors to finalize the procedures for how to get the Volume drafts reviewed and revised. In particular, we need to get Wilf Elders together with V. Kononov to redirect completion of Chapter Outlines for Volume 1 and start compilation of drafts by Section between the Co-Authors.

I have just received the enclosed letter to the Russian authors and chapter status report from Yuri Dyadkin and wish to pass them on to you quickly for your information and response. We need to get going on the chapters and prepare at least a rough draft of our Sections in time for the respective volume editors to prepare a "camera-ready" paper for presentation at the Symposium.

For Action Items, I request two efforts from each of you: (1) let your volume editor know where you are with respect to having an "agreed-upon" Outline with distribution of responsibility for first drafts of the Sections and send him a rough draft of any of your Sections for the Status paper; and (2) let me have your response to Dyadkin's INFORMATION on Chapter Preparation ... so that we can respond quickly with a U.S. version. Please also note your preferred telephone and Fax numbers and if available, your E-mail address. I will try to get, if possible, the U.S. Embassy in Moscow and the Consulate in St. Petersburg to act as a center for distributing Faxes and/or E-mail to our co-authors.

Russian Geothermal Association
199026 Saint Petersburg

15 March 93

I am writing to you as one of the co-authors of the Russian-American Monograph "Geothermal Energy" with information about the status of the project and with some suggestions.

Two years have gone by since the start of this very difficult project. It is moving forward very slowly. In 1991, almost all of the 27 brief (often - very brief) Outlines of the Monograph from the American co-authors remained unanswered. This not very polite sluggishness offended and "cooled off" our American colleagues. In 1992, on the other hand, we have a right to be perplexed: for the detailed Outlines of the chapters of Volumes 2 and 3 (you have the Outline for your chapter if it pertains to these two volumes) we have received from the USA after a year - only 4 or 5 "responses".

The International Geothermal Association expected to obtain financial support from the American administration for translations of the Russian texts and so forth. Alas! IGA has no money even for minimal support of the International Symposium in St. Petersburg and chose not to include it in their plans. (Symposium will take place in any case!)

The difficulty: we need not simply a response, but <u>productive contact</u> 27 to 27! A consoling example: from contact in 1989 with "Pergamon Press", I opportunely prepared a chapter in a 5-volume monograph for publication in 1990 (international mining encyclopedia), 300 authors). After 2 years of silence, I recently was informed that publication will be in June 1993 instead of 1990! and this is "Pergamon Press", to all authors by radiotelephone, contact at symposia, and so forth. And our American colleagues by no means can understand why Russian co-authors in place of "lengthy" post do not want to use for forwarding text of their chapters such simple means as "Fax" or diskettes? Again they are requesting from me a list of Fax numbers of all authors. It is not possible for our colleagues to understand that for our authors who have important information and new technical ideas, may not have such things as Faxes, in the office.

Our real chance is direct contact of all authors at the Geothermal Symposium in June. At this time it is necessary to have prepared text of our parts of the chapters (it would be good - if there were some translations!) for objective discussion with the co-authors. We will meet. We will discuss. We have three possibilities: give up totally, give up on participation on "non-prepared" chapters, or try harder.

Now, the main point - the Abstracts of our presentations specific (hopefully) to the content of the chapter. We have now received 25 applications from foreign participants from many countries. Around 30 offers for papers, mostly with Abstracts. But, - not one offer for a paper from the co-authors of the Monograph! Offers of papers, for the most part, are for reviews or very specific problems.

We are awaiting your Abstract. On one page, camera ready. The paper for the Proceedings, from 10-12 pages, also camera-ready, should be turned in at the Symposium. The book of Abstracts (at the Symposium) and the Proceedings (1994) will be published by our Institute in Russian and English originals, without translation.

We await your Abstracts and registrations.

With best wishes,

Prof. Yu.D. Dyadkin
VicePres Orgcomm
President RGA

INFORMATION
on Chapter Preparation of the Russian-American Monograph "Geothermal Energy"

15 March 93

Chapters of Volume 1 on the Russian part are written and for a full year - in the USA. Our colleagues are working on translation of the Russian texts, complaining, that the chapters were written without agreement between the co-authors on the plans and distribution of responsibility on the Sections. They insist on these agreements.

For Volume 2:

Chapter 2.1. P. Kruger (Stanford) and A. Kiryukhin (P.-Kamchatka) - written in both languages.
Chapter 2.2. J. Rowley (Los Alamos) and B. Kudryashov (St. Petersburg) - written in Russian and sent to USA.
Chapter 2.3. M. Gulati (Unocal) and Yu. Pariisky (St. Petersburg) - written in Russian.
Chapter 2.4. B. Robinson (Los Alamos) and T.G. Grebenshchikova (Moscow) - contact of authors made - text not in preparation.
Chapter 2.5. R. Horne (Stanford) and A. Shurchkov (Kiev) - No text.
Chapter 2.6. R. Veatch (Amoco) and N. Slyusarev (St. Petersburg) - written in Russian.
Chapter 2.7. H. Murphy (Los Alamos) and Yu. Dyadkin (St. Petersburg) - contact made, exchange of text by authors.
Chapter 2.8. P. Cheng (Hawaii) and S. Gendler (St. Petersburg) - contact made, exchange of texts by authors.
Chapter 2.9. S. Sanyal (Richmond) and E. Boguslavsky (St. Petersburg) - No text.
Chapter 2.10. J. Dunn (Sandia) and V. Sugrobov (P. Kamchatka) - contact made, no text.

For Volume 3:

Chapter 3.1. G. Huttrer (Klamath Falls) and B. Kozlov (Moscow) - text written in Russian and sent to USA.

Chapter 3.2. R. DiPippo (Dartmouth) and A. Shurchkov (Kiev) - received English text from American co-author.

Chapter 3.3. R. Campbell (Ben Holt) and O. Povarov (Moscow) - No information.

Chapter 3.4. K. Nichols (Barber-Nichols) and Yu. Petin, A. Bezizvestnikh (Novosibirsk) - No text.

Chapter 3.5. C. Bleim (Idaho) and V. Trusov (Moscow) - No information.

Chapter 3.6. G. Culver (Klamath Falls) and B. Kozlov (Moscow) - Russian text posted to USA.

Chapter 3.7. K. Rafferty (Klamath Falls) and V. Krasikov (Moscow) - Russian text requires shortening.

Chapter 3.8. D. Trexler (Reno) and F. Sharfutdinov (Makhachkala) - No information.

Chapter 3.9. R. Schoenmackers (N.M.St.U.) and A. Perederii (Moscow) - No information.

Chapter 3.10. J. Lund (Klamath Falls) and V. Adilov (Moscow) - Russian text sent to USA.

Chapter 3.11. D. Carey (Brea) and B. Ivanov (St. Petersburg) - contact made, Russian text exists.

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1GEOSYS.MS 3/18/93

NATURE OF GEOTHERMAL SYSTEMS

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INTRODUCTION

This paper will investigate some of the more important physical aspects of hydrothermal convection systems. Elder (1965), Henley and Ellis (1983) and Norton (1984) provide reviews of the character of hydrothermal systems.

The paper by Elder (1965) provides a useful discussion of the elements of a geothermal system: a heat source, recharge system, recirculation system, and a discharge system. These elements are diagrammatically shown on Figure 1. Studies of natural systems show that the magmatic heat source is also often also a source of volatiles and fluids. The recirculation system, or reservoir volume is the focus of most studies of high-temperature systems. Convective circulation is most often controlled by faults and fractures and driven by buoyancy differences resulting from temperature differences. Recharge takes place along fractures as well as through the matrix of permeable rocks. Discharge is either to the surface or as a plume in the subsurface (Goff et al., 1988).

This paper will discuss magmatic geothermal heat sources and permeability/porosity relationships. Since the recharge, discharge and recirculation systems all depend on rock permeability, the formation and destruction of permeability and porosity will be presented in a generic context, as processes generally applicable to different components of the hydrothermal convective system.

HEAT SOURCE

Although deep circulation of fluids in zones of thin crust and high heat flow also support geothermal systems in many parts of the world, most notably the Basin & Range province of the western United States (Wright et al., 1989), the heat sources for most high-temperature hydrothermal systems are igneous intrusions into the shallower levels of the crust.

Smith and Shaw (1975) developed the idea of using volcanic rocks as regional guides to high-temperature geothermal systems by estimating the heat contents of plutons from estimates of the pluton volume and radiometric ages of associated volcanic activity. The available energy was postulated to depend directly on the heat provided by the magma chamber. Smith and Shaw adopted the premise that magmas contribute little heat to the upper crust unless they form chambers. They assumed conductive cooling but recognized that hydrothermal convection would speed cooling while continued magmatic input would extend system life.

Magmas of different compositions exhibit different physical behaviors that influence the geometry of the plutons they form. Viscosity is one important, composition-dependent parameter in the movement of magma. In general, silicic melts are more viscous than mafic melts as a result of polymerization of SiO_4^{-4} tetrahedra in the silicic melts, where cation concentrations are relatively low. All melts show increasing viscosity as temperature decreases, but the viscosity of rhyolite increases faster with decreasing temperature than does the viscosity of basalt. Viscosity of silicic melts also decreases with increasing water content. Loss of fluid through the process of retrograde boiling may be sufficient to stop an ascending melt.

Figure 2 shows phase diagrams for the basalt and granite systems. Consider a liquid basalt on the saturated liquidus at a depth of about 12 Km, equivalent to about 4 Kb pressure. This melt will be starting to crystallize. If it is intruded into the upper crust with little heat loss to the wall rocks, it will reach the surface before it intersects the solidus curve and becomes completely crystallized. The effect of water in the basalt is shown by liquidus curves for 0, 2, and 4 percent H_2O (Figure 2a). Lower water content favors the ascent of the melt to the surface prior to crystallizing. The granite system (Figure 2b) behaves somewhat differently. If a melt at 4 Kb along the saturated liquidus ascends to the surface without losing heat, it will intersect the solidus curve at somewhat less than 2 Kb pressure. The surface eruption of a granitic melt is favored by either an initial temperature above the liquidus temperature or a lower water content.

Because of both viscosity and crystallization relationships, basaltic melts tend to flow to the surface through relatively narrow conduits while granitic melts tend to crystallize before reaching the surface. Silicic melts may form plutons of considerable dimension and heat content.

An overall conceptualization of magmatic systems was presented by Hildreth (1981). To summarize his thinking, magmatic systems are considered to be fundamentally basaltic since the heat of the system is derived from basalts originating in the mantle. Rocks of granitic composition are subsequently formed through either the process of fractional crystallization or fusion of pre-existing crustal material. Smith and Shaw (1975), Lachenbruch et al. (1976) and Hildreth (1981) all postulated that major silicic volcanic centers require continued thermal input from mantle-derived basaltic liquids to sustain high temperature convective hydrothermal circulation. Basaltic liquids will not ascend through granitic liquids because of their higher density. Therefore, basalts are thought to pond at the base of a volume of granitic melt and transfer heat to the granitic melt through conduction. On the surface, a shadow zone results where basaltic volcanism surrounds but does not occur within a felsic volcanic center until the felsic melt has crystallized.

Models given by Hildreth (1981) relate different styles of magmatism to various amounts of thermal input and crustal extension. Systems that produce magmas of intermediate composition occur in non-extensional areas, with andesitic stratovolcanos such as those in the Cascades representing an early stage of development. Hydrothermal systems associated with mature mafic to intermediate volcanos occur at Mt. Lassen, California (Sorey and Ingebritsen, 1984), Crater Lake, Oregon (Blackwell and Steele, 1987), Medicine Lake, California and Newberry, Oregon (Sammel, 1981). On a world-wide basis, these magmatic systems support the majority of high-temperature convective systems. High basaltic flux from the mantle in areas of extension appears to produce large amounts of rhyolitic melt, leading to explosive eruptions and the formation of calderas. The best known examples in the U. S., all of which support high-temperature convection, are Long Valley, California (Sorey et al., 1978), the Valles caldera, New Mexico (Hulen and Nielson, 1986), and the Yellowstone caldera, Wyoming (Keith et al., 1978). Rhyolitic dome fields occur in areas of crustal extension and modest amounts of heat input. Examples of hydrothermal systems are Roosevelt Hot Springs, Utah (Ross et al., 1982) and Coso Hot Springs, California (Bacon et al., 1980).

A determining factor in the efficiency of heat transfer from a magma body to an associated hydrothermal system is the level in the crust that the magma body resides. If the pluton is below a level where extensive fracturing can take place, heat transfer from the magma will be principally by conduction. At higher levels of the crust where fracturing is possible, heat transfer will occur mainly through convection of hydrothermal fluids.

Samples of the plutonic heat source for most high-temperature geothermal systems are rarely available for study. The most comprehensive data on the evolution of hydrothermal systems associated with pluton emplacement are in the literature on porphyry copper ore bodies. These plutons are normally intermediate to silicic in composition and emplaced at high levels in the crust.

Burnham (1979) presents a model for the emplacement of melts and associated hydrothermal processes developed by the expulsion of fluids from the magma. His model is for a granodiorite, with an initial content of 3% H_2O, intruded into a subvolcanic environment. Crystallization from the outer margins of the stock forms a carapace that becomes H_2O-saturated as the pluton cools. Then, as crystallization proceeds, fluids are generated through the process of resurgent boiling, increasing the fluid pressure in the carapace. When pressures exceed the least effective principal stress plus the tensile strength of the rock, fractures are propagated, breccias formed, and heat and "magmatic" fluids are transferred to the wall rocks. The generation of fluids from the magma ceases when the pluton has crystallized. However, strong temperature gradients remain, and evidence (Taylor, 1974; Beane, 1983) shows that more dilute fluids, representing meteoric sources, form convective systems that, through time, penetrate into the pluton.

Since a magma is a liquid and will not support fracturing, it is generally thought that hydrothermal fluids derived from meteoric water do not come into contact with the igneous heat source until the pluton has crystallized. Instead, these fluids derive their heat through a zone of conductive heat transport that surrounds the pluton, These relationships were nicely demonstrated by Taylor and Foster (1979) in an oxygen and hydrogen isotopic study of the Skaergaard intrusive complex and its country rocks. They showed a meteoric circulation system around the intrusion, but hydrothermal solutions only penetrated the pluton following crystallization.

Although dikes are not uncommon in geothermal wells, in only a few instances have the plutonic heat sources for geothermal systems been intersected by drilling. The best example available is The Geysers steam system located in northern California (Thompson, 1989). Here a composite felsic pluton underlies and parallels the geometry of the geothermal system. The upper part of the pluton also serves as part of the geothermal reservoir (Thompson and Gunderson, 1989). Moore (1992) found that fluid inclusions from the Geysers showed decreasing temperature and salinity with distance from the pluton. The data are consistent with a collapse of an earlier high-temperature, high-salinity hydrothermal system and its replacement by more dilute, lower temperature fluids.

It is clear that fluids of different origins contribute to active hydrothermal circulation systems (White, 1974). Although most dilute fluids have been ascribed a meteoric origin, deep acid systems and high-salinity components of some systems are most certainly of magmatic origin (Hedenquist, 1992).

PERMEABILITY/POROSITY

The recharge, discharge and recirculation volumes of geothermal systems are controlled by porosity and permeability of host rocks. The following discussion presents information on the formation of porosity and permeability through rock alteration and different rock fracturing mechanisms.

Dual Porosity Model

The dual- (or double-) porosity model considers the fluids in geothermal systems to be distributed in both fractures and matrix pore space. It has been largely utilized to explain production characteristics of vapor-dominated geothermal systems (Truesdell and White, 1973; Pruess and Narasimhan, 1982). Fractures are narrow zones, generally viewed to have permeability that is laterally continuous along strike. The permeability is non-penetrative, meaning that fracturing does not homogeneously effect the rock mass. Matrix porosity consists of isolated pores and pores that connect with fractures through passageways defined by low permeability. While fractures provide communication within the reservoir and are the source of production, the principal reservoir storage is the matrix porosity.

Hot water-, or liquid-dominated systems, are defined as those in which liquid water is the dominant mobil phase (White et al., 1971; Donaldson and Grant, 1981). Pressure gradients with depth are defined by hydrostatic pressure. Water-saturated matrix pores are of little consequence in the behavior of the system unless the fluid in the fracture system becomes severely depleted. As pointed out by Pruess and O'Sullivan (1992) the matrix pores surrounding a fracture must be liquid saturated in order for the fluid to move within the fracture. If the matrix is under-saturated, capillary forces will move fluid from the fracture to the pore space. Fractures in a water-dominated system constitute the principal reservoir fluid storage as well as the principal source of production. In order to balance the fluid flux, fractures also represent the principal conduits for fluid recharge.

Vapor-dominated geothermal systems (White et al., 1971) have steam as the pressure-controlling and most mobile phase. Pure end member systems are relatively rare, the best known of which are The Geysers, California, Lardarello, Italy, and Kamojang, Indonesia. These systems produce steam at pressures and temperatures that are close to the maximum pressure and enthalpy of steam. The buffering of these production characteristics indicates the presence of a fluid phase. White et al.'s original paper suggested a deep boiling water table, but drilling evidence suggests that liquid water is stored within the matrix pores and flashes to steam as pressure is lowered through production. Within a vapor-dominated system, the principal volume of reservoir storage is located within the rock matrix, and the fractures are low pressure conduits for steam flow into which the matrix water flashes.

Both in the natural state and as a consequence of production, hot water-dominated systems may develop a vapor cap or zones within the system that are vapor-dominated or vapor-rich (Donaldson and Grant, 1981; Ingebritsen and Sorey, 1988).

Conductively heated rocks with low permeability are classified as Hot Dry Rock (HDR). The pressure in these systems are generally defined by the hydrostatic gradient. Blocks within and marginal to active hydrothermal systems can be included in this classification.

Following Engelder (1987) a distinction can be made between the pore pressure and fluid pressure. Pore pressure results from fluid in closed pores that acts against applied tectonic stress and results in an effective stress. In contrast, the fluid pressure is produced by fluid filling a fracture and acting against the walls of that fracture. In a system open to the atmosphere, the fluid pressure is the hydrostatic pressure. Sealing can allow pressures to increase to a level defined by the applied stress plus the pressure required to either fracture or open pre-existing fractures in the rock. If this level of fluid pressure is reached, hydraulic fracturing will produce hydrothermal breccias that will be discussed in a subsequent section.

Alteration

Rock alteration is an extremely important process in high-temperature geothermal systems. Study of mineralogy and zoning relationships provides valuable insight into the dynamics and evolution that are of great importance in the exploration and assessment of the system. Numerous comprehensive summaries of hydrothermal alteration processes and the application of hydrothermal alteration mineralogy in exploration and development have been written, but will not be discussed here. The reader is referred to Browne (1978) for an overall view of mineralogy and processes. Bird et al. (1984) have discussed the formation of calc-silicate phases in active geothermal systems. A useful paper on the layer silicates in hydrothermal systems is Steiner (1968). Alteration processes will be considered here in terms of enhancement or reduction in porosity and permeability of confining rocks of the geothermal system.

Processes that Enhance Porosity.

Alteration processes that enhance porosity are dissolution of phases and metamorphic reactions that result in a decrease in volume with respect to starting phases.

Studies in high-temperature geothermal systems and in hydrothermal ore deposits suggest that the most important reaction in increasing porosity involves solution of calcite or other carbonate species (Hulen et al., 1991; McDowell and Elders, 1983; Kuehn and Rose, 1992). Figure 3 shows solubility of calcite as a function of temperature and PCO_2. The solubility is retrograde with respect to temperature, that is, calcite is more soluble in cooler fluids. The solubility also increases as the PCO_2 increases. Not shown on this diagram are the effects of pH on solubility. Carbonic, hydrochloric, sulphuric and boric acids are present in geothermal systems. Organic acids may be important at temperatures of around 100° C. A paper by Fournier (1985a) provides an excellent review of the geochemistry of the behavior of carbonates in geothermal systems.

Dramatic examples of the magnitude of calcite dissolution can be found in the outflow plumes from high-temperature systems. The volume of calcite dissolution and reprecipitation as travertine is particularly pronounced when cooling fluids flow through fractures in carbonate-rich rocks. Good examples are the deposits at Mammoth Hot Springs in Yellowstone National Park (Bargar, 1978) and Soda Dam adjacent to the Valles caldera, New Mexico (Goff and Shevenell, 1987).

In contrast with the behavior of carbonates in solution, silica will precipitate under cooling conditions and be dissolved as fluid temperature is increased. Petrographic evidence shows that solution and deposition of quartz are on-going processes within active systems. The volume of silica that can be dissolved from active systems is often high and certainly has an effect on the overall porosity of the system. One need only to consider the large volumes of siliceous sinter and silica-cemented gravels associated with upflow zones in Yellowstone National Park (White et al., 1975). Therefore, while systems, or parts of systems, are heating one expects porosity and permeability, especially along fractures, to increase as a result of silica solution.

Prograde metamorphic reactions often result in a decrease in volume of mineral phases, but this is a research topic that has not been well covered in the analysis of porosity in active systems. Certainly the reaction of carbonates to form calc-silicates, with the evolution of CO_2, results in a volume reduction of mineral products. Another common reaction is the transformation of smectite to mixed-layer illite-smectite and then to illite, that results in a volume reduction. Since these transformations are normally accompanied by an increase in depth and overburden pressure, it is likely that the developed porosity may be eliminated through compaction.

Processes that Reduce Porosity.

Most high-temperature hydrothermal fluids are saturated with respect to silica. The most prominent aspect of discussions on the geochemistry of silica in active hydrothermal systems center on precipitation of silica from solution and its importance in the sealing of geothermal pathways (Fournier, 1985b). In contrast to carbonates, the solubility of silica increases over the temperature range associated with most hydrothermal systems. Therefore, the normal means of precipitation is the simple cooling of fluids. The physical result of this precipitation is either whole-sale replacement of the host rock (silicification) or the formation of quartz veins. At temperatures above 340° C there is a region of retrograde solubility where the solubility of quartz would decrease with heating. This raises the possibility that the maximum temperature attainable in hydrothermal solutions may be limited by precipitation of quartz (Fournier, 1985b).

Boiling of hydrothermal solutions results in a reduction of the partial pressure of CO_2 and the deposition of calcite. This is a common process at the top of geothermal systems and often leads to the formation of calcite with a bladed habit.

The formation of clay minerals is a common factor in permeability reductions in active geothermal systems. Illite, in particular, forms within fluid flow channels at temperatures of greater than 200° C. Its formation may be stimulated by hydrothermal or tectonic brecciation that provides starting material of fine grain size. It may also be developed through changes in the chemistry of fluids, particularly increases in acidity.

Tectonic Brecciation

Faulting and fracturing contain mobile geothermal fluids in explored high-temperature fields. They are, therefore, the targets of exploration drilling, and a great deal of attention has been given to locating and characterizing them through geological and geophysical means. Fracturing and faulting can be best understood as a response to applied stress as shown in Figure 4.

Any applied stress may be resolved into three principal stress components. In the Basin and Range and most volcanic environments, the stress orientation is similar to that shown in Figure 1a, where the greatest principal stress is vertical, and the strike of faulting and fracturing is perpendicular to the least horizontal principal stress. In this situation, the faulting is normal. The other environment in which geothermal systems are commonly found is that characterized by strike-slip faulting. The stress orientations responsible for this style of faulting are shown in Figure 1b. In this case, both the greatest and least principal stress directions are horizontal. Important geothermal districts such as the Imperial Valley and The Geysers are developed in this type of regional environment.

Regional stress appears to fit a model where the applied stress is homogeneously distributed over large areas (Zoback and Zoback, 1980). However, a geothermal system, characterized by high heat flow, upwelling hot fluids, and perhaps an increase in fracturing, would theoretically represent an anomaly within the region. The following sections analyze the stress within geothermal systems and discuss the interface between the geothermal system and the regional stress.

The investigation of in situ stress and information from seismicity surveys indicates that the stress orientation in at least some geothermal fields is different from the regional stress. Walter and Weaver (1980) performed a detailed study of earthquakes from the Coso geothermal field in California. They noted a difference in the fault plane solutions of earthquakes in the geothermal system from those events located outside the system. They determined that strike slip movement on nearly vertical fault planes occurred everywhere except in the geothermal system. The regional motion is right lateral along NW striking planes and left lateral along the NE striking conjugate planes. This is consistent with the greatest principal stress oriented horizontally approximately NS and the least principal stress also oriented horizontally and in an EW direction. Within the geothermal system the fault plane solutions show predominantly normal movement with a small strike-slip component along NNE-trending planes. This implies that the least principal stress is horizontal and oriented WNW and that the greatest principal stress is vertical.

A change in stress orientation can also be documented in the Roosevelt Hot Springs (RHS) geothermal system in Utah. This system is located within the transition zone between the Colorado Plateau and Basin & Range Provinces. In a nearby study of earthquakes, Arabasz and Julander (1986) have determined that the regional orientation of the least principal stress is 102 degrees, consistent with the EW extensional tectonics of the Basin & Range Province. Geologic mapping of the area around RHS (Fig. 5) shows that Recent normal faulting to the west of the geothermal system is north to NNE trending, consistent with the results of Arabasz and Julander.

However, much of the geothermal production at RHS is controlled by EW normal faults as exemplified by the Negro Mag fault (Fig. 5). Nielson et al. (1986) demonstrated that the Negro Mag is located along the axis of a complex graben structure. This structure would not form under the present regional stress orientation; it requires a least principal stress oriented approximately NS, at nearly a right angle to the regional orientation.

Pre-production seismicity from RHS is also shown in Figure 5. The earthquakes are clearly located along faults that are parallel to the Negro Mag fault. Analysis (G. Zandt, written communication) shows that the movement on the faults is predominantly normal with a strike-slip component. These data are consistent with the fault orientations discussed above and imply a roughly NS orientation of the least horizontal principal stress which is nearly perpendicular to the regional direction. It is also notable in Figure 5 that the earthquake swarms continue up to but do not cross the NNE-trending Opal Mound fault. The Opal Mound orientation is consistent with formation under the regional stress system. Sinter deposits and production wells along this fault also indicate that it contains geothermal fluids. Dry holes and a decrease in heat flow to the west suggest that the Opal Mound serves as the western boundary of the geothermal system.

Data from well bore breakouts at RHS (Allison and Nielson, 1988c) also demonstrate that the least horizontal principal stress within the geothermal system is oriented approximately NS and not in the regional direction.

In conclusion, the data from both RHS and Coso geothermal fields demonstrate that there is a difference in the orientation of the stress within these geothermal systems from the regional stress environment. These observations require 1. different forces within the geothermal system and 2. mechanisms of structural decoupling of the geothermal system from the regional stress. At RHS, this decoupling apparently takes place along the Opal Mound fault to the west. Extent of the local stresses in the other directions is not known.

Faults and fractures are mechanical heterogeneities. Their strength is a function of the character of brecciation during fault movement and of mineral deposition along the features. It is not uncommon to find fractures that have been totally sealed by silica and are tougher than the host rock. However, fractures that exhibit high fluid to rock ratios are zones of weakness relative to the surrounding rock. As such, they serve as zones of stress release through faulting, and, by this mechanism, permeability is maintained rather than lost through the process of hydrothermal mineral deposition.

Allison and Nielson (1988a, b) have discovered that in many geothermal wells there is a dramatic change in stress orientation with depth. They have documented that, in some instances, this change takes place across faults. This, in addition to the data from RHS cited above, makes it clear that geothermal faults, due to their inherently weak nature, serve as zones of decoupling between different stress systems. In addition, Allison and Nielson found that there were often variations in stress orientation between wells within systems. The problem remaining is to explain the reason that stress may change orientation at the boundary of a geothermal system or within the system.

The evaluation of data from the Baca system (Nielson, 1989) shows that the stress due to temperature gradients is significant and in many cases may be the principal cause of stress variation within a geothermal system. In some instances, differences in fluid may also be important, but they were much less so in the example analyzed. Stress due to upper level volcanic processes may be important in some fields and promote a difference in orientation from the regional environment.

It has been shown that faults within a geothermal system have low strength due to the presence of hot fluids. Theoretically the regional stress is distorted by the presence of a geothermal system. This could be used as an exploration tool; however, there is not at present any evidence that this distortion process is measurable. The evidence from RHS does demonstrate, however, that the geothermal system is effectively decoupled from the regional stress along a single fault zone on one side of the field. This change in orientation should be considered in an effective exploration and development strategy.

One of the principal problems in exploration concerns the location and orientation of fractures that could provide geothermal production. Although determination of stress orientation will not locate fractures, it makes it possible to predict the orientation of fractures that are forming under the present-day stress system, or that will be kept open by the _in situ_ stresses. This allows directional drilling programs to be designed such that wells cut across the fracture trend resulting in the maximum opportunity to intersect an open fracture.

It can be visualized that the geothermal fluid in a fracture exerts pressure against the fracture walls, helping to keep the fracture open. Removal of fluid from the fracture could result in a decrease in permeability. The solution to this problem would be injection along the structure to maintain fluid pressures, but care must be taken to avoid significant enthalpy decrease.

It is also evident from this analysis that the processes of production and injection will change the stress orientation in a reservoir as the temperatures are modified. This could have the effect of generating new permeability depending on the positions of the production and injection wells with respect to the stress system.

Hydrothermal Brecciation

Surface expressions of hydrothermal explosions (Muffler et al., 1971; Hedenquist and Henley, 1985) and their subsurface breccias (Grindley and Browne, 1976; Hulen and Nielson, 1988) are common features in geothermal fields. The breccias often show evidence of fluid flow such as rounding of fragments and flow foliation in comminuted open-space fillings. Identification of these breccias during drilling is often obscured by the lack of core. These are termed phreatic breccias by Sillitoe (1985) and are distinguished from magmatic-hydrothermal breccias that were described previously as resulting from resurgent boiling above plutonic bodies.

In general, breccias can form naturally through a variety of pressure release mechanisms that result in boiling at depth. They are developed within fault zones that contain geothermal fluids whose temperatures have exceeded the boiling point with depth curve. Phreatic explosions can also take place as a consequence of production.

Hulen and Nielson (1988) described hydrothermal breccias in the Jemez fault zone near the Valles caldera in New Mexico and proposed a model for their formation. The breccias consist of angular to rounded clasts, that average about 1.5 cm in diameter, in a rock-flour matrix. Both the rock flour and the clasts are intensely altered with the principal alteration phases being quartz and illite. Vapor- and two-phase fluid inclusions are present and allowed a determination of the thermal history leading up to formation of the breccias. Hydraulic rupture of the rock requires that the fluid pressure exceed the least principal stress plus the tensile strength of the rock. It was possible to estimate the pressures required to break the rock on the basis of nearby hydrofracture experiments. A boiling point with depth curve was then calculated at pressures required to brecciate the rock. This curve is shown in Figure 6 and exceeds the boiling point curve based on a hydrostatic pressure gradient. Fluid inclusion homogenization temperatures from the breccias are also plotted on Figure 6 and show that these data are compatible with temperatures that exceeded the boiling point curve but not the temperature required to fracture the rock. This degree of superheating could only take place where the rocks had been effectively sealed. This allowed fluid temperature to reach the point where the vapor pressure was sufficient to brecciate the rock. The triggering event was probably an earthquake that instantly lowered the pressure resulting in flashing of fluids to steam and brecciation of the rock. Alternatively, the brecciation could have been initiated by the superheating of the rock. In either case, the subsequent flashing of the contained water to steam both brecciated and altered the rock. Finely comminuted rock particles were easily and rapidly altered to illite and decreased the porosity of the breccia soon after its formation.

Lithologic Controls

Lithologic variations are responsible for much of the fluid-flow heterogeneity seen in active geothermal systems. The differences are generally related to the ability of different lithologies to sustain open fractures.

There are strong lithologic controls on fracturing at The Geysers steam field. Sternfeld (1989) demonstrates that fractures are sustained through graywacke, but not through the interbedded argillic horizons. These relationships are shown in Figure 7 where conjugate fractures are bounded by argillite below and by lithologic variations in the graywacke reservoir rock above.

Grindley and Browne (1976) have summarized some of the lithologic controls on fluid production that stem largely from the ability of different lithologies to support open fractures. They cite fractured andesites at Kawerau, rhyolitic pyroclastics at Wairakei, welded tuffs at Matsukawa, Japan, and scoreaceous contacts between basalts and hyaloclastites at Reykjanes in Iceland.

Impermeable lithologies are often as important to the hydrology of geothermal systems as the permeable rocks that comprise the reservoir volume. Hulen et al. (1989) have shown that a Paleozoic sedimentary sequence, consisting of shales, sandy shales, and carbonates, vertically separates hydrothermal convection systems in the Valles caldera of New Mexico. Figure 8 shows lithologic relationships in scientific corehole VC-2b. The section of the well above about 750 m is composed of Quaternary volcanic and volcanoclastic rocks erupted during the formation of the Valles caldera. These rocks have been intensely altered by hydrothermal fluids to assemblages of quartz-sericite at the top passing into chlorite-sericite in the lower portion of the section. Also fracturing is abundant through the volcanics. The sedimentary section shows a dramatic decrease in the intensity of alteration and fewer preserved fractures. Thermal gradients through this zone also suggest a conductive heat flow regime attesting to the lack of fluid circulation. Beneath the sediments is Precambrian granite where the intensity of alteration again increases and excellent examples of open veins are preserved in core. Water entries were found in this lower portion of the well, and fluid samples support the physical separation of this higher-temperature circulation system from the hydrothermal system in the volcanic section.

The above example points out also the ability of granitic rocks to serve as geothermal reservoirs. Crystalline rocks serve as some of the best reservoirs being present at Roosevelt Hot Springs, Utah, (Nielson et al., 1986), Zunil, Guatemala (Adams et al., 1990), Coso, California (Bishop and Bird, 1987; Wright et al., 1985), and The Geysers, California (Thompson and Gunderson, 1989). This is largely due to the brittle nature of granite at temperature conditions of hydrothermal systems and low susceptibility to hydrothermal alteration.

Halfman et al. (1984) contrast the effects of different lithologies in the Cerro Prieto field on fluid flow. A thick shale unit, that is relatively impermeable, confines the flow of geothermal fluids to underlying sandstones. Where the shale unit is sandy, it allows the fluids to flow into higher sandstone units.

System Margins

The margins of geothermal convection systems respond differently under production, and this serves to illustrate some of the processes that are taking place. The typical model of a system has a cap and sides that are formed of hydrothermally altered rock with low permeability, typically termed a cap or "self-sealed" zone. Vapor-dominated systems require low-permeability margins; however, the different responses of water-dominated systems suggest that capping and sealing may or may not be present around all or parts of the convective system.

At Wairakei, mudstones have been suggested to act as a cap, but their existence is not relevant in the production response of the system. Because of the motion of the freewater surface, the field responds as if it were unconfined (Donaldson and Grant, 1981). Similar results were reported for Momotombo (Dykstra and Adams, 1977).

At Cerro Prieto, Elders et al. (1984) report "at the top of the reservoir detrital or authigenic clay minerals, like montmorillonite and kaolinite, are progressively replaced by pore-filling chlorite, illite, and especially calcite."

The development of a cap at the Salton Sea field has been studied in detail (Moore and Adams, 1988). They suggest that initially, the cap consisted of low permeability lacustrine and evaporite units. Subsequently, underlying deltaic sandstones were incorporated into the cap through the deposition of calcite and anhydrite that reduced their permeability.

Structural origins of system caps have also been proposed. Nielson and Moore (1979) showed how low-angle faulting at the Cove Fort-Sulphurdale geothermal systems in Utah could serve as effective cap on the high-temperature convective system.

SUMMARY

This paper has summarized some of the more important physical aspects in high-temperature hydrothermal convection systems. Shallow plutons provide heat, and in some cases, volatiles and fluids to the convention system. Andesitic volcanos have the strongest association with magmatic fluids. Fluids and volatiles are contributed by the pluton up to the time that it is crystallized. Normally, the magmatic fluids mix with meteoric fluids, and, as crystallization proceeds, the meteoric component increases and then dominates. Silicic dome complexes and continental silicic calderas have either vented their fluids in pyroclastic eruptions or had low fluid contents to begin with because associated hydrothermal systems do not have large magmatic components.

High-temperature systems are favored by large plutons that are emplace relatively close to the surface. In the U. S., they tend to be associated either with large caldera complexes or rhyolite dome fields. On a world-wide basis, mature andesitic volcanic complexes, that are underlain by shallow intrusions of dioritic composition host significant active systems. Geologic models for such systems are those that have been often proposed for the development of porphyry copper deposits.

Porosity and permeability control hydrothermal circulation as well as the recharge and discharge components of the system. The dual-porosity model provides a framework for understanding fluid-rock relationships. In most liquid-dominated reservoirs, fractures serve as reservoir storage as well controlling communication within the reservoir. In vapor-dominated systems, the principal volume of reservoir storage is in the rock matrix, while the fractures again serve to connect the different portions of the reservoir. Fractures also govern recharge and discharge paths of the system.

The importance of fracturing in hydrothermal circulation results from the tendency of systems to seal themselves through the precipitation of alteration phases. This process dominates at system margins where temperature gradients are steep and silica is deposited as geothermal fluids cool. Within the system, recurrent fracturing is required to keep fluid-flow paths open. Mineral precipitation at system margins forms a confining cap in some systems, where lithologic changes serve the same role in others. Although much of the fracturing is of tectonic origin, hydrothermal brecciation has been observed to be important in many systems.

Stress orientation within some liquid-dominated systems has been found to be different from the regional applied stress. This may result from the presence of a buried plutonic body or from differences in temperature.

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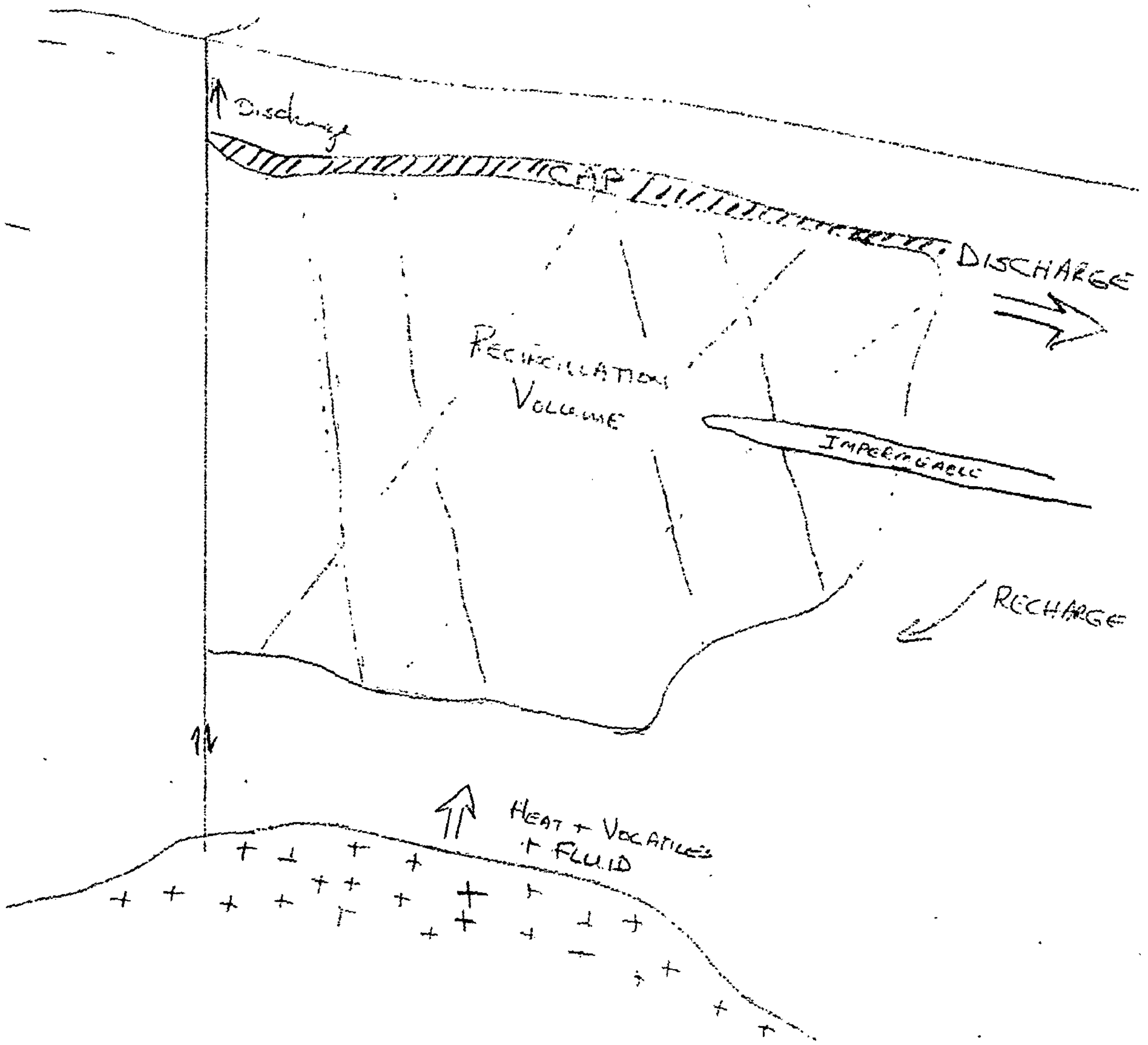


FIGURE 1: General model of a high-temperature hydrothermal convection system.

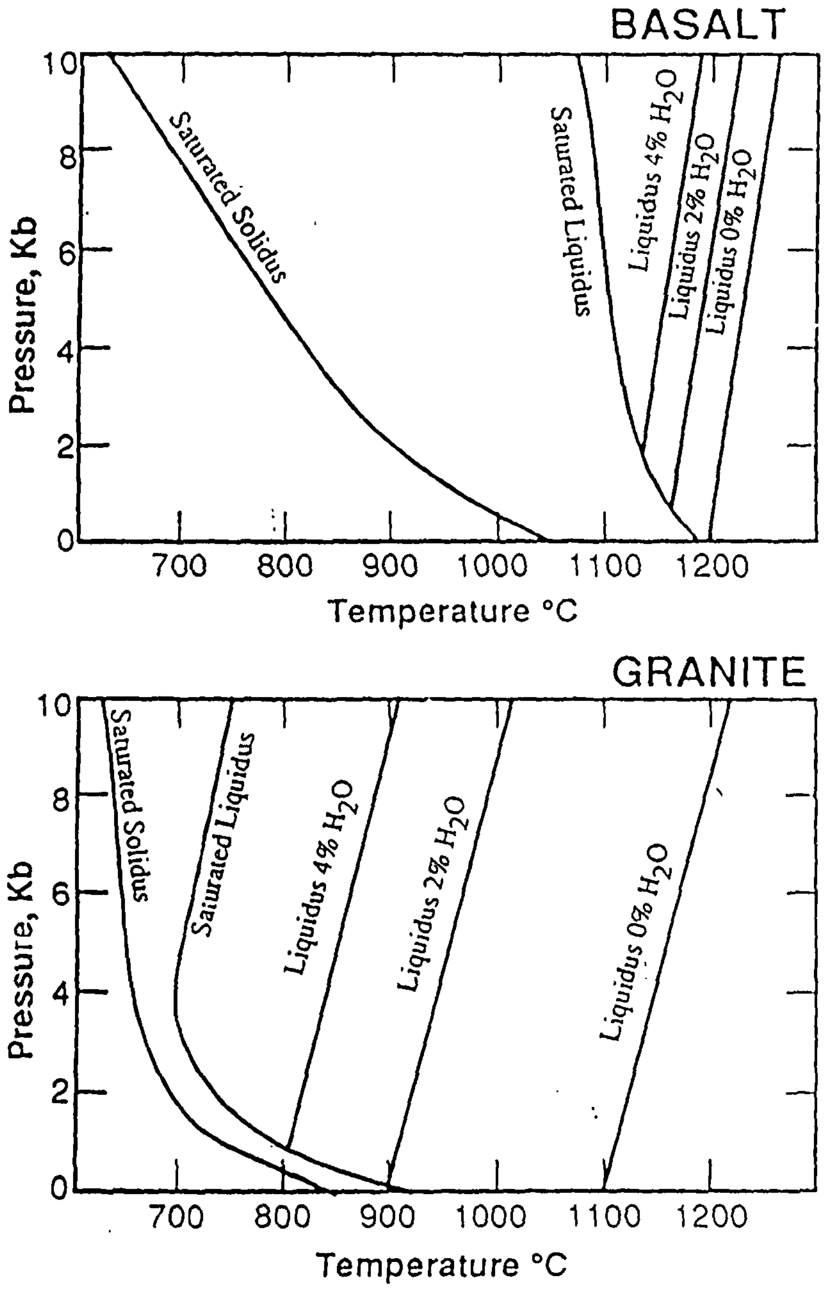


Figure 2 Phase relationships for rocks of basaltic composition (2a) and granitic composition (2b). (from Harris, Kennedy and Scarfe, 1970).

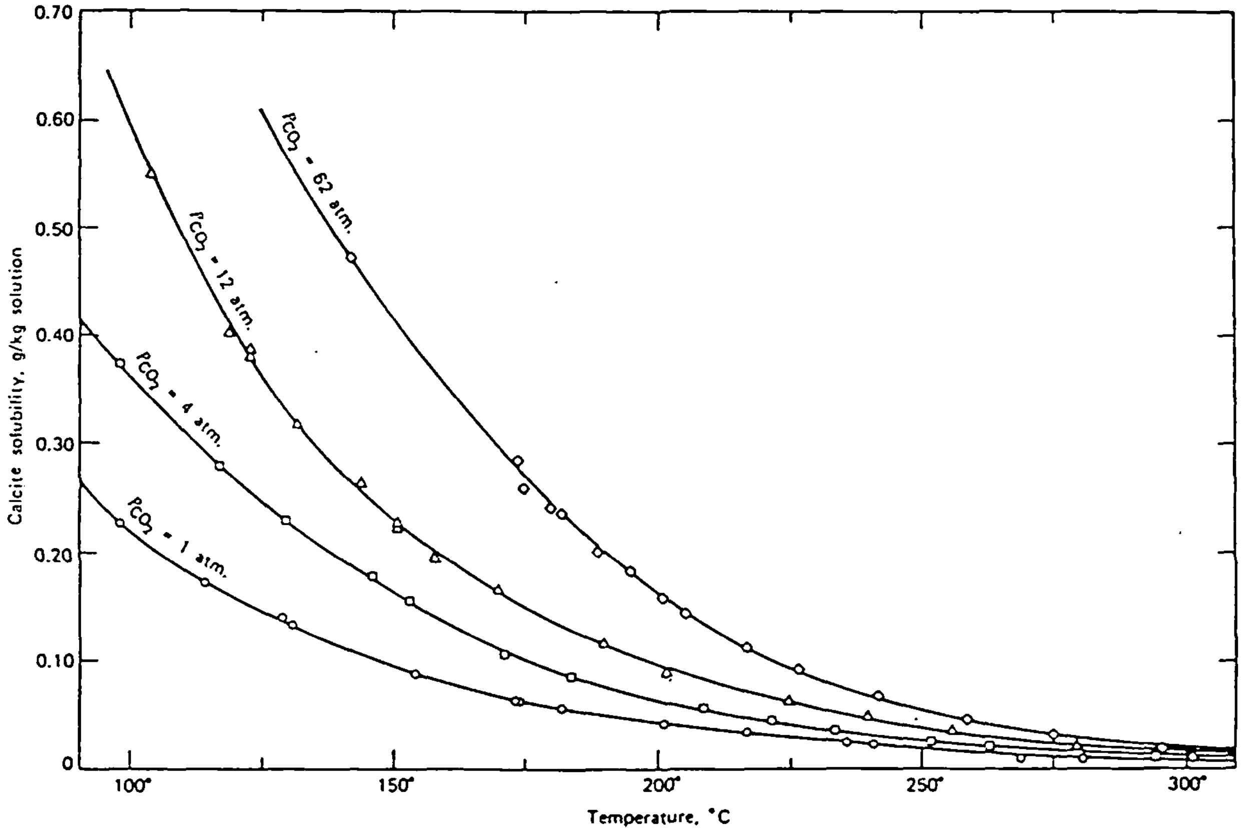
the saturated liquidus ascends without losing heat, it will intersect the solidus curve and crystallize at somewhat less than 2 kb pressure. The surface eruption of a granitic melt is favored by either an initial temperature above the liquidus or a lower water content.

From the above observations, one concludes that because of viscosity and crystallization differences, basaltic melts can move through relatively narrow conduits and tend to flow to the surface while granitic melts require larger conduits and tend to crystallize before reaching the surface. Silicic melts may form plutons of considerable dimension and heat content. Smith and Shaw (1975) pointed this out, and emphasized that silicic volcanic rocks of age less than about 1 Ma are strong evidence for a subsurface magma chamber whose heat content may be sufficient to sustain substantial hydrothermal convection.

Hildreth (1981) also studied magmatism and made contributions pertinent here. He considered magmatic systems to be fundamentally basaltic since the heat for operation of the system is derived from basalts originating in the mantle. Rocks of granitic composition are formed through either the process of fractional crystallization or fusion of pre-existing crustal material. Smith and Shaw (1975), Lachenbruch et al. (1976) and Hildreth (1981) all postulated that major silicic volcanic centers require continued thermal input from mantle-derived basaltic liquids to sustain high temperature and convective hydrothermal circulation. Basaltic liquids cannot ascend through granitic liquids because basaltic liquids are denser. Basalts appear to pond at the base of granitic melts and transfer heat to the granitic melt through conduction. A shadow zone results on the surface where basaltic volcanism surrounds, but does not occur within, a felsic volcanic center.

Models given by Hildreth (1981) relate different styles of magmatism to various amounts of thermal input and crustal extension. Systems that produce magmas of intermediate composition occur in non-extensional areas, with andesitic stratovolcanos such as those in the Cascades representing an early stage of development. These convergent environments produce hydrothermal systems around the Pacific "ring of fire" and elsewhere world wide. High basaltic flux from the mantle in areas of extension appears to produce large amounts of rhyolitic melt, leading to explosive eruptions and the formation of calderas. The best known examples in the U. S., all of which support high-temperature convection, are Long Valley, California (Sorey et al., 1978), the Valles caldera, New Mexico (Hulen and Nielson, 1986), and the Yellowstone caldera, Wyoming (Keith et al., 1978). Rhyolitic dome fields appear to occur in areas of crustal extension and modest amounts of heat input. Examples of dome fields that contain hydrothermal systems are Roosevelt Hot Springs, Utah (Ross et al., 1982; Nielson et al., 1978) and Coso Hot Springs, California (Bacon et al., 1980).

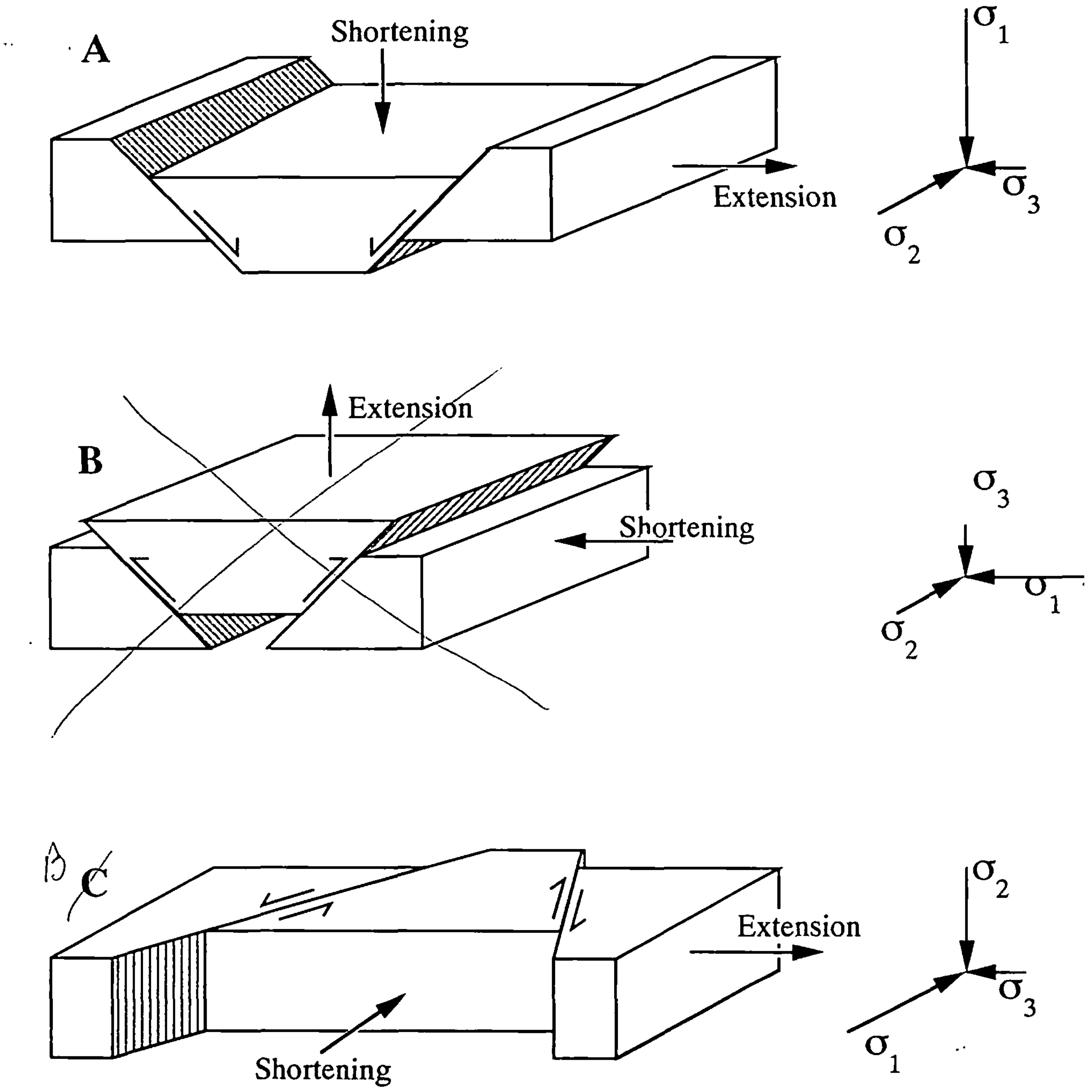
In summary, igneous activity in the last one million years and the occurrence of silicic volcanic rocks form important regional guides to geothermal resources. Magmatic processes produce various kinds of volcanism, from the quiet eruptions of basalt directly from the mantle at shield volcanos such as those in Hawaii and Iceland to violently explosive eruptions that create calderas such as those at Long Valley, California and Valles, New Mexico. Calc-alkaline volcanism at stratovolcanos and the formation of silicic dome fields are processes that fit between these two extremes. All of these magmatic processes can and do host hydrothermal convection systems.



The solubility of calcite in water up to 300°C at various partial pressures of carbon dioxide. (From Ellis, 1959, *Am. J. Sci.*, *257*, 354-365.) The solubility values have been revised downward slightly by Ellis (1963).

HOLLAND AND MALININ (1979)

Fig. 3



A: Normal fault
~~B: Reverse fault or thrust fault~~
b ~~C~~: Strike-slip fault

Fig 4

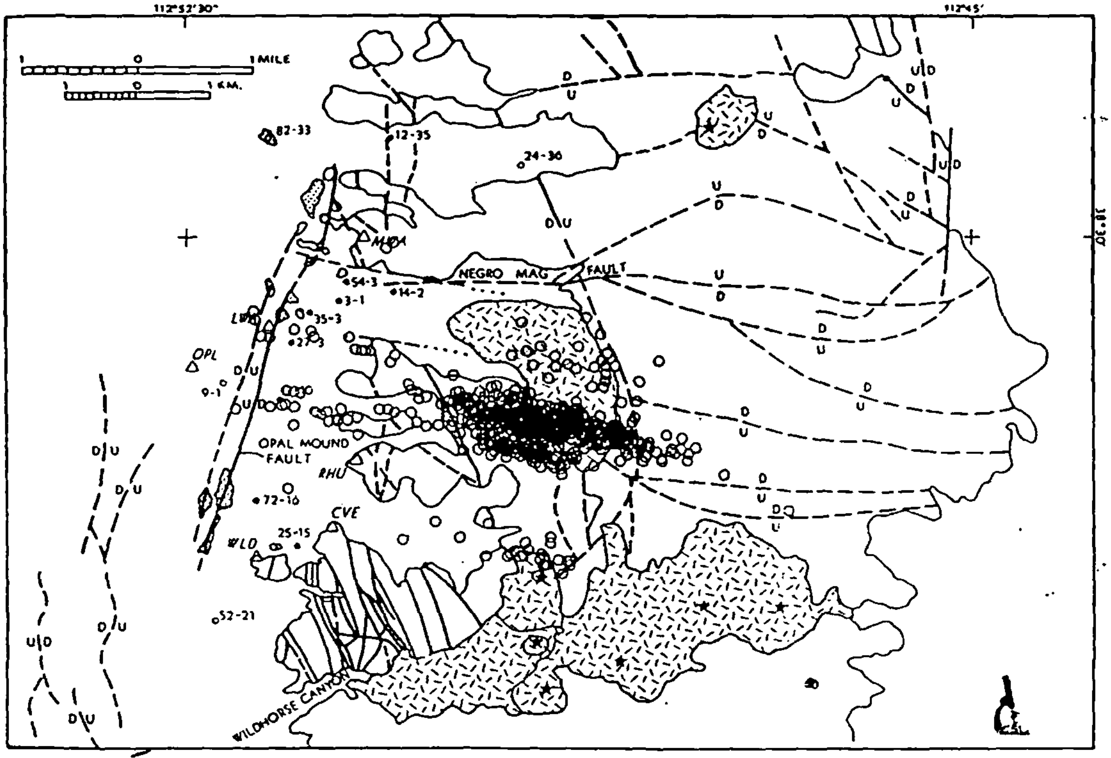


Figure ~~1~~ 5. Geologic map of Roosevelt Hot Springs geothermal field, Utah. Closed circles are producing wells and small open circles are dry holes. Large open circles are earthquake epicenters (G. Zandt, written communications). Dotted units are hot spring deposits. Dashed unit is Pleistocene rhyolite with stars showing vent locations. Triangles and three letter abbreviations show location of seismic stations. Faults and relative movement shown by heavy dashed and solid lines. Outline defines Mineral Mountains.

of the fault to that reorientation has had a favorable impact on permeability. Some of the wells along this trend have the capacity to produce over one million pounds of total mass flow per hour.

Other examples of the use of older structures as geothermal reservoirs are Beowawe, Nevada and Coso, California. These geothermal fields are located in areas that had very complex structural histories prior to the initiation of the present geothermal activity. Faults formed prior to the geothermal activity presently serve as hosts for fluids.

Calderas represent magmatic systems with high thermal flux in extensional environments. Since most faults are obscured by volcanic cover, studies in the Valles caldera, New Mexico have been based on an extensive subsurface data base including wells drilled under the U. S. Department of Energy's Continental Scientific Drilling Program.

In contrast to RHS, faulting at the Valles caldera is dominated by structures formed during eruption of ash-flow tuffs and subsequent resurgent doming; however, some of these intracaldera faults were inherited from regional faults. The caldera was formed at the intersection of two regional structures, the Rio Grande rift and the Jemez fault zone. The influence of north-south normal faults of the Rio Grande Rift on faulting within the caldera is unknown, but they may control the downdropping of the caldera floor during eruption (Goff, 1983).

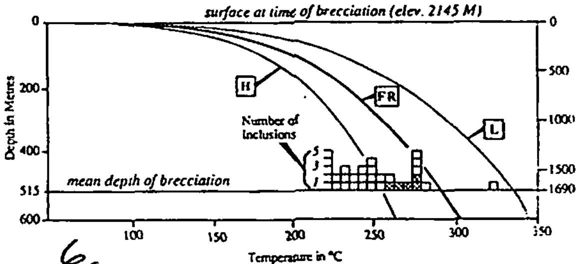


Fig. 6 ~~13~~. Depth versus temperature plot and boiling point curves of Figure 12, showing homogenization temperatures for dilute, probable interbreccia fluid inclusions in the VC-1 hydrothermal breccias. Crosshatching indicates primary inclusions.

duced by hydrothermal fluid overpressuring accompanying formation of the late Cenozoic Valles caldera complex.

Fluid-inclusion characteristics, when studied in conjunction with alteration assemblages and textures as well as the local geologic history, can be used to deduce the mechanisms of hydrothermal brecciation. Homogenization temperatures for 13 of the 28 low-salinity fluid inclusions in the VC-1 hydrothermal breccias, when plotted at the assumed depth of brecciation, exceed temperatures defining the hydrostatic boiling point versus depth curve for pure water (curve H, Figure 13). This relationship supports the proposal that at the VC-1 site, the Jemez fault zone was hydrothermally sealed prior to each episode of hydrothermal brecciation, allowing pressures to approach those of curve FR. Hydrothermal brecciation was triggered through a rapid release in confining pressure or renewed heating. Boiling which produced and accompanied this brecciation is documented by coexisting, liquid- and vapor-rich, low-salinity fluid inclusions.

Once the boiling point was exceeded, flashing fluids in fractures and intergranular pores ruptured and comminuted enclosing rocks. In some cases, the resulting three-phase mixture (liquid + vapor + solid rock) was involved in fluidization, with further attrition of entrained rock particles. The increased surface area of these comminuted fragments facilitated hydrothermal alteration.

Homogenization temperatures of high-salinity fluid inclusions, when plotted at the same mean depth of brecciation at the VC-1 site (Figure 14), by contrast with those of coexisting dilute inclusions are well below temperatures defining a corresponding hydrostatic boiling point curve. This relationship clearly indicates that these saline fluids were not involved in the hydrothermal brecciation recorded by their younger, dilute counterparts.

The occurrence of molybdenite in the hydrothermal breccias of VC-1 further strengthens the hypothesis that these breccias are genetically related to the Valles caldera complex. The only other reported occurrence of this sulfide in the Jemez Mountains is in young (<1.12 Ma) intracaldera tuffs penetrated by CSDP core hole VC-2A, at Sulphur Springs in the Valles caldera (Figure 1) [*Hulen et al.*, 1987]. Molybdenite in the Sulphur Springs rocks, like that of VC-1, is intimately associated with hydrothermal brecciation and intense quartz-sericite alteration. Hydrothermal phengite, an uncommon layer silicate abundant in the VC-1 breccias, is also common in VC-2A.

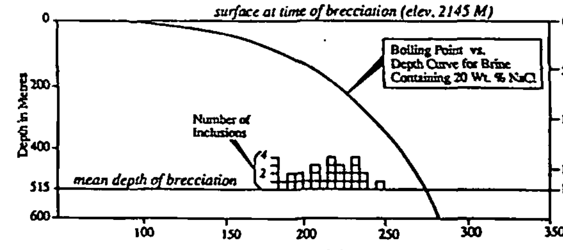


Fig. 14. Depth versus temperature plot and boiling point curve appropriate for fluid of 20% (weight) salinity [from *Haas*, 1971] under hydrostatic pressure at the time of brecciation at the VC-1 site, showing homogenization temperatures for high-salinity fluid inclusions in hydrothermal breccias.

The shallow molybdenum mineralization intersected in VC-2A is very similar to that occurring above some deeply concealed, Climax-type, stockwork molybdenite deposits [*Hulen et al.*, 1987]. The molybdenite, associated alteration, and hydrothermal brecciation encountered in VC-1 and VC-2A could represent high-level leakage from a deep, Climax-type hydrothermal system.

Our studies of the two Valles CSDP core holes have shown that, as in many New Zealand geothermal systems [*Grindley and Browne*, 1976; *Hedenquist and Henley*, 1985], hydrothermal brecciation has created or enhanced structural permeability in high-temperature geothermal systems of the Valles caldera. Discovery of these hydraulically fractured rocks, not recognized from previous studies based on rotary drill cuttings, exemplifies the value of continuous core from carefully monitored scientific drilling.

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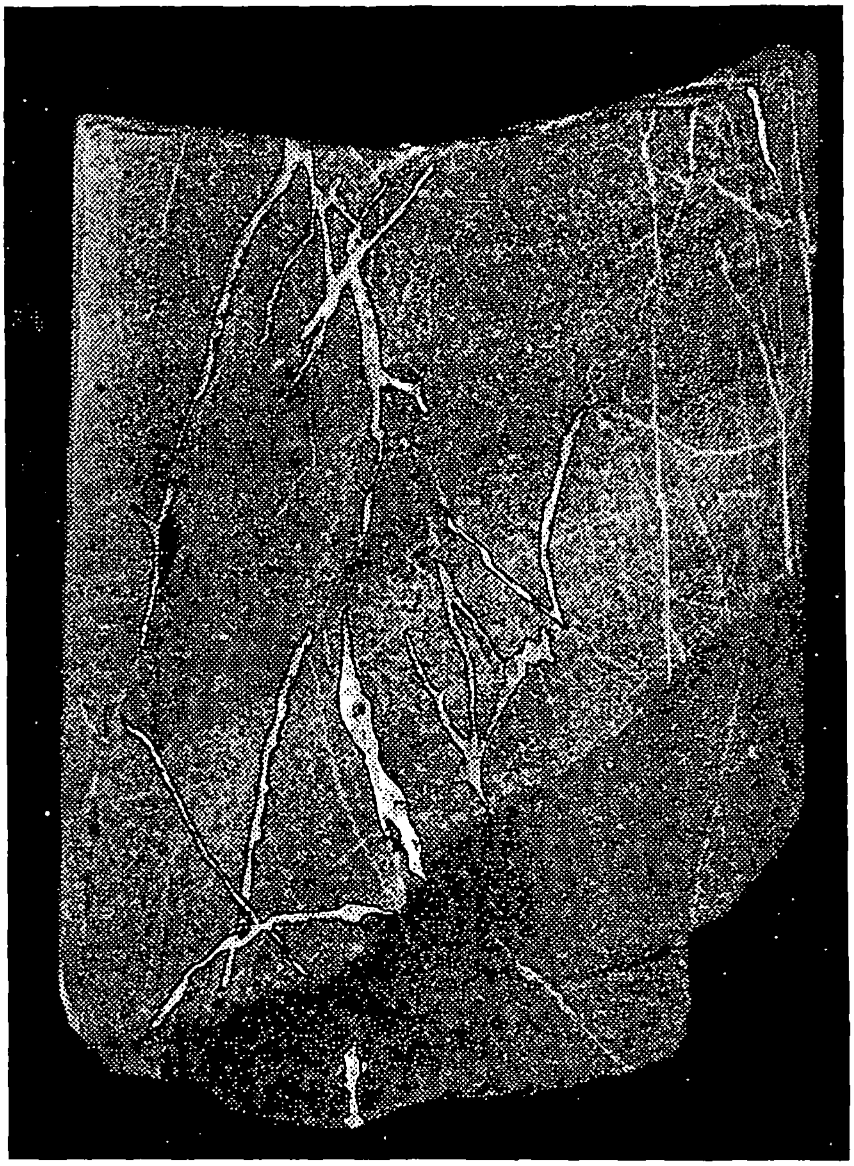

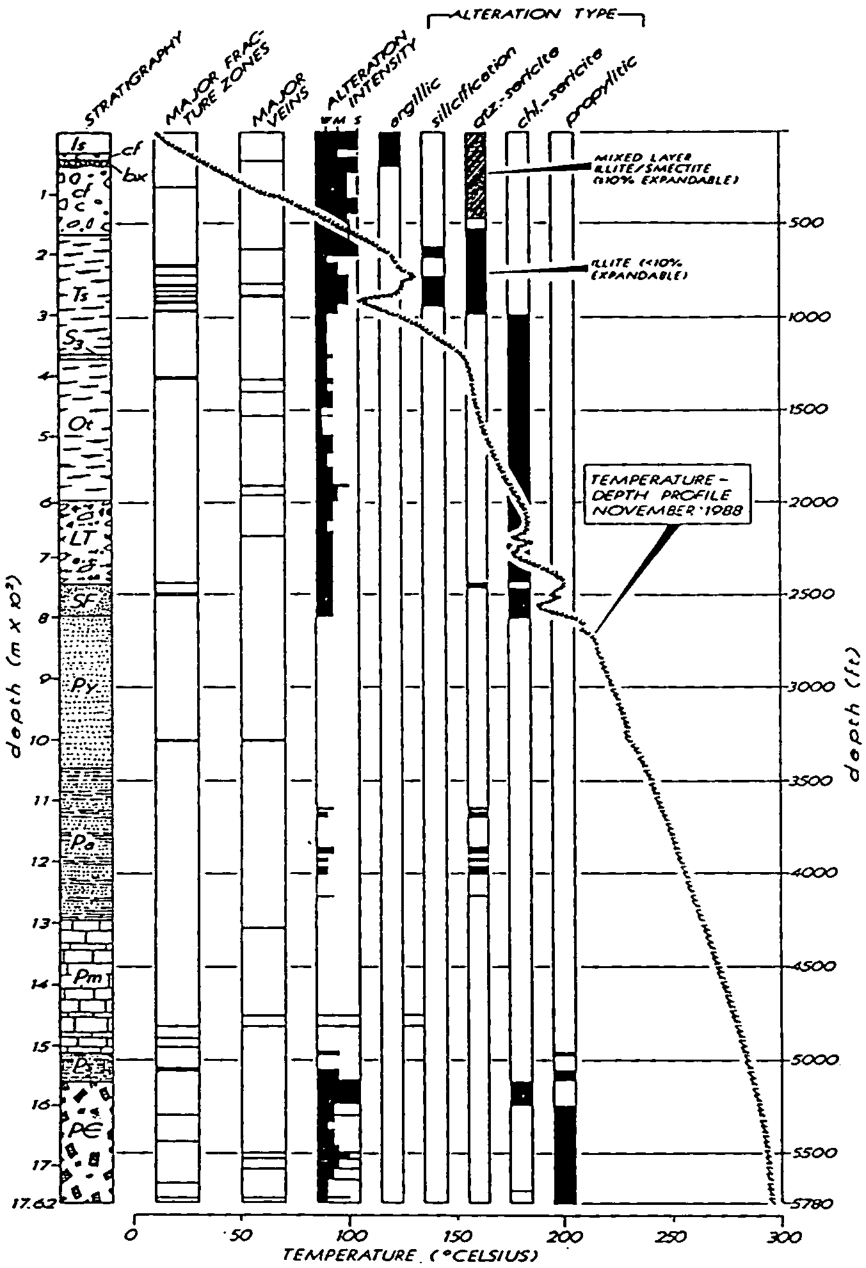

Figure ~~2~~ 8. Summarized geologic log for CSDP core hole VC-2b, Sulphur Springs area, Valles caldera, New Mexico (ls = landslide; cf = caldera-fill clastic rocks; bx = hydrothermal breccia; Ts = Tshirege Member of Bandelier Tuff; S_3 = S_3 clastic deposits; Ot = Otowi Member of Bandelier Tuff; LT = Lower Tuffs; SF = Santa Fe Group sandstone; Py = Permian Yeso Fm.; Pa = Permian Abo Fm.; Pm = Penn. Madera Limestone; Ps = Penn. Sandia Fm.; PC = Precambrian quartz monzonite). (Figure from Hulen and Gardner, 1989.)

STRATIGRAPHY AND STRUCTURE

The stratigraphy encountered in VC-2b is shown, generalized from the log of Hulen and Gardner (1989), in Figure 2. The sequence consists of variably altered Quaternary volcanic and volcaniclastic intracaldera rocks, Tertiary sedimentary deposits, Paleozoic red beds and carbonates, and Precambrian quartz monzonite. In general, the stratigraphic sequence fits well with those previously recognized within the caldera and the Jemez Mountains region (Smith et al., 1970; Nielson and Hulen, 1984; Gardner et al., 1986). The top 168 m of the caldera-fill sequence consists of interbedded accretionary lapilli tuffs, coarse clastic breccias, and fine-grained lacustrine rocks that exhibit hydrothermal alteration that apparently pre-dates soft sediment deformation. These relations imply that a lake, with temperatures approaching the boiling

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Soviet-American Monograph on Geothermal Energy

To: Wilf Elders, Hugh Murphy, John Lund
and American Co-Authors

Subject: NewsMemo No. 12

Date: 30 January 1993

It has been a long time since the last Newsletter (No. 11 of 30 Sep 92) about the Status of our Monograph. Momentum has slipped considerably, but the negative comments heard at the SGP Workshop this week about the success of the Monograph (and therefore the RGA Symposium in June 1993) should re-stimulate our efforts, especially as the "critical" time is approaching.

Following telephone conversations with the three Volume Editors this week, it was agreed that each of the Editors would request the chapter Authors to send a short letter to the Russian Co-Author either confirming the current Outline or suggesting revisions; and indicating which Sections are (or will be) in preparation for the First Draft of the Chapter.

Enclosed is a copy of the Second letter announcement of the RGA Symposium from SPMI Rector Proskuryakov with the Preliminary Program and Registration Form. Plenary Sessions 2, 3, and 4 are expected to start with Status Reviews of the respective Volumes by the Volume Editors followed by contributed papers from as many Chapter Authors as possible. We have requested DOE travel assistance for at least the three Volume Editors. For those able to participate in the Symposium with papers based on the Chapter topic, a one-page Abstract is due by 15 March.

It also appears that in spite of the difficult budget problems at DOE Geothermal Division, some assistance for translation services may be forthcoming. This will assist us markedly in getting the Chapters prepared efficiently. I appeal to each of you to prepare the designated Sections for the First Draft of your Chapter and send it to your Volume Editor and Russian Co-Author before 15 March.

As the 15 March critical time approaches, lets bear down and get the Monograph underway. I look forward to hearing from each of you soon.

With Best Wishes,

Paul Kruger

SAINT PETERSBURG MINING INSTITUTE
AND
RUSSIAN GEOTHERMAL ASSOCIATION

INTERNATIONAL SYMPOSIUM ON PROBLEMS OF GEOTHERMAL ENERGY

June 21-27, 1993
St. Petersburg, Russia

Saint Petersburg
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199026, St. Petersburg/Russia
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Johann Fößmeier
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Tel: (040) 34-06-01
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Foreign Co-Chairman of the Programm Committee
Professor Paul Kruger
Department of Civil Engineering
Stanford University
Stanford, California 94305 USA
TELEX: 372871 STNFRD-STNU
FAX: (415) 725-8662

Dear Participant:

Geothermal energy is of fundamental importance for our understanding of natural history. It is the energy for all geologic processes. However, our knowledge of geothermal phenomena is insufficient to control catastrophic earth energy transformations such as earthquakes and volcanic eruptions.

Resources of geothermal energy are almost unlimited. Geothermal energy is environmentally safe and one of the cheapest energy sources. But today utilization of geothermal energy in the energy balance of the world is rather small, primarily due to the limited knowledge of the distribution of geothermal resources, the scientific basis for the technology of extraction, and practical utilization of geothermal energy.

The general aim of our symposium is the improvement of the scientific basis for the complex problems concerning the nature of resources, the technology of extraction, and utilization of geothermal energy.

We hope that your participation in the symposium will be useful, successful and pleasant. We welcome you to Saint Petersburg, one of the most beautiful cities in the world, and we look forward to greeting you at the St. Petersburg Mining Institute, the oldest academic engineering school in Russia.

Sincerely,

Nikolay M. Proskuryakov
Symposium Chairman
Rector - St.P.M.I.

Preliminary Programme

Monday 21 June	9:00-10:00	Conference and Hotel Registration
	10:00-13:00	Plenary Session1: Welcoming Addresses and Symposium Opening Review Reports from Geothermal Countries
	13:00-14:00	Lunch
	14:00-18:00	Visit to Mining Museum and St. Petersburg Bus Excursion
	19:00	Welcoming Supper
Tuesday 22 June	10:00-13:00	Plenary Session 2: Problems of Heat Flow, Geotemperatures Field and Geothermal Resources (A) Review Reports from Geothermal Countries
	13:00-14:00	Lunch
	14:00-17:00	1st Parallel Sessions of Sections A, B, C
Wednesday 23 June	10:00-13:00	Plenary Session 3: Problems of Technology of Geothermal Energy and Fluids Extraction (B)
	13:00-14:00	Lunch
	14:00-17:00	2nd Parallel Sessions of Sections A, B, C
Thursday 24 June	10:00-13:00	Plenary Session 4: Problems of Geothermal Energy and Thermal Water Utilization (C)
	13:00-14:00	Lunch
	14:00-17:00	3rd Parallel Sessions of Sections A, B, C
Friday 25 June	10:00-12:00	Final Plenary Session: Short Reports from Sections A, B, C
	12:00-13:00	Lunch
	13:00-18:00	Bus Excursion: Sites in and around St. Petersburg
	19:00	Farewell Supper
Saturday and Sunday 26-27 June		Tours by Cultural Program Participants and Guests Departure

REGISTRATION FORM

Surname: First name: Title:

Institution: Department:

Mailing Address:
Street: City: Country:

Postal Code: Telephone: FAX:

Title of Paper:

Have you already submitted your abstract?:

_______ yes

_______ no; I shall submit it by March 15, 1993.

Your section:
1 A.........
2 B.........
3 C.........

Accompanying Person(s):

Registration Fees:
Participant: US$ 250.00:_________
RGA Memeber: US$ 200.00:_________
Accompanying Persons: US$125.00:_________

Hotel Reservations:
St. Petersburg Mining Institute Hotel: (Meals included)
Single: US$ 95.00 _____ Double US$ 135.00 _____
Hotel Pribaltyskaja: (Meals not included)
Double: US$ 160.00 _____ Suite: US$ 230.00 _____

Date of Arrival: Date of Departure:

Signature: ______________________________ Date: ______________

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27 April 1992

Dr. Phillip M. Wright
Univ. of Utah Res. Inst.
391-C Chipeta Way
Salt Lake City, UT 84108

Dear Mike:

Enclosed is the "Original" copy of the material for Ch-1.4 given to me by Prof. V. I. Kononov in Moscow last October, which I then forwarded (with other material of Vol.1) to Pat Muffler for distribution. I just recently received these back from Pat, who you know has quit as Editor of Volume 1 and I am sending the Originals directly to the volume authors. Grant Heiken of LANL has replaced Pat as Editor of Volume 1.

At this late time, I am suggesting that you look over the draft material in Russian (as best you can) and respond to it directly with Dr. Kononov (who speaks good English) to finalize the Chapter Outline and first draft responsibilities. Please send copies of any correspondence to both Grant and me so that we can keep track of progress.

So far we are still on target for compiling the Volume drafts by the end of the year and preparing for the June 1993 Symposium in Saint Petersburg.

Sincerely,

Paul

Paul Kruger

CC: Grant Heiken
Geology Group MS-D462
Los Alamos Nat'l Lab
Los Alamos NM 87545
Eds., Vol.1,2
Y.D. Dyadkin, SPMI

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Soviet-American Monograph on Geothermal Energy

To: Grant Heiken, Hugh Murphy, John Lund
American Co-Authors of Volume 1

Subject: Change in Editorship

Date: 14 April 1992

It seems like the Monograph is starting to move forward, again !

As you probably already know, the USGS has pulled out of the Russian-American Monograph; Wendle Duffield has given up on Chapter 1.1 and Pat Muffler on Chapter 1.3 and as Volume 1 editor. We have been fortunate in getting excellent replacements: Dennis Nielson (UURI) for Chapter 1.1 and Grant Heiken (LANL) for Chapter 1.3 and Volume 1. Grant has recently edited two beautiful books and his expertise will be most welcome.

I am enclosing a recent letter to Yuri Dyadkin which announces these changes. It appears that the Monograph is very much alive with a milestone coming up for having the First Drafts in time for the First Russian International Symposium, now scheduled for 21-27 June 1993. We have the "Responses" to the draft Outlines for Volumes 2 and 3 from the Russian Co-authors and Hugh Murphy and John Lund are in the process of getting them translated and off to the chapter Authors to begin preparation of the drafts. I hope to move the Russians on Volume 1 (Nielson's draft of new Ch 1.1 is enclosed) and when I have the new draft for Ch 1.3, will request a set of Russian "Responses". That should get the drafts for Vol 1 well underway in time. However, I still advise, if you stick to your current Outlines, to begin preparation of your Sections and send them to your Co-authors.

Hope to have more news soon.

Paul Kruger

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10 April 1992

Prof. Yuri D. Dyadkin
St. Petersburg Mining Institute
21 Liniya, dom 2
Saint Petersburg, 199026 USSR

Dear Yuri:

I have received your letter of 24 March with the Second set of three Picture calendars (for which I thank you very much). The news items were very interesting (I have passed on to LANL the news about the drilling of the Second well). With respect to the Monograph, there are several new developments:

(1) the Russian versions of the Chapter Outlines for Volumes 2 and 3 have been received. These have been sent to the Respective Volume Editors for translation into English and sending to the Chapter authors for initiating the First Drafts of the chapters

(2) for Volume 1, we are essentially starting over again! The new Editor of Volume 1 is Grant Heiken of LANL. He will also (with an American co-author) be the author of Chapter 1.3. I will send you the proposed Chapter 1.3 Outline as soon as I can. For the first Chapter, 1.1, we have been fortunate to obtain Dennis Nielson (from UURI) to prepare this first chapter. I am enclosing a copy of the First Draft of the new Chapter Outline for review of the two Russian co-authors.

(3) Several of the chapters are underway: (Ping Cheng with Semen Gendler; you with Hugh; and Mohinder Gulati with Ostapenko). The others have not yet had any author-author contact. I have not had any word from Alexei Kiryukhin since October'91. If I don't hear from him soon, I will proceed with the chapter alone. (Perhaps a change in Russian co-author is needed?) Norman Goldstein of LBL is still waiting to hear from Anna Vainblat. It would be very useful to accelerate the contacts (especially for Vol 1).

We look forward to hearing from you with developments on the Monograph and Symposium. We understand that life in Saint Petersburg is very difficult these days and hope that you and Irina and Tatyana are managing well. We wish you good fortune!!

Yours sincerely,

Paul

CC: G. Heiken (LANL)
D. Nielson (UURI)
H. Murphy (LANL)
J. Lund (OIT)

Chapter 1.1
NATURE OF GEOTHERMAL SYSTEMS

American CoAuthor: Dennis L. Nielson
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Tel: 801+524-3439
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Tlx: tbd

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Moscow 109017 USSR
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Fax: tbd
Telex: tbd

Chapter Outline (24 Mar 92)	Suggested Responsible Co-Author
I. Introduction	DLN
II. Convective Hydrothermal Systems	DLN*
A. Heat Sources	
B. Fluids	
1. Hot Water	
2. Vapor	
C. Porosity and Permeability*	
D. Alteration*	
E. Case Studies	
1. USA (Geysers, Roosevelt Hot Springs)*	
2. CIS	AAS/BGP
3. Other	AAS/BGP
III. Regional Aquifers	AAS/BGP
A. Heat Source	
B. Fluids	
C. Porosity and Permeability	
D. Alterations	
E. Case Studies	
1. USA	DLN
2. CIS	
3. Other	
IV. Conductive (HDR) Systems	AAS/BGP
A. Heat Source	
B. Porosity and Permeability	
C. Alteration	
D. Case Studies	
1. USA (Fenton Hill)	DLN
2. CIS	
3. Other	
V. Geopressured Systems	AAS/BGP
A. Heat Source	
B. Fluids	
C. Porosity and Permeability	
D. Alteration	
E. Case Studies	
1. USA (Gladys McCall)	DLN
2. CIS	
3. Other	
VI. References	(as compiled)

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April 10, 1992

Dr. John E. Mock
Geothermal Division, CE-122
U.S. Department of Energy
1000 Independence Avenue, S.W.
Washington, D.C. 20585

Dear Ted:

In preparation for the trip to Morelia on 11 May for the Administrative meeting with CFE Gerencia under the DOE-CFE Geothermal Agreement, I have 'finalized' the 30 Oct 91 Meeting Report with all Project Summaries on hand as of 10 April 92. I have received a copy of the available Summaries (in Spanish) from CFE. Copies of the Final Meeting Report are being distributed to the meeting participants and a copy is being Express Mailed to Dr. G. Hiriart at CFE.

Per your request, a draft Agenda for the meeting is being prepared. Among the major items that need to be discussed are: (1) undoing the damage of the M.Reed DOE letter to CFE on the funded and unfunded joint studies; (2) planning for continuation (with and without direct funding) of the ongoing and proposed joint projects; (3) planning for the Second Technical Meeting (during the GRC Annual Meeting, San Diego, October, 1992); and (4) discussion on future activities.

Sincerely,

Paul Kruger

Distribution:
    LBL (Lippmann)
    LANL (Robinson)
    OIT (Lund)
    SGP (Kruger)
→ UURI (Wright)
CC: CFE (Hiriart)

DOE-CFE GEOTHERMAL AGREEMENT

PROJECT SUMMARIES

FIRST TECHNICAL MEETING

CERRO PRIETO, MEXICALI

29-30 October 1991

Final Meeting Report
Dr. G. Hiriart (CFE) Dr. P. Kruger (DOE)
10 April 1992

INTRODUCTION

The first technical meeting of Co-Principal Investigators of the initial list of projects defined for the renewed DOE-CFE Geothermal Agreement was held at Cerro Prieto, Mexicali, B.C. on 29-30 October 1991. The Agenda for the meeting is given in Appendix 1. The meeting consisted of joint presentations by the co-principal investigators of both the existing projects under the agreement and proposed projects for inclusion for the following year of the agreement. The output from the meeting consisted of a set of draft Project Summaries prepared by each pair of principal investigators. The summaries constitute the current technical status of the DOE-CFE Geothermal Agreement. A Draft Report was distributed on 30 October 1991. This report constitutes the Final Report.

ATTENDANCE

for DOE

P. Kruger, SGP
(for J. Mock, DOE)
M. Reed, DOE
M. Lippmann, LBL
A. Truesdell, LBL
C. Grigsby, LANL
(for B. Robinson, LANL)
J. Lund, OIT
J. Moore, UURI
P. Kruger, SGP
(for M. Wolfe, IGA)

for CFE

G. Hiriart, GPG
(for M. Ramirez, CFE)
L. Quijano, GPG
H. Gutierrez, GPG
F. Arellano, GPG
A. Manon, GPG
M. Rangel, GPG
C. Suarez, GPG
R. Marquez, RGCP
B. Terrazas, RGCP
H. Lira, RGCP

DECISIONS

(1) The Project Summaries prepared on the second day of the meeting constitute the Acta of the First Technical Meeting.

(2) The next Administrative meeting (and get-together of available principal investigators) was planned to be held in conjunction with the 16th Annual SGP Workshop at Stanford University during 29-31 January 1992. The meeting was postoned until 11 May 1992 in Morelia, Mich.

(3) The Second Technical Meeting is scheduled to be in conjunction with the Annual Conference of the Geothermal Resources Council in San Diego during October 1992.

Appendix 1

DOE-CFE First Technical Meeting
Mexicali, B.C.
29-30 October 1991

AGENDA
(Revised for Actual Summary Outlines)

	for DOE	for CFE
29 October		
Opening Remarks		F. Soto, RGCP
Status Reports	P. Kruger, DOE	G. Hiriart, CFE
1. C.P. Evaluation	M. Lippman, LBL	R. Marquez, RGCP
2. C.P. Chemistry	A. Truesdell, LBL	L. Quijano, GPG B. Terrazas, RGCP
3. L.Az. Tracers	B. Robinson, LANL	H. Gutierrez, GPG
4. L.Az. ChemResEng	P. Kruger, SGP	H. Gutierrez, GPG
5. L.Hu. Model	M. Lippmann, LBL	C. Suarez, GPG
6. L.Hu. Geochem	A. Truesdell, LBL	A. Manon, GPG
7. L.Az. Heat Extr	P. Kruger, SGP	H. Gutierrez, GPG
New Studies		
8a. Expl-Tres Virg.	J. Moore, UURI	S. Venegas, GPG
8b. Expl-Ceboruco	M. Wright, UURI	F. Arellano, GPG
9. Direct Uses	J. Lund, OIT	M. Rangel, GPG
10. Hydrogen	P. Kruger, SGP	M. Rangel, GPG
Open Discussion	P. Kruger, DOE	G. Hiriart, CFE
30 October		
Preparation of Project Summaries	DOE Pr. Invest.	CFE Pr. Invest.

PROJECT SUMMARY No.1
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

MODELING OF CERRO PRIETO

M. Lippmann
LBL
DOE

R. Marquez
RGCP
CFE

PROJECT SUMMARY NOT AVAILABLE

PROJECT SUMMARY No.2
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

GEOCHEMICAL EVOLUTION OF PRODUCED FLUIDS AT CERRO PRIETO

A. Truesdell
LBL
DOE

B.Terrazas, J.L. Quijano
Gerencia
CFE

PROJECT SUMMARY NOT AVAILABLE

PROJECT SUMMARY No.3
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

STUDIES OF USE OF TEMPERATURE-SENSITIVE TRACERS

Bruce Robinson
LANL
DOE

Hector Gutierrez
Gerencia
CFE

Program:
Tasks.

1. Design and Perform Conservative Tracer Tests

Previous tracer tests at Los Azufres used Ir-192 as a Tracer. However, Iridium was never observed in any of the production fluids probably due to absorption in the reservoir. This task is to (a) review possible conservative tracers for use at Los Azufres, (b) test tracer absorption using actual geothermal fluid and reservoir rocks, (c) field a tracer test at Los Azufres, and (d) evaluate data with a reservoir tracer model.

2. Design and Perform Reactive Tracer Test.

Based on results of the conservative tracer tests and on laboratory screening of potential reactive tracers, a reactive tracer test can be designed for Los Azufres. The steps involved in this task are (a) test the detectability of the proposed reactive tracer and reaction products in the actual geothermal fluid, (b) test for absorption of the tracer and of the reaction products, (c) field a reactive tracer test in conjunction with a conservative tracer test, and (d) evaluate the results of the combined tests.

Schedule

1992	
Jan	Select conservative tracer (conservative, reactive)
May-Jun	Perform conservative tracer test
Oct (at GRC)	Present conservative tracer results Preliminary selection of reactive tracer
1993	
Jan-Feb	Perform reactive tracer test
Oct	Present reactive tracer results.

PROJECT SUMMARY No.4
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

CONTINUATION OF THE JOINT STUDY ON CHEMICAL RESERVOIR ENGINEERING AT LOS AZUFRES and LOS HUMEROS PRODUCTION WELLS

Paul Kruger	Hector Gutierrez
SGP	Gerencia
DOE	CFE

Background:

The joint study has been underway since the startup of the initial 5-MWe Units at Los Azufres to examine the thermal drawdown in the production zones based on combined analyses of the thermodynamic and chemical behavior during production. Analyses were prepared for several wells after 2.5, 4, and 5 years of production. Further analysis of these and newer wells is currently underway. The results of these analyses have been published.

Objective:

The joint study evaluates the extent of the small changes observed in the reservoir around the production wells of the small Units in the potentially large Los Azufres (and Los Humeros) geothermal fields. The evaluation provides information concerning the extent of thermal drawdown in production fluid and hydraulic drawdown in the reservoir.

Program:

The study consists of each-sample and semester-averaged analysis of fluid production with respect to temperature, enthalpy, and thermal extraction rate, chemical characteristics with respect to near-well and far-field geochemical temperatures, and drawdown evaluation based on saturation temperatures and estimation of total production volume. For the joint study, continued evaluation will be made of wells Az-5 and Az-13 in the Maritaro zone, well Az-9 in the El Chino zone, and wells Az-16AD and Az-22 in the Tejamaniles zone at Los Azufres and for one or more representative wells at Los Humeros.

PROJECT SUMMARY No.5
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

MODELING OF LOS HUMEROS

Marcelo Lippmann
LBL
DOE

Cesar Suarez
Gerencia
CFE

PROJECT SUMMARY NOT AVAILABLE

PROJECT SUMMARY No.6
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

PRODUCTION OF HCl IN WELLS OF LOS HUMEROS

A. Truesdell
LBL
DOE

A. Manon
Gerencia
CFE

PROJECT SUMMARY NOT AVAILABLE

PROJECT SUMMARY No. 7
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

CONTINUATION OF THE JOINT STUDY ON THERMAL RECOVERY FROM REINJECTION RECHARGE AT LOS AZUFRES

Paul Kruger
SGP
DOE

Hector Gutierrez
Gerencia
CFE

Background:

Prior efforts under the original DOE-CFE Geothermal Agreement involved the evaluation of the effects of reinjection recharge on the potential for both premature thermal breakthrough and for secondary recovery of the thermal resource in 10 study areas of the three Los Azufres production zones. The results indicated possible fluid temperature decline ranging from early breakthrough in closely spaced well pairs (e.g., Az-31 - Az-26) to very long heat sweeps (e.g., Az-40 - Az-5,Az-13).

Objective:

The joint study is focused on estimating, for a given CFE production-reinjection operating strategy, the temperature decline curve to a given abandonment temperature, the potential for enhanced recovery of reservoir energy, and insight on optimum selection of reinjection wells.

Program:

The continued study will involve re-evaluation of the current production-reinjection strategies contemplated by CFE for the older and newer Unit production areas at Los Azufres (and also, if desired by CFE, for the new Unit wells at Los Humeros) and simulation of the potential heat sweep characteristics under these strategies.

PROJECT SUMMARY No.8a
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

A PETROLOGIC AND FLUID INCLUSION STUDY OF SAMPLES FROM THE TRES VIRGENES GEOTHERMAL FIELD

J. Moore
UURI
DOE

S. Venegas
Gerencia
CFE

Background

Tres Virgenes is a volcanic-related geothermal system that is hosted in granite. To date, exploration efforts have included geologic mapping, resistivity, gravity, magnetic and radon surveys and the drilling of a 1112 m exploration hole (LV-2). This well recorded a bottom-hole temperature of 220°C and displayed increasing temperature with depth throughout its length.

Project Description

We propose to jointly conduct petrologic and fluid inclusion studies of cuttings from the exploration well to better evaluate the nature and stratigraphy of the rocks, the extent and distribution of the hydrothermal alteration, and the temperatures and compositions of the fluids responsible for the observed changes. This data will be compared with the drilling results and the compositions of the hot springs and produced fluids to better evaluate permeability variations in these rocks and refine the existing hydrogeochemical models of the system.

CFE will conduct the initial petrologic studies of the well samples. UURI will augment these analyses by providing chemical, X-ray diffraction and fluid inclusion data.

The results of this work will be jointly integrated with the geophysical data to evaluate the causes of the observed anomalies.

Schedule

The proposed work will require approximately 18 months to complete. Additional wells will be studied jointly as they are drilled.

Benefits

Granite-hosted geothermal systems will account for the majority of the electric power produced in the Basin and Range province of California, Nevada, and Utah. This work will benefit DOE by providing additional information on the hydrogeochemical and geophysical characteristics of granite-hosted geothermal systems.

PROJECT SUMMARY No.8b
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

AN ASSESSMENT OF GEOPHYSICAL EXPLORATION TECHNIQUES: A CASE STUDY OF THE CEBORUCO GEOTHERMAL FIELD

M. Wright
UURI
DOE

F. Arellano
Gerencia
CFE

Background

The Tepic graben is an important structural and volcanic province that holds significant potential for the discovery of new geothermal resources in the state Nayarit. Ceboruco is located in the southeast part of the graben in an area of numerous warm springs and recent volcanism. Since 1988, detailed aeromagnetic and MT data have been collected by CFE to evaluate the structural setting and geothermal potential of the region. A Preliminary interpretation of the data has been completed by CFE. Five thermal gradient holes are scheduled to be drilled in the near future.

Project Description

The primary purpose of the proposed joint CFE-DOE investigation is to assess the application of these geophysical methods to regional exploration. Toward this goal, we propose the following tasks:

1. Complete interpretation of the aeromagnetic and MT data.
2. Integrate the different geophysical data sets with each other and known geologic relationships to assess the application of these techniques.
3. Cooperate in the petrographic analysis of cuttings and rock samples from the gradient holes and outcrops.

Schedule

Task 1 will require approximately 1 year to complete. We anticipate that Tasks 1 and 2 will require an additional year. Petrographic studies (Task 3) will be conducted as the gradient wells are drilled.

Benefits

The proposed program will benefit both CFE and DOE. The project will be an important case study of the application of MT and aeromagnetic surveys to regional exploration in volcanic environments. Such information will be of use to the U.S. geothermal industry currently investigating similar environments in the northwest.

PROJECT SUMMARY No.9
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

DIRECT USE OF GEOTHERMAL ENERGY IN MEXICO

J. Lund
OIT
DOE

M. Rangel
Gerencia
CFE

Background:

Mexico, at present, has the third largest geothermal power generating capacity in the world, primarily located at Cerro Prieto and Los Azufres. However, direct utilization of geothermal energy is minimal. The USA among other countries, on the other hand, has considerable experience in the evaluation and use of geothermal energy for direct use project. The Geo-Heat Center has performed extensive work in this area.

In Mexico, the first studies of direct use was made in the years 1983-85 in cooperation with the government of Baja California; a bank, and private industry. They investigated, on a limited scale, projects in aquaculture, agriculture, animal husbandry, and space conditioning (cooling). However, for economic reasons, these studies did not lead to an actual field demonstration project.

In the middle of 1989, CFE-Mexico analyzed the development of an industrial park adjacent to the Cerro Prieto geothermal field. The purpose of this park was to make comprehensive utilization of the residual heat and solid by-products (silica, salts, etc.) from the brine produced by the power generation process. Presently, the legal and economic implications of this 580 ha (1400 acre) industrial park is being reviewed. Land can also be made available for industrial development at Los Azufres.

Objectives:

The objectives of this joint study between CFE-Mexico and DOE-USA are to investigate the potential utilization of:

1. The residual heat, and
2. The residual solids (silica, salts, etc.)

from the geothermal brines at Cerro Prieto and Los Azufres based on the characteristics of the two sites according to their unique locations, and the heat content and chemical composition of the brines.

Program:

In the first year, the investigators propose to accomplish the following:

1. Review of existing direct use projects in the USA and other countries which would be applicable to either the Cerro Prieto or Los Azufres sites.

2. Evaluate the residual heat and solids at both sites.

3. Determine the thermal conductivity of existing mixtures of silica and other products in the form of bricks for building construction (CFE).

4. Evaluate mixtures of silica with asphalt and other additives (cement, lime, etc.) for road surfacing (Geo-Heat Center).

5. Based on results from tasks #1 - 4: Define the projects that are most promising for either sites based on engineering and economic analyses.

In the second year of the investigation, it is proposed to:

6. Develop, design and construct a pilot "plant" at each site to demonstrate to local industry the economic and practical feasibility of utilizing either the residual heat or residual solids.

PROJECT SUMMARY No.10
DOE-CFE GEOTHERMAL AGREEMENT
30 October 1991

FEASIBILITY STUDY OF THE POTENTIAL TO USE EXCESS GEOTHERMAL CAPACITY FOR GENERATION OF LIQUID HYDROGEN AS A FUTURE TRANSPORTATION FUEL

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Background:

World-wide interest is growing in the possibility of utilizing renewable energy resources on a larger scale, following the decline of fossil fuels, especially for progressive replacement of petroleum as a transportation fuel. Specific interest has developed in the potential for utilizing excess geothermal capacity, in areas having large reserves, for base-load generation of electrical energy for electrolysis of water to produce liquid hydrogen. Two regions have been suggested for initial evaluation: (1) Alaska and the Kamchatka Peninsula for distribution of liquid hydrogen between the USA, USSR, and Japan, and (2) the northern region of Mexico for distribution between the USA and Mexico.

Objective:

The joint study will be a feasibility study of the technical and economic potential to develop sufficient excess capacity of geothermal electric power in Mexico for production and distribution of liquid hydrogen as a commercial product.

Program:

The study would involve an estimation of the potential excess geothermal generating capacity that could be developed based on volumetric heat content of prospective resources in Mexico and potential extraction efficiency, the energetics of hydrogen generation and compression to liquid state, and economic modes for distribution to markets.

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GEOTHERMAL ENERGY
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(Draft:11Dec89)

Volume 1 Resources

Volume Editors
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1.1 Nature of Geothermal Energy
USSR:
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1.2 Heat Flow Distribution and Geothermal Anomalies
USSR:
USA: D. Blackwell (SMU)

1.3 Resource Base and Resource by Type
USSR:
USA: P. Muffler (USGS)

1.4 Exploration Geosciences (geology,geophysics,geochemistry)
USSR:
USA: P. Wright (UURI)

1.5 Prospect Evauation
USSR:
USA: N. Goldstein (LBL)

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Volume 2 Extraction

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2.1 Characteristics of Geothermal Reservoirs
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2.2 Drilling and Completion of Geothermal Wells
USSR:
USA: (a) JD,DT (Sandia); (b) ? (LANL); (c) ? (Unocal)

2.3 Well and Reservoir Testing
USSR:
USA: M. Gulati (Unocal)

2.4 Reservoir Diagnostics
USSR:
USA: B. Robinson (LANL)?

2.5 Reinjection
USSR:
USA: ? (Unocal)

2.6 Stimulation
USSR:
USA: R. Veatch (Amoco)

2.7 Artificial Geothermal Systems
USSR:
USA: H. Murphy (LANL)

2.8 Heat and Mass Transfer Processes in Geothermal Systems
USSR:
USA: P. Cheng (UHa)

2.9 Management and Economics of Geothermal Fields
USSR:
USA: S. Sanyal (Geothermex)

2.10 Potential for Magmatic Heat Extraction (?)
USSR:
USA: ? (Sandia)

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Volume 3 Utilization

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3.2 Thermodynamics of Conversion Processes
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3.3 Electric Power Plants and Steam Cycles
USSR:
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3.4 Binary Conversion Cycles
USSR:
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3.5 Advanced Conversion Cycles
USSR:
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(E. Hughes EPRI)
3.6 Basic Direct heat Technology
USSR:
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3.7 Municipal Heat Supply Systems
USSR:
USA: K. Rafferty (Geo-Heat Center OIT)
3.8 Industrial Heat and Mineral Extraction
USSR:
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3.9 Agricultural and Aquacultural Heat Supply
USSR:
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3.10 Thermal Water Balneology
USSR:
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3.11 Environmental Aspects of Geothermal Power Engineering
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Volume 1. Resources (Volume Editors: V. Kononov, P. Muffler)

1.1 Nature of Geothermal Energy
1.2 Heat Flow Distribution and Geothermal Anomalies
1.3 Resource Base and Resources by Type
1.4 Exploration Geosciences (Geology, Geophysics, Geochemistry)
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Volume 2. Extraction (Volume Editors: E. Boguslavsky, H. Murphy)

2.1 Characteristics of Geothermal Reservoirs
2.2 Drilling and Completion of Geothermal Wells
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2.7 Artificial Circulation Systems
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2.9 Management and Economics of Geothermal Fields
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Volume 3. Utilization (Volume Editors: G. Gaidarov, J. Lund)

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