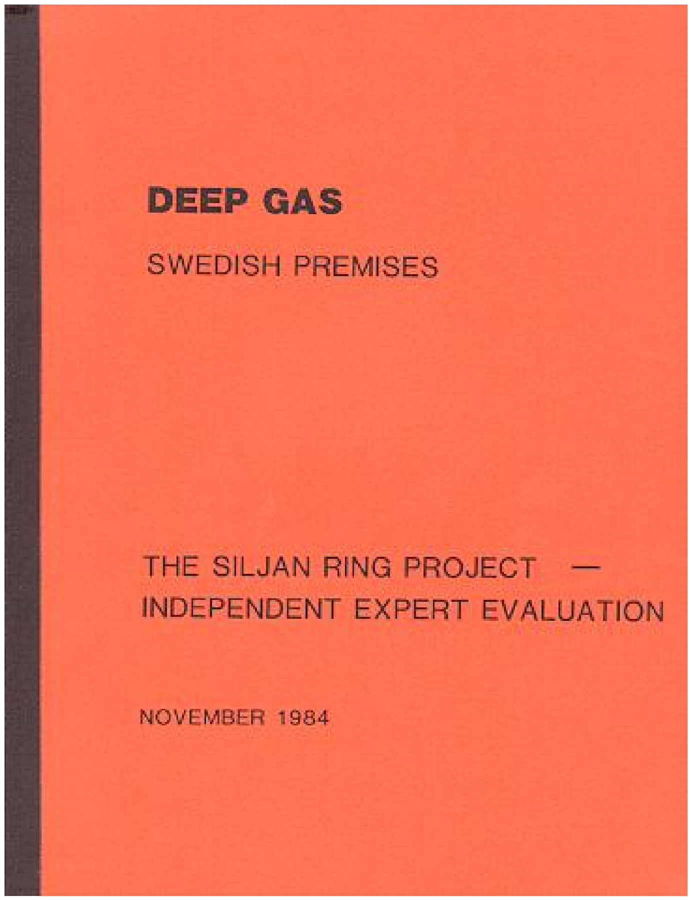
Siljan Crater Findings Reported to Vattenfall in 1984 Remain Unchanged

Richard R. Donofrio, EDGe Research Associate, August 2005



The Siljan Ring (Siljan impact structure) is Europe's largest meteorite-impact crater, having a diameter of ~50-km. In 1984 Vattenfall (Swedish State Power Board) convened an independent team of geoscientists to evaluate this crater for commercial abiogenic gas production. The findings of the independent group were printed by Vattenfall and circulated primarily as an internal report. This 63-page document, pictured above, has been shown on European TV but is rarely found in the literature or online. For example, the comprehensive Earth Impact Database lists over 70 references for Siljan, but no mention of the above. This report was the only independent team evaluation of Siljan prior to drilling.

The findings in the unheeded report discouraged commercial exploration. Today, after renewed interest in abiogenic hydrocarbons, dozens of Siljan publications, two deep wells (one reached ~6,800 m [22,300 ft]), expenditures of tens of millions of dollars, a multitude of displeased investors, and over 20 years of controversy, the independent team findings remain valid and are presented here without restraint.

The Independent Group

The independent / expert group selected by Vattenfall to evaluate the Siljan crater for exploratory drilling of commercial abiogenic hydrocarbons consisted of 5 geoscientists; 3 from the United States and 2 from Sweden:

Richard R. Donofrio - Astro Geological Resources, USA – petroleum geology

Kenneth H. Olsen - Los Alamos National Laboratory, USA – geophysics

Fred W. Vlierboom - Occidental, USA – petroleum geochemistry

Fred Witschard - Studsvik Analytica, Sweden – regional geology

Goran Petersson - Studsvik Analytica, Sweden – regional geology

We were at the Siljan crater in June of 1984 and in Stockholm on several occasions in the fall of the same year. A meeting was also held at a Washington D.C. law firm, which represented Professor Thomas Gold and Vattenfall. The report was written in the USA and Sweden and compiled, edited, and printed at Vattenfall Headquarters in Stockholm during the final group meeting. The language barrier was negligible in both oral and written communication. The **preface**, **conclusions**, and **recommendations** from this 1984 report are provided verbatim below for those who are interested in the Siljan impact structure and abiogenic hydrocarbons. Also included is the expectation model, *written by* Vattenfall. Readers can compare this 1984 evaluation to the later drilling results at Siljan and understand why our independent group discouraged commercial drilling. Typographical errors in the report have been corrected and do not alter the content.

PREFACE

The Deep Gas Project conducted by Vattenfall is based on a theory that methane migrates from the inner regions of the earth and can subsequently be trapped and collected in geological structures of a suitable composition and configuration. This abiogenic deep gas theory is being developed by Professor Thomas Gold, USA, among others. It implies, in opposition to the generally accepted biogenic origin theory, that it could be possible to find natural gas not only in sedimentary basins but also, under special geological conditions, in crystalline rocks, which are the predominant type of bedrocks in Sweden. Proper reservoir conditions caused by fracturing of these rocks could exist, for instance, in the Siljan Ring structure, the largest known impact structure in Europe.

[Vattenfall's expectation model for the Siljan Ring is as follows:]

In the Siljan area the geological preconditions may exist for a gas reservoir in the crushed, crystalline rock. The gravimetric surveys carried out suggested that the crushed zone could be approximately 5 km deep with a porosity of about 5%. Other interpretations also had to be considered.

The most likely caprock structure in the area should consist of fairly shallow calcite-cemented granite rock. The depth of this calcite-cemented granite is unknown, but preliminary seismic surveys in 1983 showed some form of discontinuity at depths of 500 and 650 m.

In order to test this model the following studies were carried out:

The site-associated studies in the Siljan area have, in this stage, comprised the compilation of existing information and the drilling of 7 core-drill holes to depths between 100 and 700 m.

The core-drill holes have served to increase knowledge on the geology of the near-surface rock and determine the structure of the granite. The core-drill holes have been investigated by means of core examination, different types of logging, measurement of water losses, and geochemical sampling.

Geochemical analysis has been used to detect the existence and origin of seeping methane gas.

In addition to core drilling, a comprehensive compilation and analysis of existing data have been carried out, for instance, aerial geophysical surveys.

Moreover, a number of tests have been performed to investigate applications of different investigation techniques in crystalline basement rock. Some of these have contributed to valuable knowledge of geological conditions below current coring depth.

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(The entire report is 63 pages and includes 21 tables, diagrams, and figures. Topics included the origin of natural gas, the US ad hoc Committee on abiogenic methane, the Commission of the European Communities, Siljan regional geology and geophysics, energy estimates of the Siljan impact, extent of excavation and uplift, fracturing and mineralization vs. depth, erosion estimates, hydrocarbon potential, lithology, caprock geochemistry, carbon isotopes vs. depth, wireline well logs, pyrolysis of potential source rock samples, hydraulic conductivity, and other related items. It should be noted that Richard A. F. Grieve, one of the foremost authorities on impact cratering, was brought into the Siljan investigation by our independent group. He also authored a separate paper for Vattenfall on Siljan impact dynamics).

CONCLUSIONS

We fully recognize the strategic importance of future energy requirements for Sweden and the possible contribution of deep earth gas.

This evaluation is based on existing Siljan data accessible to us through Vattenfall. All of the information is not yet available. Recognizing this, we have analyzed given data to the best of our ability and have interpreted and presented our findings in an objective manner. Whenever expertise was required outside of our areas of specialization, we have resorted to authorities in specific fields. We express our deep appreciation to all of Vattenfall's personnel who have assisted us with our efforts. We conclude the following:

The Impact

Sufficient evidence exists to support the origin of the Siljan feature by meteorite impact. Fracturing could occur to depths of 8-10 kilometers. Estimations of fracturing at deeper levels are derived from theoretical considerations and remain speculative.

Regional Geology/Geophysics

Satellite imagery and airborne geophysics (magnetic and radiometric) indicate that the Siljan impact structure is intersected by a dense system of linear structures, mainly striking NW-SE. The most remarkable of the "lineaments" is filled with diabase and therefore reaches the mantle. It is interpreted as a major fault, limiting two vertically displaced blocks. The above pattern is common in granite-gneiss terrain of the Baltic shield and corresponds to a segmentation of the crust into roughly rectangular blocks with spacing of 1-10 kilometers. A detailed study of these dislocation zones in northern Sweden shows that we are often dealing with open fractures (reactivated faults, etc.). The hypothetical caprock at Siljan has therefore a good chance of being strongly fractured and sheared along the main linear structures mentioned above to at least a depth of a few kilometers.

Lithology and Geophysics

Measured porosities and permeabilities fall in the range of 0.5 to 2% and 10^{-9} to 10^{-10} m/s respectively (these are consistent with millidarcy units quoted elsewhere in this report). These values show that the near-surface (upper 1 km) Siljan granite is too tight and of insufficient porosity to function as an effective (and economic) <u>reservoir.</u> Probably more important, it is also too permeable to be a <u>caprock</u>. While gravimetric, magneto-telluric, and seismic data all suggest that greater porosity may exist at depths below 2 to 4 km, a realistic interpretation of these data indicates porosity in the lower region is possibly about 5% - certainly less than 10%. Similarly, while we expect permeabilities to decrease because of increasing lithostatic forces, our experience suggests that permeabilities at 2-4 km depth may only be marginal for effective caprock conditions. Worldwide drilling results in metamorphic, igneous, and sedimentary rocks usually show a consistent decrease in porosity and permeability with depth. We recognize, however, the complexities of an impact feature such as Siljan and leave open the possibility of porosity and permeability inversion at deeper levels in the central crater area.

The upper calcite caprock layer does not exist. The possible existence of additional calcite seals at deeper levels is speculative.

Geochemical Properties and Mineralogy of the Caprock

Mineralogical evidence indicates that calcite precipitation is not the predominant cause of mineralization. Comparison of calcite mineralization to iron oxide mineralization indicates that iron mineralization becomes more important than calcite below a depth of about 300 meters. Carbon isotope data from calcite indicate that the measured values are the most negative in the center of the ring and become more positive closer to the sedimentary rocks. If calcite were derived from a single oxidized methane gas source, no such differentiation in carbon isotope values should be evident. If calcite formed from oxidation and biodegradation of the Siljan crude oil, it should have values in the range of –28 to –31. No such values were found. In fact, all the carbon isotope values observed in the Siljan area fall in the same range as values observed elsewhere in Sweden. The contention that a caprock was formed by precipitation of calcite is not supported by observed data.

Source Rock

Unmistakable evidence found by geochemical analysis of oils, oil-stained rocks, and organic rocks points to the Ordovician bituminous Tretaspis Shale as the source for the oil found in the Siljan crater. Professor Gold's contention that the oil is abiogenic is without merit.

All the source rocks investigated were still immature and could not have reached maturity as indicated by their burial history. A relatively short period of additional heat flow could locally have matured the known source rocks enough to make generation and expulsion of the immature Siljan crude possible.

In general, hydrocarbon gas shows in the Siljan crater are minor, except in the Solberga well. As water in the Siljan area normally contains small amounts of hydrocarbon gas of bacteria origin (marsh gas), it is difficult to separate this background gas from observed gas in the boreholes. A number of gas shows are considered to be of bacterial origin.

In the Solberga well two basically different hydrocarbon gasses were found: one, a "wet" gas, is clearly related to the oils in the sedimentary rocks, while the other "dry" gas could be originating from a different source. No carbon isotope data were available to indicate the type and origin of this gas. It is purely speculative to assume it is abiogenic.

Varying quantities of hydrogen gas were found in the Siljan area. These could have originated from several different sources, such as: oxidation of ferrous oxide, reactions between surface and formation water, solid state reactions in minerals, and association with organic matter and or petroleum. Sufficient evidence is lacking to define the different sources.

Economic Considerations

Economics of the Siljan venture was not part of our original assignment, but we have included a rough estimate of production requirements for a shallow reservoir.

Depth

A hypothetical abiogenic gas reservoir has been placed immediately below 3 km. A shallower reservoir cannot be justified with existing seismic and magneto-telluric data. We will assume that the 3 km horizon represents some type of caprock (with structural closure) and that a 3.5 km well will be sufficient to penetrate the underlying reservoir. We will further assume that the reservoir has no complexities, occupies the central uplift, and that it will be discovered on the first well.

Well Cost

The expense of a 3.5 km test well has been investigated. A slim-hole (4 ¼") continuous coring operation would take about 5 ½ months to drill and cost $1.5 to $2.0 million. A larger rig would be needed for development drilling (7 7/8" hole) and completion and would require $3.5 to $4.0 million.

Gas Flow Rate

The petrophysical properties of the Dala granites are known from core analysis and indicate a porosity of about 1.5% at 500 meters. We have assumed, however, the porosity of this rock to be 5% at 3.5 km. This is in correspondence with the magneto-telluric data.

We further assume that calcite and other minerals, which partially plug the fractures at shallow depths, have been totally eliminated at 3.5 km. Any existing gas, therefore, will flow without impedance at a permeability of 0.1 millidarcys. We will assume that somehow these fractures remain open at depth. Higher permeabilities cannot be supported with existing data.

Assuming dry methane with no water influx, a maximum flow of 4,000 cubic feet of gas per day per foot of pay zone is calculated. About 300 meters thick of gas-filled reservoir would be necessary for the well to produce 4 million cubic feet of gas per day. Considering all factors (including unsuccessful wells) we believe that this flow rate would most likely be necessary to recover the high development and operating costs at Siljan and provide a moderate return on investment.

300 meters of gas-filled reservoir at Siljan equates to about 54 trillion cubic feet (TCF) of recoverable gas. Well spacing of 1.3 km (or closer) is required for reservoirs with low permeabilities. Siljan, therefore, would need 600 or more wells for adequate drainage.

Siljan gas reserve estimates are hypothetical and omit such things as realistic pay zones, flow rates, and production difficulties in low permeability basement rock. Estimated reserves of 54 TCF or even twenty times this amount have little meaning when placed in their proper context. All calculations based on hypothetical assumptions by numerous experts cannot improve the geology of a given area in the real world. The “bottom line” is simply to examine the known information and decide how to proceed.

Siljan data show little evidence that abiogenic gas exists. The Siljan oil, which Professor Gold claims to be abiogenic is clearly not, nor does his proposed calcite caprock layer exist. Seismic events at possibly 4.6, 7.5, and 9 km do not mean that caprocks are present. No evidence of structural closure is seen at Siljan. Magneto-telluric data, suggesting the possibility of 5% porosity at depth, have large uncertainties. If abiogenic gas does exist, the odds are that only noncommercial amounts could be produced from the Dala granite as revealed by core analysis.

We are led to conclude that the chances for commercial gas production are remote. We recognize the complexities of an impact feature such as Siljan, but are unable to comment with existing data on any unusual process that may be operating at depth.

RECOMMENDATIONS

(The paragraph below was censored by Vattenfall and removed prior to printing the report).

Privacy

The integrity of Expert Groups working under contract with Vattenfall should be respected and maintained at all times. Individuals representing firms and / or third parties, which have “special interests” in the Deep Gas Project, should not be permitted to influence members of the Expert Group. Under no circumstances should “special interest” individuals be allowed to associate with or attend any meetings with the Expert Group during the final report period. Vattenfall should take strict measures to assure that this request for privacy is honored.

Siljan

Vattenfall has undertaken an exploration project for an unconventional source of gas. The information gathered on the Deep Gas Project to date, including the 7 drill holes and over 3,200 meters of core, undoubtedly exceeds any preliminary exploration project ever undertaken. We are unable to find a comparable data-gathering project in the literature. Vattenfall must now decide on the desired balance between scientific and economic objectives.

As a purely profit-making venture in competition with the conventional gas industry of the western world, the weight of evidence suggests a very low probability of success.

On the other hand there are valuable basic scientific objectives that are worth pursuing. These include:

- Better basic understanding of structure of one of the largest terrestrial impact craters.

- Basic research in the structure and ongoing processes in shallower regions of the Precambrian continental crust below levels where significant drilling is presently taking place anywhere in the world. For instance, the Earth science community presently has a poor understanding of processes involving interstitial fluids in the deep continental crust, but is beginning to realize that these may hold the key to understanding of many important basic and applied questions. Such interstitial fluid processes include testing of the "water-filled caprock" concept proposed by Tord Lindbo [Vattenfall's Director of the Deep Gas Project].

Although we reiterate that we believe the purely economic prospects are very poor, most of the basic questions raised by Gold's hypothesis remain unanswered by the relatively shallow Phase I drilling program. There are several of these, such as: (1) the details of fracture/porosity variations in crystalline rocks at depth, (2) whether unambiguous traces of primordial deep methane can be found below levels where present results are open to question because of possible contamination, etc. Scientific implications of these are very great (but very expensive) and are usually dealt with in large cooperative national or international pure scientific programs. In a sense, we have only begun to test Gold's hypothesis for scientific purposes. We recommend:

- Several combined reflection and refraction seismic lines at different azimuths crossing the Siljan ring structure and extending somewhat outside the rim.

- A detailed study of the fracture-diabase type structures intersecting the Siljan ring structure.

- A more extensive magneto-telluric survey over the same area covered by the seismic lines. Attempts at 3-dimensional interpretations should be made using seismic structure information as a guideline.

- Attempts to do a new 3-dimensional gravity interpretation, which makes use of recent information derived from seismic and gravity surveys. Some additional gravity measurements in the field may be helpful.

- A decision on the siting of an expensive deep Phase II drill hole must await analysis of the above three geophysical surveys.

- Deeper wellbores need to be of adequate diameter to accept sophisticated modern logging equipment.

- At present we do not see the utility of any more shallow (500m) boreholes.

- Complementary near-surface geochemical testing inside and outside the Siljan ring area is necessary. This should include Delta C and trace element analysis.

Potential of Other Areas in Sweden

The results of the geochemical investigation on the sedimentary rocks collected in the Siljan area suggest that similar source rocks might be present in Sweden, in particular, offshore in the Baltic Sea and the Gulf of Bothnia.

The quality of the source rocks in the Siljan area was found to be excellent for generation of oil. It is known from source rocks in carbonate environments that they produce oil at relatively early stages of maturity. The Siljan crude was expelled at a maturity of vitrinite reflectance 0.70, which is at the beginning of the oil window. Although still having the character of an early expulsion crude before biodegradation, it is of good quality with an API value of about 15.

The fact that oil and tar shows occur in a fracture zone (Singo line) that leads to the Gulf of Bothnia suggests that oil generation has taken place, or is at present taking place. Although the Basin is relatively shallow, the amount of the overburden and the time of burial apparently were sufficient to mature the potential source rocks.

The oil from Gotland has a similar character as the oil in Siljan but is more mature. Potential source rocks occur in the sediments of Cambrian, Ordovician and Silurian age. It has to be pointed out however, that occurrences of organic-rich rocks are bound to specific environments of deposition and do not usually keep the same character over large geographic areas. In the Siljan crater in the Ordovician two different types of very good to excellent source rocks were found, which were deposited in two totally different environments. The first one, which generated the oil of Siljan, was deposited in shallow lagoonal facies with growth of numerous laminated algae, while the second, was most likely deposited in the anoxic zone of the shelf and contained, next to numerous individual algae, some terrestrial-derived material and biomass.

A careful study of the environments of deposition in the offshore basins of Sweden by seismostratigraphic analysis might reveal the presence of potential source rocks and their geographic distribution. It would also indicate where the best reservoirs might be found.

Reconstruction of burial history and time of generation, expulsion, and migration can reveal the way oil was formed and could have migrated to potential reservoirs.

The fact that oil shows occur in the immediate vicinity of the Gulf of Bothnia and that oil is being produced on both sides of the Baltic suggests that both basins have oil potential. By using the right scientific and technical approach it might be possible to produce oil in the future.

Regarding other areas for testing the abiogenic gas hypothesis, we point out that Lake Vattern graben has sedimentary rocks which could provide acceptable caprock + reservoir conditions. A seismic survey of the area would provide considerable information prior to any drilling.

---------------------------------- End of 1984 Independent Report**-------------------------------------**

NOTES

Two commercial wells were drilled in the Siljan crater; Gravberg 1 (1986-90) and Stenberg 1 (1991-92). The reported total cost was over $60 million, most of which was borne by investors. It is not known if investors were aware of the 1984 independent report.

The drilling results can be summed up as follows: very low porosity (1 to 5%), very low permeability (in the millidarcy range), no calcite caprocks, and no commercial amounts of hydrocarbons, either gases or liquids. Exactly what gases and liquids were found will undoubtedly be debated for years.

Additional Articles

Forbes, April 4, 1988, A tulip wilts in Stockholm: thousands of Swedish investors wish they had never heard of Cornell's Thomas Gold and his theories about oil and gas, p. 49, 52.

Fish, F., and Gorody, A.W., 1988, Siljan drilling experiment: participation of the Gas Research Institute, *in* Deep drilling in crystalline bedrock, v.1: The deep gas drilling in the Siljan impact structure, Sweden and astroblemes: Boden, A., Eriksson, K.G., eds., Berlin, Springer-Verlag, 364 p.

Oil and Gas Journal, January 14, 1991, Commercial wildcat planned in Sweden's Siljan crater, p. 77.

Castano, J.R., 1994, Prospects for commercial abiogenic gas production: implications from the Siljan Ring area, Sweden, *in* The future of energy gases: U.S. Geological Survey Professional Paper 1570, p. 133-154. (The late John Castano worked as the Chief Scientific Officer for the Gas Research Institute mainly at the Siljan wellsite. This publication is replete with Siljan well data).

Durhan, L.S., AAPG Explorer, June 2005, Gas origin views get spotlight, p. 34, 49.

Comments: Parwest512@aol.com

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