A New Energy Frontier: Potential Submarine Geothermal Resources Off-shore North America

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Abstract
The Iceland Deep Drilling Project (IDDP) is a consortium of industry, government and academia collaborating to investigate the technical and the economic feasibility of producing electricity from *supercritical geothermal resources* on land. Modeling indicates that a well producing from a supercritical reservoir would have ten times the power output of a typical moderate-enthalpy, but not supercritical, well. In 2009 the IDDP planned to drill a deep supercritical well at Krafla in NE Iceland. However, drilling had to be terminated at only 2.1 km depth when 900°C rhyolite magma flowed into the well. The resultant well was highly productive capable of generating >35 MWe from superheated steam at a well-head temperature of ~450°C. In 2015-16 the IDDP will drill a 4.5 km deep well in a high temperature geothermal field in SW Iceland on the Reykjanes peninsula, the landward extension of the Mid-Atlantic Ridge spreading center. This well will penetrate the roots of a hydrothermal system similar to the heat source of black smokers on mid-ocean ridges.

Plans for drilling to explore for deep potentially supercritical geothermal resources are already underway in other countries, such as the Taupo Volcanic Zone of New Zealand (Project HADES), and in northeast Japan. The "Japanese Beyond the Brittle Project" (Project JBBP) is an ambitious program attempting to create an EGS reservoir in ~500°C rocks. In North America there is a significant potential to develop similar supercritical geothermal systems in Alaska, Canada, Hawaii, the western USA, and the Trans-Mexican Volcanic Belt.

However, although in the short term more difficult and expensive to develop as practical power source, the *offshore geothermal resource base* of Canada, USA, and Mexico far exceeds the equivalent potential on land. For example, a preliminary estimate for the energy resources of the Gorda, Explorer, and Juan de Fuca Ridges indicates the geothermal resources base exceeds many thousands of GWe. Similarly, off-shore Mexico very large potential high-enthalpy, and possibly supercritical, geothermal resources also exist, for example, on the Revillagegido Ridge and in the Sea of Cortez.

The higher costs of offshore drilling, power production and electrical transmission, could be offset by developing production from the hottest, supercritical, submarine resources yielding higher productivity per well, by clustering the power plants, and possibly by using high-temperature electrolysis to produce hydrogen as a fuel. Another approach to mitigating the cost issue would be to form a consortium of industry, government and academia to share the costs and broaden the scope an investigation, as was done by the Iceland Deep Drilling Project.

Keywords: Supercritical fluids, high-enthalpy geothermal systems, off-shore resources, submarine hydrothermal vents, mid-ocean ridges.

Una nueva frontera energética: Recursos geotérmicos submarinos potenciales costa afuera de Norteamérica

Resumen

El proyecto de perforación profunda en Islandia (IDDP: Iceland Deep Drilling Project) es un consorcio de la industria, el gobierno y la academia para investigar la factibilidad técnica y económica de generar electricidad a partir de recursos geotérmicos supercríticos en tierra. El modelado indica que un pozo que produzca de un yacimiento supercrítico podría generar diez veces más energía que un pozo típico de entalpía moderada. En 2009 el IDDP empezó a perforar un pozo supercrítico en Krafla, al noreste de Islandia, pero la perforación debió ser suspendida a sólo 2.1 km de profundidad debido a que un magma riolítico a 900°C de temperatura fluyó dentro del pozo. Este resultó un pozo muy productivo, capaz de generar más de 35 MWe de vapor sobrecalentado a una temperatura de cabezal de unos 450°C. En 2015-16, el IDDP perforará un pozo a 4.5 km de profundidad en un campo de alta temperatura en el suroeste de Islandia, en la península de Reykjanes que es una extensión terrestre del centro de dispersión de la dorsal del Atlántico Medio. Este pozo llegará la raíz de un sistema hidrotermal semejante a la fuente de calor de las ventilas hidrotermales de las cordilleras oceánicas.

Ya hay proyectos en desarrollo en otros países para perforar pozos exploratorios en potenciales recursos geotérmicos supercríticos, tales como el proyecto HADES en la zona volcánica de Taupo, Nueva Zelanda, y otro en el noreste de Japón. El proyecto Japanese Beyond the Brittle Project (JBBP) es un ambicioso plan que intenta crear un yacimiento geotérmico mejorado (EGS: Enhanced Geothermal System) en rocas a unos 500°C. En América del Norte hay un importante potencial para desarrollar sistemas geotérmicos supercríticos similares en Alaskam Candá, Hawai, el occidente de Estados Unidos y la Faja Volcánica Mexicana.

Y aunque a corto plazo es más difícil y costoso de desarrollar como una fuente práctica de energía, el recurso geotérmico básico mar adentro de Canadá, Estados Unidos y México excede fácilmente el potencial terrestre. Por ejemplo, una estimación preliminar de los recursos energéticos de las cordilleras oceánicas de Gorda, Explorer y Juan de Fuca indica que el recurso geotérmico básico es mayor de varios miles de GWe. De manera semejante, México tiene también un elevado potencial en recursos geotérmicos de alta entalpía y posiblemente supercríticos, por ejemplos en la cordillera de las Revillagigedo y en el Mar de Cortés.

El alto costo de la perforación mar adentro y de la generación y transmisión de esa energía puede compensarse si se hacen producir los recursos submarinos supercríticos más calientes que darían una más alta producción por pozo, si se agrupan las plantas generadoras y posiblemente si se utiliza una electrólisis de alta temperatura para producir hidrógeno como combustible. Otra manera de reducir los costos es formar un consorcio de la industria, el gobierno y la academia para compartir costos y ampliar el alcance de la investigación, como se hizo en el IDDP.

Palabras clave: Fluidos supercríticos, sistemas geotérmicos de alta entalpía, recursos mar adentro, ventilas hidrotermales submarinas, cordilleras medio-oceánicas.

1. Introduction

The Iceland Deep Drilling Project (IDDP) is investigating the potential of naturally occurring *supercritical* hydrous fluids as geothermal energy resources (Friðleifsson and Elders, 2005; Elders, Friðleifsson and Albertsson, 2014; Friðleifsson et al., 2014). The IDDP is funded by a consortium consisting of three Icelandic power companies, an agency of the Icelandic government, and an international oil and gas company. The project has selected three high-enthalpy magma-hydrothermal systems, Krafla, in the northeast, Reykjanes, in the southwest, and Hengill, to the north of Reykjanes, as sites for deep drilling to investigate supercritical geothermal resources. The IDDP could become a model for similar projects that investigate high-enthalpy hydrothermal systems both *on* and *offshore* elsewhere in the world.

2. Supercritical geothermal resources

The critical point for pure water is at 22.1 MPa and 374°C, but at higher temperatures and pressures for water containing dissolved salts (Schmidt and Grigull, 1979). Thus supercritical water has very high enthalpy, for example, according to Tester et al. (2006) water with a temperature of 400°C and a pressure of 25 MPa has more than five times the power producing potential than that of hydrothermal liquid water at 225°C. On the other hand, Suárez and Samaniego (2012) state that, "Supercritical reservoirs at high temperature and pressure, beyond the critical point, could provide more than 20 times as much enthalpy per cubic meter as the geothermal fluids used in the current technology".

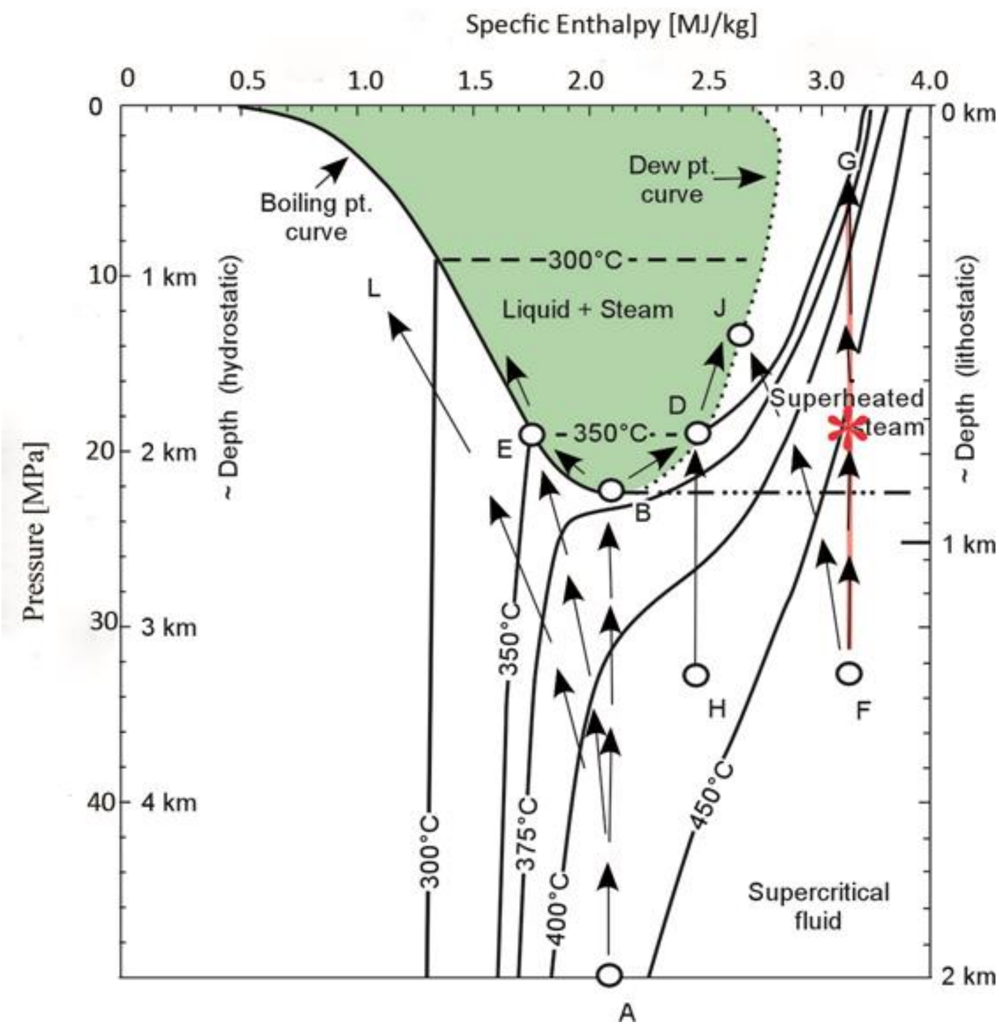

Fig. 1. Pressure–enthalpy diagram for pure water, with equivalent depths for hydrostatic (left) and lithostatic (right) pressure conditions. The red star on the line F-G shows the pressure/enthalpy conditions in the exploratory well IDDP-1. (Elders and Friðleifsson, 2010, modified from Fournier, 1999).

Figure 1 shows the pressure-enthalpy diagram for pure water, showing selected isotherms (Fournier, 1999). The heat source for many high–temperature geothermal systems most likely originates in supercritical conditions like point A in Figure 1. As supercritical fluids rise to shallower levels they may encounter the two phase field of steam and liquid at point B, the critical point for pure water, or at points such as D or E. Flash geothermal plants condense steam separated from the two phase field which, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20-

30% of the total mass flow. The concept behind the IDDP program is to bring supercritical fluid to the surface in such a way that it transitions directly to superheated steam along a path like F-G (red) in Figure 1, resulting in a much greater power output than from a typical subcritical geothermal well.

There are large changes in fluid transport properties near the critical point that can lead to extremely high rates of mass and energy transport (Norton and Knight, 1977; Hashida et al., 2001; Hyaba and Ingebritsen, 1997; Fournier, 1999; Yano and Ishido, 1998). Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena play a major role in high temperature water/rock reaction and the transport of dissolved metals.

In Iceland geothermal wells typically range up to 3.0 km in depth and produce steam at <300°C, at a rate sufficient to generate about 4 to 10 megawatts (MWe) of electricity. Our modeling suggested that producing superheated steam from a supercritical reservoir could potentially increase the power output of geothermal wells by an order of magnitude relative to the output of lower enthalpy wells (Friðleifsson and Elders, 2005). A conventional dry-steam well with a down hole temperature of 235°C and pressure of 30 bar and a volumetric flow rate of 0.67 m^3/s can generate ~5 MWe, whereas we estimate that a supercritical well with the same volumetric flow rate, but with a down hole temperature of 430-550°C and pressure of 230-260 bar and the same volumetric flow rate of 0.67 m^3/s could generate ~50 MWe. The IDDP aims to produce supercritical fluid to the surface such that it transitions directly to superheated steam.

2.1 Do supercritical conditions occur in nature at drillable depths?

There are several reasons for believing that supercritical conditions occur in nature. For example, some high enthalpy geothermal wells produce superheated steam that is most likely derived from supercritical fluids at depth. Similarly, the superheated steam commonly produced by volcanic fumaroles may also be derived by decompression of deeper supercritical fluids. However, perhaps the best direct evidence for the existence of supercritical fluids in nature comes from black smokers at Mid-Ocean Ridges. Some of these discharge fluids with only 10% of seawater salinity, whereas others discharge fluids with twice seawater salinity (Cathles, 1993; Elders and Friðleifsson, 2010; Jupp and Schultz, 2000; Van Damm, 1990). The only credible explanation for these observations is that phase separation of dilute and concentrated fluids is occurring at supercritical pressures and temperatures. Finally, black smokers at 5°S on the Mid-Atlantic Ridge have been observed discharging supercritical seawater at temperatures of up to 464°C at a water depth of 3 km (Koshchinsky et al., 2008).

Potentially exploitable supercritical geothermal resources are an integral part of magmatically-heated hydrothermal systems and readily form in permeable rocks, such as basalt, with a brittle-ductile transition temperature of 450°C. A recent numerical simulation shows that supercritical water plays a key role in transferring heat from magmatic intrusions and controlling the thermal structure of high enthalpy geothermal systems (Scott et al., 2014a, b). They modeled heat transfer and fluid flow above a 900°C intrusion at a depth of 3 km, in rocks with permeabilities of 10^{-14} and $10^{-15} m^2$. They showed that above the intrusion supercritical pressure temperature conditions could extend for a height of >500 m, with temperatures >400°C and fluid enthalpies of >3 MJ. According to Scott et al. (2014a, b), conventional subcritical high enthalpy geothermal systems above supercritical resources result by mixing between rising supercritical water and shallower cooler water.

3. The Iceland Deep Drilling Project (IDDP)

The first IDDP well was drilled in the Krafla geothermal field within a volcanic caldera in the central active rift zone of NE Iceland. During 1975-1984, a rifting episode occurred that involved nine separate volcanic eruptions. A large magma chamber, believed to be the heat source of the active geothermal system, at 3-7 km depth within the center of the caldera was detected by S-wave attenuation and MT surveys. The well IDDP-1 was sited to reach 4.5 km depth close to the upper margin of this magma chamber (Friðleifsson et al., 2014). However, in 2009, at only 2104 m depth a rhyolitic magma filled the bottom 10 m of the drill hole. Geothermometry indicates a temperature >900°C for the rhyolitic magma. Our studies indicate that this magma formed by partial melting of hydrothermally altered basalts within the Krafla caldera (Elders et al., 2011; Zierenberg et al., 2013). The size of the intrusion responsible was evidently below the resolution of the earlier geophysical exploration methods. The decision was made to terminate drilling, cement production casing, allow the well to heat and to flow test the well.

3.1 Flow Testing the IDDP-1 Well

The resultant well had very high enthalpy and produced superheated steam from the contact zone above the intrusion. With a well-head temperature of 450°C and well-head pressures of up to 13.8 MPa, it became the hottest producing geothermal well in the world. With a flow rate of 45 kg/s of dry steam it was estimated to be capable of generating >35 MWe (Figure 2). When, after ten months of full scale flow, the well as shutdown in July 2012 to recondition some of the surface equipment, it was found that the master valves need replacing due to failure of the valve stems. The future utilization of this magmatic resource at Krafla is still being discussed. It may be possible to recondition the IDDP-1, or several new wells could be drilled towards the contact zone of the magma. In the future it may even be possible to produce energy directly from the magma, either utilizing a downhole heat exchanger or by creating the world’s first EGS production and injection wells in magma.

Fig. 2. The flow of the IDDP-01 into a rock muffler produced dry superheated steam with only 0.1-0.2% of non-condensable gases. (Photograph courtesy of Kristján Einarsson).

Initially corrosion products gave the steam a dark color but after a few minutes it became clear and transparent. The condensate had a pH 2.5-3 due to its HCl content. However experiments on wet scrubbing to remove acid gases from the dry steam were very successful (Hauksson et al., 2014). The IDDP-1 engendered considerable international scientific and engineering interest. A special issue of the journal Geothermics was published in January 2014 reporting some of this work.

3.2 Future plans in Iceland

Two new IDDP wells, >4 km deep, are planned to be drilled deep enough to reach supercritical conditions at the Hengill and the Reykjanes geothermal fields in SW Iceland (Friðleifsson et al., 2013).

If these new IDDP wells prove successful, in future such very high enthalpy geothermal systems could become significant resources worldwide, wherever suitable young hot volcanic geothermal systems occur. In early 2016 the IDDP-2 will be drilled in the Reykjanes geothermal field on the Reykjanes Peninsula, in southwest Iceland on the landward extension of the Mid-Atlantic Ridge where it comes on land.

In contrast to the fresh water systems at Krafla and Hengill, the geothermal fluids discharged by wells at Reykjanes are seawater modified by water/basalt reactions at ~ 300°C (Table 1). The geology of the Reykjanes peninsula is a classic ophiolite model with pillow basalts and lavas overlying sheeted dikes, diabases and gabbros. Processes at depth in the active hydrothermal system at Reykjanes should be quite similar to those responsible for black smokers on oceanic rift systems.

	T (°C)	Cl	Na	SiO_2	K	Ca	Mg
Seawater	4	19,800	10,700	6	400	400	1300
Reykjanes wells	275-315	19,600	9,700	670-750	1,400	1,600	1

Table 1. Partial chemical analysis of seawater compared with fluid from a typical well on the Reykjanes Geothermal Field (mg/l).

4. Developing ultra (supercritical or other high-enthalpy) geothermal resources

There is now a growing interest in ULTRA or supercritical or other high-enthalpy geothermal resources (Elders, 2013; Elders et al., 2014). Developing ultra high-enthalpy supercritical geothermal resources at drillable depths is most credible at: (1) young volcanic rocks along plate boundaries and at hot spots, (2) at or near shallow, still hot (or partially molten) igneous intrusions, and (3) at well-established geothermal fields. Examples include (a) Iceland: Reykjanes, Hengill, Krafla, (b) Northeast Japan, (c) New Zealand in the Taupo Volcanic Zone, (d) Philippines, Indonesia, Italy, (e) Mexico: Cerro Prieto, Los Humeros, (f) USA: Hawaii, California, Alaska, Basin & Ranges, Cascades Volcanic Chain?, and (g) Offshore Ocean Rifts, e.g. Gorda and Juan de Fuca Ridges.

In fact, projects comparable but differing in approach to the IDDP are already underway in both Japan and New Zealand. The Japan Beyond the Brittle Project (JBBP) plans to drill beyond the brittle/ductile transition in a 500°C or hotter neogranite and to thermally fracture the rocks to form permeability in the ductile zone and thus create a self-contained "ultra" EGS system as is explained on the website: www.icdp-online.org/fileadmin/icdp/projects/doc/jbbp/JBBP_Concept_poster_En.pdf.

The expectation is that a combination of government and industry funding will permit drilling to begin in two or three years. A similarly ambitious project is underway in New Zealand, although possibly not so far advanced as the IDDP or the JBBP. "Hotter and Deeper Exploration Science" (HADES) is a long-term program of exploration in the North Island of New Zealand that aims to use geological, geochemical and geophysical data to assess the resource potential of deep (up to 7 km) geothermal systems in the Taupo Volcanic Zone. Preliminary indications of the HADES project suggest that by 2025 New Zealand's deep geothermal resources (3-7km) could supply at least 20% of New Zealand's electricity requirement. Conservative estimates point to the total potential of accessible deep geothermal resource in the Taupo Volcanic Zone (TVZ) exceeding 10,000 MWe. See the website: www.gns.cri.nz/Home/Our-Science/Energy-Resources/Geothermal-Energy/Research/Hotter-and-Deeper.

4.1 The potential for ULTRA geothermal resources on land in the USA

In contrast to IDDP, JBBP, and HADES, there is no systematic activity in the USA directed towards developing ULTRA geothermal resources. This is not because there are no valid targets for exploration for high-enthalpy geothermal resources. An assessment of geothermal resource base to 10 km depth in the USA for different categories of geological environment was reported in Tester et al., 2006. The major thrust of that report was to assess the potential of Enhanced (or Engineered) Geothermal Systems (EGS) in the USA. The overall conclusion of that comprehensive assessment was clearly that the largest part of the EGS geothermal resource base resides in the form of thermal energy contained in sedimentary and basement rocks that are dominated by radiogenic heat sources and conductive heat transfer, and that its size is at least two orders of magnitude greater than the resource base of "conventional" geothermal systems associated with hydrothermal temperature anomalies. In addition to the enormous conductive EGS resources base, there is also a large potential to develop supercritical volcanic resources in the USA. Supercritical geothermal systems not requiring EGS technology could be developed where convective heat transfer persists due to the existence of appropriate combinations of pressure, temperature and lithology, such as in basaltic terrains, like Iceland, where the brittle ductile transition occurs at much higher temperatures than in the granitic terrains, such as those being investigated by the JBBP.

Efforts to promote interest in investigating ULTRA Geothermal Systems in the USA are underway (Elders, 2013; Elders et al., 2014). As part of that effort, a thematic workshop, "Drilling into High-enthalpy Geothermal Systems: A Collaborative Initiative to Promote Scientific Opportunities", was held in Southern California on October 2013 and a planning committee was formed (http://csdworkshops.geo.arizona.edu/LakeArrowhead.CA.html). The committee developed the following criteria to choose potential sites to develop ULTRA geothermal resources.

- The site must contain ULTRA-high enthalpy resources at depths attainable by current drilling technology on the basis of existing surface and subsurface data.
- The site must have substantial infrastructure, access, and permitting, as well as availability of testing facilities.
- The site must have an existing operator willing to be an active partner in the project.
- The site should maximize the scientific and technological benefits and transferability.
- The initial site must be one in which this project could readily demonstrate the proof of concept that the development of ULTRA high-enthalpy resources is viable.

In the USA potential sites that meet the above criteria include, but are not limited to: the Salton Sea, The Geysers, Coso, and Long Valley/Inyo Domes, in California, and on the Big Island of Hawaii. At Puna in Hawaii, on the southern flanks of the active volcano Kilauea, drilling has also penetrated a magma body at shallow depth (Teplow et al., 2009). However, its development as a large resource in the near future is limited by the market for additional electric power on the island of Oahu. In addition, to the developed high-enthalpy resources in California, there is also future potential in the Cascade Volcanic Chain and in Alaska.

4.2 Submarine geothermal systems

Supercritical fluid-rock interactions are important in the overall heat and fluid budgets of hydrothermal systems on mid-ocean ridges (Figure 3). In the intermediate to long term, there is a very large resource potential for submarine ULTRA geothermal resources along ocean rift systems and submarine volcanoes where they are reasonably close to land and to markets for electric power (Orcutt and Shnell, 2015; Parada et al., 2012; Shnell, 2009).

Some candidate sites include:

- Red Sea
- North of the Taupo Volcanic Zone of New Zealand
- The Gulf of California
- The Juan De Fuca and Gorda Ridges (Figure 3).

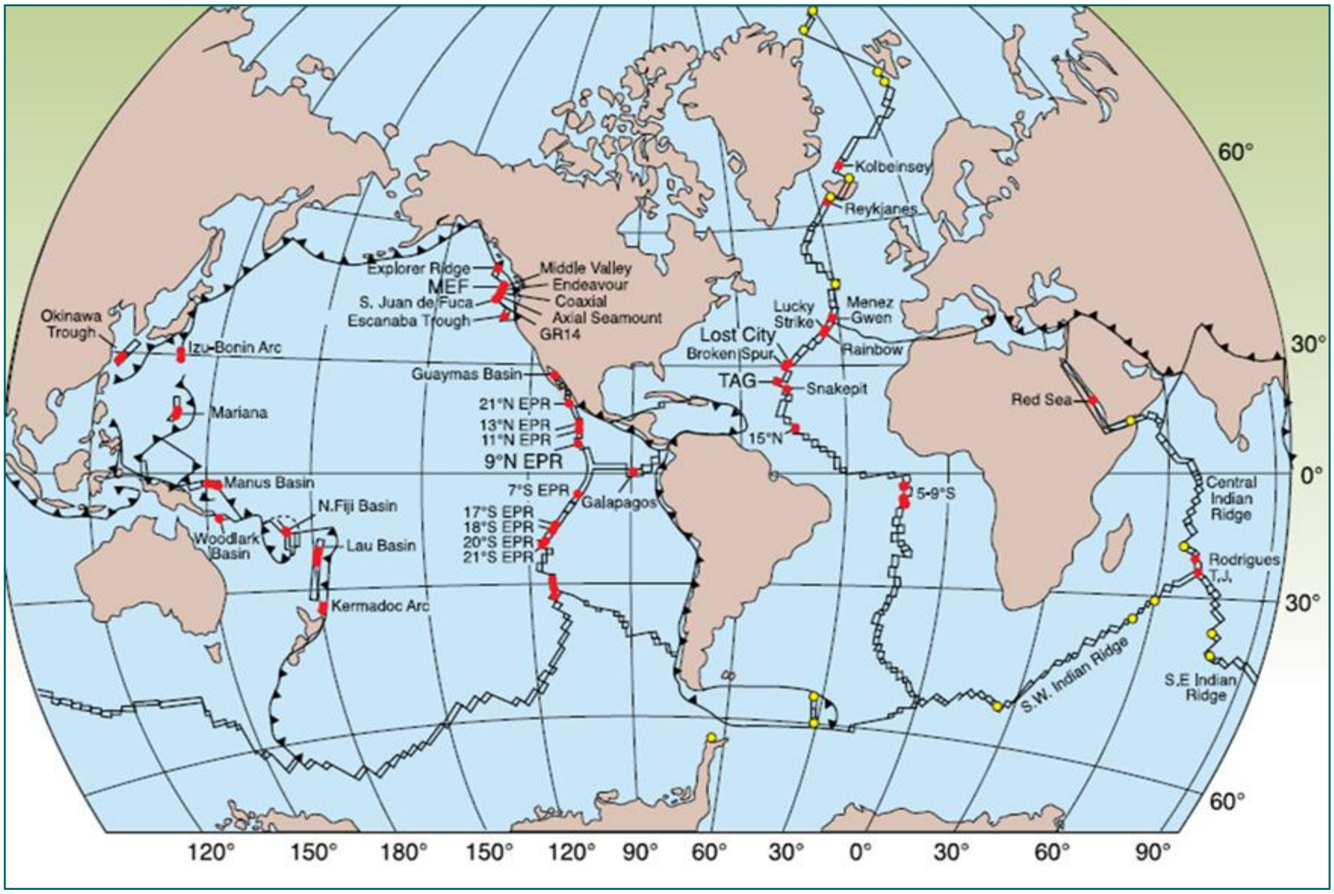

Figure 3. The Black Smokers and high-enthalpy hot springs of Mid-Ocean Ridges.

4.3 Geothermal resources off-shore the Pacific Northwest

One estimate of the high-enthalpy geothermal resources of the Gorda Ridge, offshore Oregon and northern California, suggests that its geothermal resource base is sufficient to support an electrical power output of thousands of GWe (Ajito Chada, personal communication, 2014). Further north, on the Juan de Fuca Ridge, at only 3 km depth there are numerous hydrothermal vents above an axial volcano, that last erupted in 2011 (Figure 4).

A magma body has recently been identified beneath the axial volcano measuring 14 km long by 3 km wide and 1 km thick. The volume of the 1000°C magma reservoir in this intrusion beneath the axial volcano is estimated to be 18-30 km^3 (Arnulf et al., 2014). Producing electricity from only a few percent of the energy stored in that intrusion would be an enormous resource.

Fig. 4. The plate boundaries and spreading centers off-shore California, Oregon, Washington and British Columbia of western North America.

4.4 Potential geothermal resources off shore Mexico

The spreading centers of the East Pacific Rise where it approaches Mexico and its continuation into the Gulf of California (Sea of Cortez) are also sites of potential high-temperature geothermal resources that have already drawn interest from Mexican investigators (Hiriart and Hernández, 2010; Hiriart et al., 2010). High enthalpy and supercritical geothermal reservoirs are likely to occur on the Revillagigedo Ridge on which the young volcanoes of San Benedicto, Socorro, and Roca Partida islands occur. However closer to land and potential markets for electricity are the deep marine basins of the Gulf of California which are separated by the transform faults that are the continuation of the East Pacific Rise.

In particular black smokers vents in the Guaymas Basin have exit temperature in excess of 320°C and have been the subject of numerous studies including drilling by the Ocean Drilling Program (Figure 5).

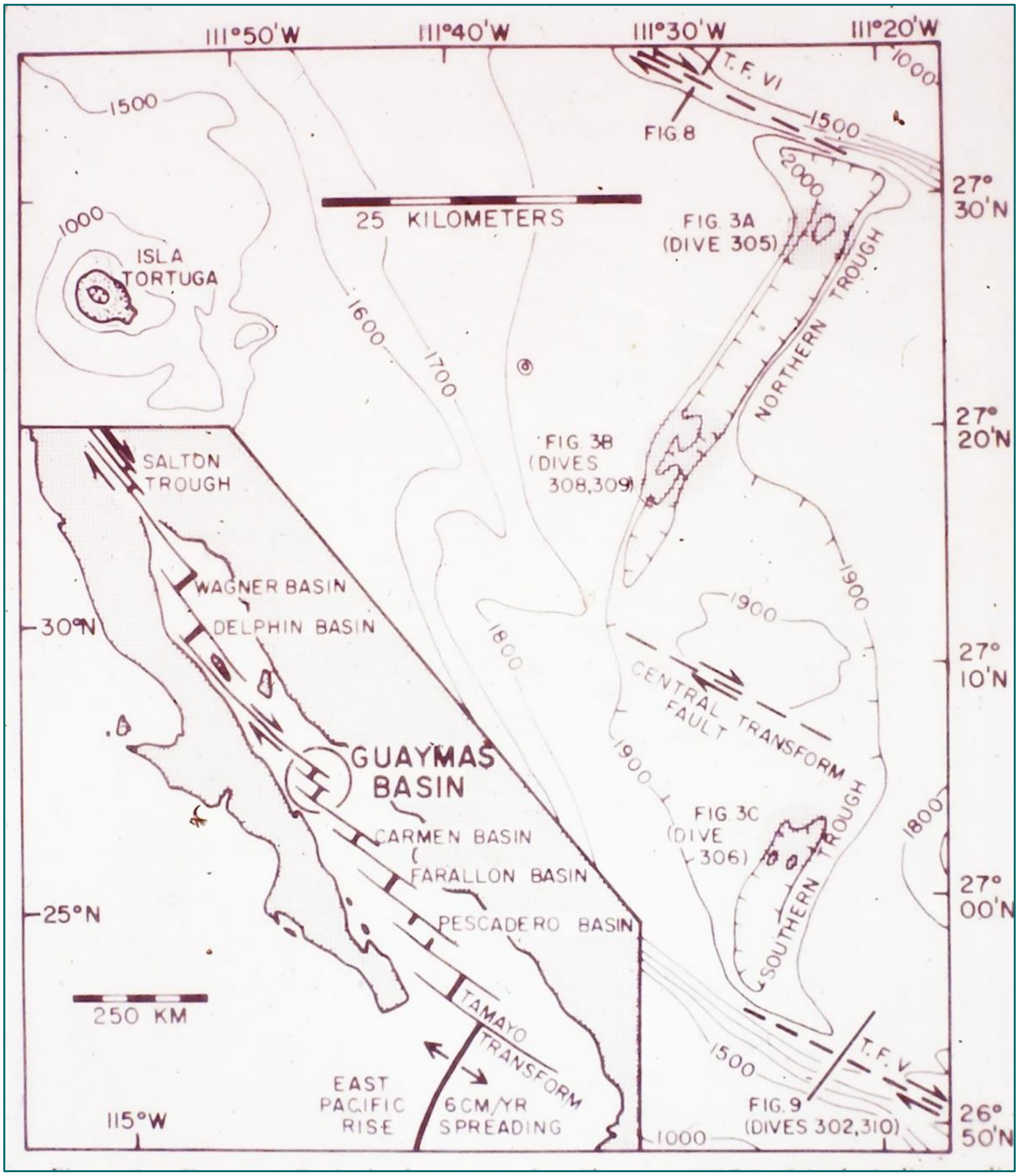

Figure 5. The bathymetry of the Guaymas Basin , Sea of Cortez (Gulf of California) (Inset). The tectonics of the Gulf showing the en-echelon *transform rifts and the series of deep basins each with high heat flow.*

5. Discussion

The barrier to the development of such offshore ULTRA geothermal systems is the technical difficulty and cost of deep drilling offshore, constructing floating or seabed electricity generating plants, and building the necessary transmission cables needed. Another possibility where distance from shore makes the cost of submarine transmission too high, would be to use the electricity generated to produce liquefied hydrogen by electrolysis of sea water and transport the hydrogen by tankers. However, given the large size and high enthalpy of these offshore systems they remain attractive targets for future development.

6. Conclusions

Amongst approaches to improve the economics of the geothermal industry would be the development of ULTRA Geothermal Resources. Producing supercritical fluid and/or high-enthalpy dry superheated steam would reduce the number of wells needed for a given power output by increasing the power output of each well. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. Accessing supercritical fluids within drillable depths could yield a significant enlargement of the accessible geothermal resource base both on and off-shore. The off-shore potential appears to be many times larger than that on shore. However, overcoming the technical and economic problems of developing these resources, both on shore and off-shore, is a major challenge. An approach to mitigating the cost issue could be to form a consortium similar to IDDP, to share the costs and broaden the scope of investigations of the economic feasibility of producing electricity from the ULTRA geothermal reservoirs.

The practical significance developing submarine ULTRA Geothermal Resources is that (1) the resource base is much higher than that on land, (2) fewer wells are needed for a given power output, (3) the power cycle has a higher thermodynamic efficiency using higher temperature and pressure turbines, (4) for a given power output the environmental footprint is smaller.

The scientific significance of investigating submarine ULTRA Geothermal Systems is that it allows direct study of active supercritical phenomena, the coupling of hydrothermal & magmatic systems, high temperature hydrothermal alteration and ore formation, fluid circulation at rift systems analogous to that at mid-ocean ridges, black smokers, and related volcanic hazards.

Supercritical zones are most important for the practical goals of the ULTRA Geothermal Development Project. It is predominantly there that mobile fluids are heated and interact chemically with their host rocks, where most of the geologically important heat flow, chemical alteration, and hydrothermal ore formation take place. Supercritical fluid-rock interactions are important in the overall heat and fluid budgets of mid-ocean ridges. Studying analogous systems on land is much more practical than drilling from a ship in deep water. And finally supercritical fluid and/or superheated steam represent an attractive source for electric power generation if and when the technical challenges are overcome.

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