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GEOTHERMAL ACTIVITY AND DEVELOPMENT IN SOUTH AMERICA: A SHORT OVERVIEW OF BOLIVIA, CHILE, COLOMBIA, ECUADOR, AND PERU

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ABSTRACT

South America holds vast stores of geothermal energy that are largely unexploited. These resources are the product of the convergence of the South American tectonic plate and the Nazca plate that has given rise to the Andes mountain chain, with its countless volcanoes. High-temperature geothermal resources in Bolivia, Chile, Colombia, Ecuador and Peru are mainly associated with the volcanically active regions, although low temperature resources are also found outside them. All of these countries have a history of geothermal exploration, which has been reinvigorated with recent changes in global energy prices and the increased emphasis on renewables to combat global warming. The paper gives an overview of their main regions of geothermal activity and recent developments in the geothermal sector are reviewed.

1. INTRODUCTION

South America has abundant geothermal energy resources. In 1999, the Geothermal Energy Association estimated the continent's potential for electricity generation from geothermal resources to be in the range of 3,970-8,610 MW, based on available information and assuming the use of technology available at that time (Gawell et al., 1999). Subsequent studies have put the potential much higher, as a preliminary analysis of Chile alone assumes a generation potential of 16,000 MW for at least 50 years from geothermal fluids with temperatures exceeding 150°C, extracted from within a depth of 3,000 m (Lahsen et al., 2010). In spite of this enormous potential, the only geothermal power plant which has been operated on the continent is the 670 kW binary demonstration unit in the Copahue field in Argentina, which was decommissioned in 1996 (Bertani, 2010).

Global warming and the global energy market have among other factors led to a renewed world-wide interest in clean indigenous energy sources, and several South American countries are currently pursuing the development of their geothermal resources. Among these are Bolivia, Chile, Colombia, Ecuador and Peru. The following sections are intended to give a basic overview of geothermal activity and the state of geothermal development in these countries.

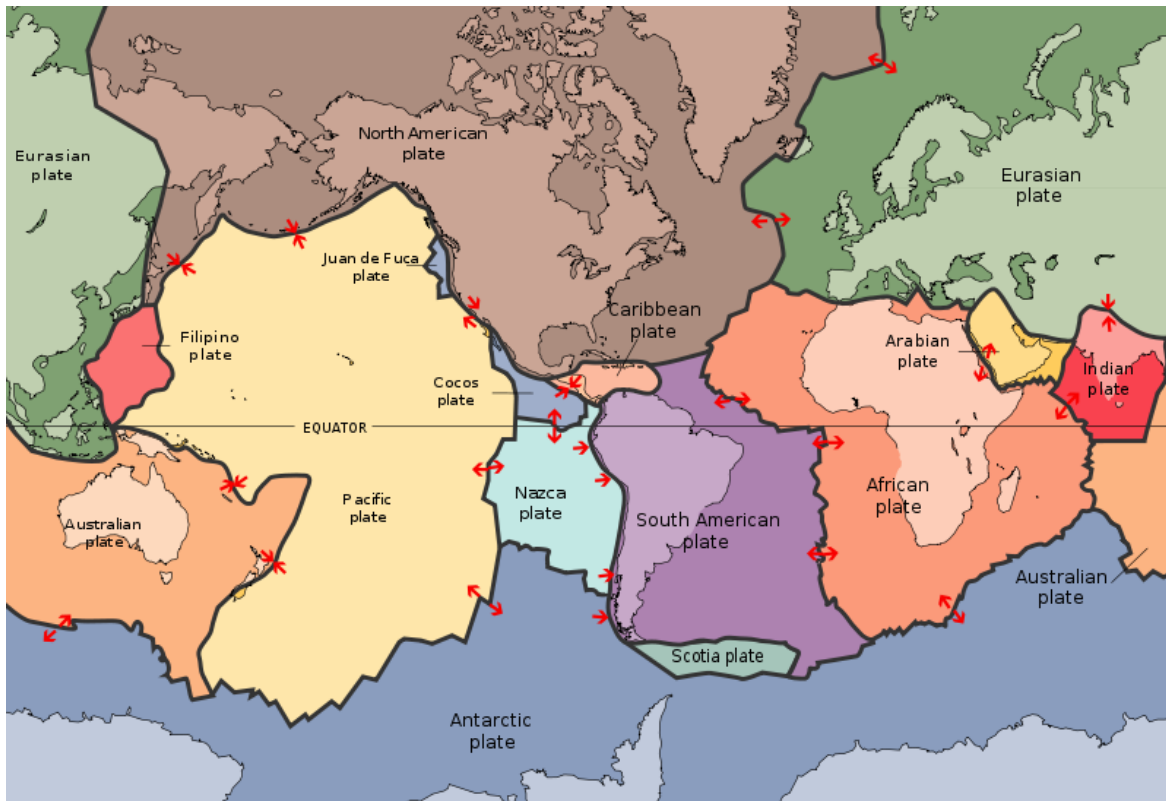


FIGURE 1: The tectonic plates of the world (en.wikipedia.org/wiki/Plate_tectonics)

2. BACKGROUND

The South American tectonic plate, on which the South American continent rests, is bordered by the Nazca and Antarctic plates to the west (Figure 1). These three plates meet at the Chile triple junction. The Caribbean plate also borders the South American plate to the northwest, which in addition to the Nazca plate form another triple junction. The Nazca plate subducts underneath the South American plate in a convergent boundary (Figure 2) that manifests in the Peru-Chile trench that runs along the western coast of the continent, approximately 160 km from shore and reaches a maximum depth of over 8,000 m. Part of the Antarctic plate also subducts under the South American plate. The friction and pressure created by the sliding plates and the melting of the subducting plate cause earthquakes and volcanic activity, which are both conducive to the formation of geothermal reservoirs. Earthquakes produce faults and fissures through which water can flow and volcanic activity and shallow magma chambers provide heat sources.

The convergence has given rise to the Andes mountain range that runs from Venezuela in the north to Patagonia in the south and reaches maximum altitude of 6,962 m at Aconcagua peak in Argentina, which is entirely the result of uplift. The Andes are the longest continental mountain chain in the world, spanning 7 countries, and the highest outside of Asia. They are split into several ranges (cordilleras) that are separated by intermediate depressions. They are widest at the Altiplano plateau, the most extensive high plateau outside of Tibet, and are home to many important cities, such as Bogotá, Quito, La Paz, Sucre

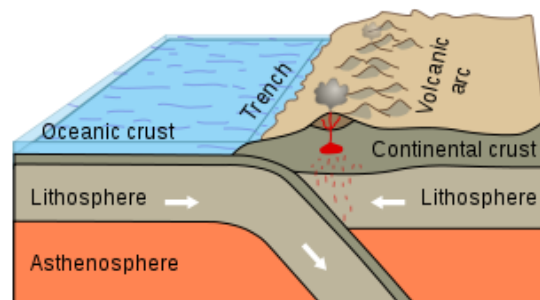


FIGURE 2: Oceanic-continental convergent boundary (en.wikipedia.org/wiki/Convergent_boundary)

and Santiago de Chile.

In a recent study, Cardoso et al. (2010) employed updated data sets on crustal seismic velocities, gravity anomalies, radiogenic heat production, terrestrial heat flow and thermal springs to produce a heat flow map of South America (Figure 3). Their results indicate that most of the continent's high temperature resources occur within:

- Well known sectors of magmatic activity in Chile;
- The Altiplano region of Bolivia;
- Isolated pockets along the western Andean belt in Peru;
- Several localities along the magmatic arc covering western Ecuador, central volcanic belt of Colombia and southern Venezuela.

While many of these regions have long been known for volcanic and geothermal activity, the heat flow map is helpful for visualization on a continental scale.

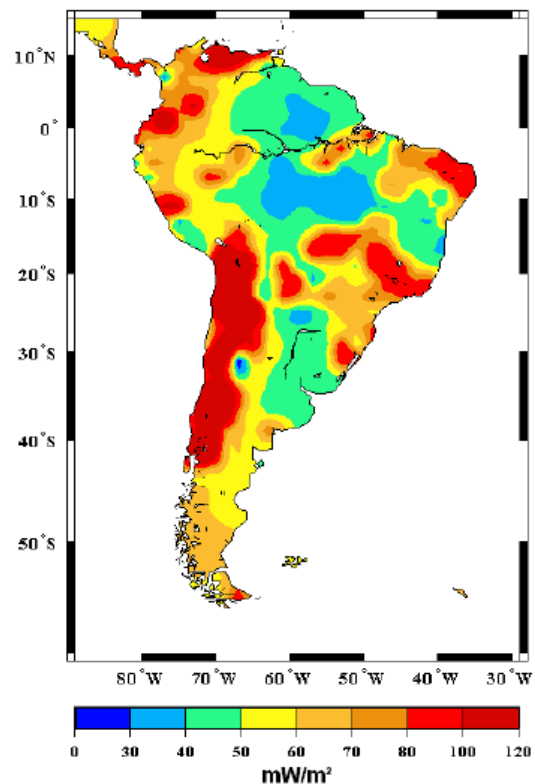


FIGURE 3: Heat flow map of South America (Cardoso et al., 2010)

3. BOLIVIA

3.1 Geographical/Geological setting

Bolivia is divided between the Andes to the west and lowlands of platforms and shields to the east. The Bolivian Andes are comprised of three main ranges (Figure 4):

- Cordillera Occidental to the west on the border with Chile, which are characterized by volcanoes and geothermal areas;
- Cordillera Central, the northern section of which is referred to as the Cordillera Real, and is rich in minerals; and
- Cordillera Oriental to the east, which is a fold and thrust belt lower than the other two.



FIGURE 4: Geographical visualization of Bolivia (www.travel-bolivia.com)

In addition to these mountain ranges, the Altiplano extends over a large area between the Cordillera Occidental and the Cordillera Central. The plateau is around 700 km long and has a maximum width of approximately 200 km. The average elevation is close to 3,750 m.

3.2 Geothermal manifestations

In 1984, Aliaga reported on more than 70 areas with geothermal manifestations in Bolivia, including hot pools, mud pools, fumaroles and steaming ground (Aliaga, 1984). They are found on the eastern slopes of the Cordillera Occidental, in the southern part of the Cordillera Oriental and in the eastern central part of the Altiplano. In the Cordillera Oriental, geothermal activity is associated with faults, fractures and volcanic bodies and in the Altiplano it is related to igneous bodies and probably faults. Temperatures of many surface manifestations are as high as 85°C, but most do not exceed 50°C. The largest flow measured at the time was 67 l/s at Lanza (Figure 5). The waters vary from acidic to alkaline and most of them are used for bathing.

3.3. Geothermal exploration

According to Terceros (2000), geothermal exploration in Bolivia began in the 1970s. These early efforts established the existence of high enthalpy resources, mainly along the Cordillera Occidental. Pre-feasibility studies were carried out in the Salar de Empexa and Laguna Colorada fields between 1978 and 1980, after which interest was mainly concentrated on the Sol de Mañana field of Laguna Colorada. Feasibility studies were carried out between 1985 and 1990, including the drilling of new wells, which allowed the quantification and evaluation of the geothermal reservoir. The goal was to proceed with the installation of an experimental 4-10 MW power station. To that end a new well was drilled successfully and another one deepened between 1991 and 1992, although the installation of the experimental power station was not realized.

3.4 Laguna Colorada project

Terceros (2000) reports that the Laguna Colorada prospect is located in the Cordillera Occidental in the far southwest of Bolivia, near the Chilean border (Figure 5). The area consists of high plains constituted by deposits of lava and glacier material at an elevation of 4,900 m, which are dominated by the presence of volcanic structures. In 2000, 6 wells had been drilled with an average depth of 1,500 m. Reservoir studies and numerical simulation indicated a potential for at least 120 MW for 20 years and a possibility for up to 300 MW for 25 years.

The state power company Empresa Nacional de Electricidad (ENDE) intends to construct a 100 MW power plant at Laguna Colorada. The project is comprised of three parts (URS Corporation Bolivia S.A., 2010):

- Resource development, including the drilling of new production and reinjection wells;
- The construction of a 100



FIGURE 5: Modified physical map of Bolivia showing some geothermal sites mentioned in the text (www.travel-bolivia.com)

MW power plant; and

- The construction of a single circuit 230 kV transmission line with a length of 170 km to connect the plant with the national grid.

3.5 Electricity generation

Electricity generation capacity in Bolivia is divided between thermal (60%) and hydro (40%). The generation capacity in 2008 amounted to 1,454 MW and the gross generation was 5,982 GWh which indicates a capacity factor of 0.47 (EIA, 2010). In 1999, GEA estimated Bolivia's geothermal electricity generation potential at 510-1,260 MW (Gawell et al., 1999), which is 35-87% of the installed capacity in 2008. Electricity availability in rural areas is among the lowest in Latin America.

4. CHILE

4.1 Geographical/Geological setting

Andean orogeny has shaped three main features in Chile parallel to the subduction zone (Figure 6):

- Cordillera de la Costa (the Chilean coastal range) to the west, which runs from the very north to the triple junction;
- The Andean cordillera to the east; and
- Valle Central (Intermediate Depression) in between the other two features, consisting of a fertile graben which has been filled with the by-products of volcanic activity and erosion of the surrounding mountains.

According to Lahsen et al. (2010), Chilean geothermal resources occur in close spatial relationship with active volcanism. There are two main volcanic zones. The northern one extends from 17°S to 28°S and is characterized by Quaternary volcanism along the high Andes and the Altiplano. Volcanic vents and hydrothermal manifestations occur within the small grabens associated with fault systems with an approximate N-S trend that have been created by differential uplift. The southern zone extends from 33°S to 46°S and is also characterized by Quaternary volcanism that is restricted to the Andean Cordillera. This activity has given rise to stratovolcanoes, pyroclastic cones, and calderas that have covered extensive areas of the Valle Central with Lahar type flows. All the Chilean high temperature thermal springs are associated with the Quaternary volcanic zones.



FIGURE 6: Terrain map of Chile
(www.freerentacarchile.com)

4.2 Geothermal resources

Lahsen et al. (2010) report that geological, geochemical and geophysical surveys have been carried out in many geothermal areas in Chile and a preliminary assessment of the geothermal potential of the country indicates an electricity generation potential in the order of 16,000 MW for 50 years from geothermal fluids with temperatures exceeding 150°C, withdrawn from a depth less than 3,000 m. At the end of 2009, 38 concessions with surface manifestations were under geological, geophysical and geochemical exploration to narrow the focus. These surveys are to be followed by exploration drilling in promising areas.

The northern geothermal/volcanic zone (Figure 7) encompasses approximately 90 geothermal areas, largely of the chloride type. In late 2009, 6 prospects were under exploration in the zone by Empresa Nacional de Geotermia (ENG), Energia Andina and other companies that are connected to copper mining. At that time ENG was owned by Empresa Nacional de Petróleo (ENAP) and ENEL (51%), while Energia Andina was a joint venture between ENAP and Antofagasta Minerals S.A. (Lahsen et al., 2010). In 2011, ENAP sold its 40% share in Energia Andina to Origin Energy Ltd., with the intention of also selling its share in ENG, in order to concentrate on its core business (MarketWatch, 2011).

Exploration has been carried out at Surire, Puchuldiza, Lirima, Apacheta and El Tatio. At Apacheta and El Tatio, 4 wells have been drilled up to a depth of 1,700 m. A preliminary estimate for these areas puts their electricity generation potential at 400-1000 MW, with a contribution of 5-10 MW_e per well (Lahsen et al., 2010).

The southern geothermal/volcanic zone (Figure 8) encompasses more than 200 geothermal areas of acidic-sulfate, bicarbonate, and chloride type. In late 2009, the prospects of Tinguiririca, Calabozos, Laguna del Maule, Chillán, Tolhuaca, Sierra Nevada, and Puyehue-Cordón Caulle were under exploration by ENG, Universidad de Chile, and some private companies. Exploration slim holes have been drilled at Calabozos, Laguna del Maule, Chillán, and Tolhuaca. Preliminary estimates for electricity generation from these areas vary from 600 MW to 950 MW, with a contribution of 3-10 MW_e per well (Lahsen et al., 2010).

4.3 Grid system and electricity generation (Lahsen et al., 2010)

There are two independent electricity grid systems in Chile. The Northern Interconnected Power Grid (SING) has an installed capacity of 3,600 MW with a gross generation of 14,500 GWh/yr, out of which 99.6% is generated by fossil fuel based power plants. The main customers are large copper mines. The Central Interconnected Power Grid (SIC) has an installed capacity of 9,348 MW, out of which 52% is provided by hydropower and the rest from fossil fuel based power plants. The grid supplies 90% of the population.

The total installed capacity for electricity generation in December 2009 was 13,086 MW, producing approximately 56,676 GWh/yr with a capacity factor of 0.49. The total projected capacity for 2015 is 19,568 MW, of which anticipated geothermal capacity is 75 MW_e. These numbers can be put in context with the estimated 16,000 MW_e geothermal potential of the country.

4.4 Legal environment

The Non-Conventional Renewable Energy Law requires energy providers in systems of an installed capacity of 200 MW or greater to demonstrate that 10% of the energy provided comes from non-conventional renewable energy resources by 2024 (OECD/IEA, 2010). A Geothermal Law was enacted in 2000, providing a framework for the exploration and development of geothermal energy (Lahsen et al., 2010).

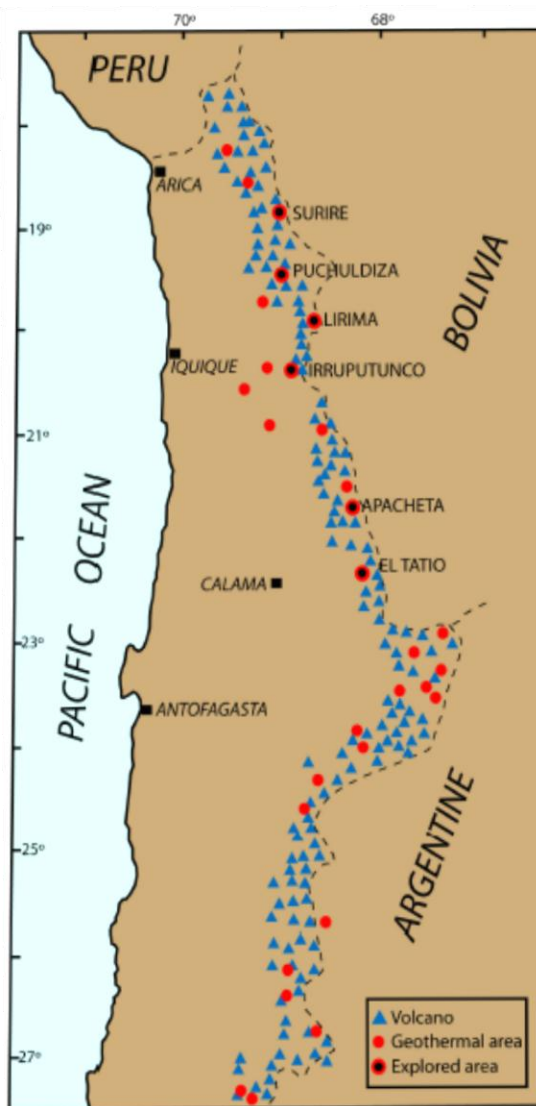


FIGURE 7: Geothermal areas of Northern Chile (Lahsen et al., 2010)

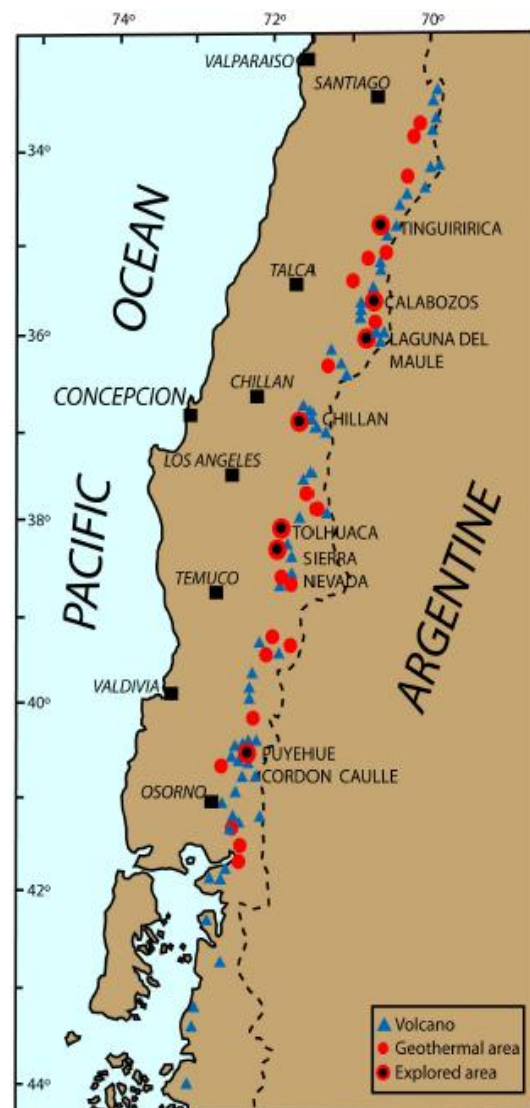


FIGURE 8: Geothermal areas of Central-Southern Chile (Lahsen et al., 2010)

4.5 Concessions and developers

In early September 2010, the Chilean Ministry of Energy announced a tender for 21 new geothermal exploration concessions (ThinkGeoEnergy, 2010a). Further licensing of concessions is planned in the next few years.

5. COLOMBIA

5.1 Geographical setting/Geological setting

The geography of Colombia can be divided into 5 main regions on the South American continental landmass, in addition to islands off the coast (Figure 9):

- The Andean region, covering the three ridges of the Andes mountains found in Colombia;
- The Caribbean region, comprised of the area next to the Caribbean Sea;
- The Pacific region, adjacent to the Pacific Ocean;

- The Orinoquía region (Llanos Orientales) along the border with Venezuela, mainly in the Orinoco river basin;
- The Amazon region; and
- The Insular region comprised of islands in the Caribbean Sea and Pacific Ocean.

The 3 branches of the Colombian Andes are (Figures 10; Figure 11):

- Cordillera Occidental adjacent to the Pacific coast;
- Cordillera Central running up the center of the country between the Cauca and Magdalena river valleys; and
- Cordillera Oriental extending north-east toward the Guajira Peninsula.

Colombia has 15 active volcanoes that lie at the junction of 3 tectonic plates: the Nazca, Caribbean and South American plates (Figure 1). The major ones are Nevado del Ruiz, Tolima, Huila, Purace, Doña Juana, and Galeras (Figure 12) and high temperature geothermal resources are associated with some of them.

5.2 Geothermal resources (Alfaro et al., 2000; Alfaro et al., 2005; Alfaro et al., 2010)

The first geothermal reconnaissance study in Colombia was a geological exploration effort of the Ruiz volcanic complex in 1968. Since then, numerous studies have been done on both high and low temperature areas. These studies indicate that high temperature systems are to be found by the Nevado del Ruiz, Chiles-Cerro Negro, Azufral, and Paipa volcanoes (Figure 12). Most of the studies have been confined to the surface, though a well was drilled on the west flank of Nevada del Ruiz in 1997. Studies on the geology of the borehole suggested a high temperature system, but the well did not reach the reservoir.

Colombia has about 300 hot springs. The highest density is found in the Cerro Bravo – Machín volcanic complex in the Cordillera Central. At least 42 thermal springs can be found in the Cundinamarca Department in the Cordillera Oriental.

5.3 Direct utilization (Alfaro et al., 2005)

Geothermal utilization in Colombia is restricted to bathing and swimming for recreational purposes. Medical balneology is also an object of interest as indicated by the establishment of the Colombian Hydrothermal Techniques Association in 1998. Local communities with hot spring areas recognize their healing properties, and the localities of Paipa and Santa Rosa de Cabal have implemented programs for relaxation and health tourism to utilize their hot springs.

5.4 The Tufiño-Chiles prospect

In early 2012, the governments of Colombia and Ecuador announced their joint study on the feasibility of developing geothermal power projects in a remote border region between the two countries with three active volcanoes: Chiles, Tufiño, and Cerro Negro. Both governments will contribute equally to the USD 4 million study, with the aim of developing a geothermal power plant generating up to 150 MW_e. The study is to be completed by the end of 2013 (ThinkGeoEnergy, 2012).

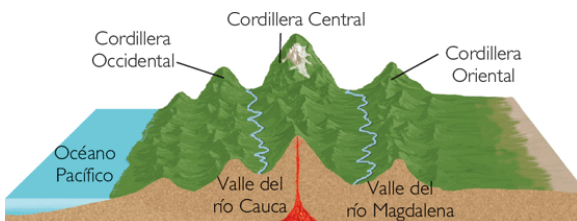
The development area of the prospect lies across the Ecuador-Colombia border, in Nariño department on the Colombian side, and in Carchi province on the Ecuadorian side. Gas thermometers indicate temperatures as high as 230°C and resistivity data confirm a reservoir under the Volcán Chiles massif. Assessment based on surface data indicates an electricity generation potential of 138 MW. Likely drilling elevation is between 3,800 and 4,200 m a.s.l. (Beate and Salgado, 2010).



FIGURE 9: The regions of Colombia (en.wikipedia.org/wiki/Natural_regions_of_Colombia)



FIGURE 10: The Colombian Andes (www.embajadacolombia.ca)



Perfil del área emergida actual.

FIGURE 11: Cross section of the Colombian Andes (co.kalipedia.com)

5.5 Recent developments

In 2010, the Japanese Trust Fund Consultancy financed a prefeasibility study for two selected sites in the Macizo Volcanico del Ruiz geothermal field through the Inter-American Development Bank (IDB). The study was to develop a model of two selected sites, identify the type of resource, temperature and the potential capacity, provide recommendations regarding further geoscientific studies, and carry out an assessment on environmental and sociological factors (IDB, 2012).

On July 5th 2011, a USD 2.7 million grant from the Global Environment Facility, which is



FIGURE 12: Volcanoes and geothermal areas in Colombia (Alfaro et al., 2000)

administered by the IDB, was approved to promote investment in non-conventional renewable energy sources in Colombia and lay the groundwork for its first geothermal project. The operation includes an assessment of the regulatory framework for renewables, the environmental and sociological conditions of the Macizo Volcanico del Ruiz area, and an analysis of a suitable financial structure for the construction of a geothermal power plant, depending on the results of the other studies and subsequent exploratory drilling (IDB, 2011).

6. ECUADOR (Beate and Salgado, 2010)

6.1 Geographical/Geological setting

Geographically and geomorphologically, mainland Ecuador consists of three regions (Figure 13):

- Costa (the coastal range);
- Sierra (the Andes mountain chain); and
- Oriente (the Amazon basin).

The Galapagos islands are the fourth region about 1,000 km west of the mainland. They are thought to be the product of a hot spot and consist of about 15 basaltic shield volcanoes, increasing in age towards the east.

The Ecuadorian Andes consist of two parallel NNE striking mountain chains:

- Cordillera Real to the east; and
- Cordillera Occidental to the west.

Both cordilleras have been uplifted and are capped by late Tertiary volcanics. Volcanic activity is extinct in the southern part, but a well developed Quaternary volcanic arc that extends into Colombia covers both in their northern half. It consists of more than 50 volcanoes, out of which 30 are still active. The Inter-Andean Valley is between the cordilleras.



FIGURE 13: Geographical visualization of Ecuador

6.2 Geothermal exploration and resources

A reconnaissance study carried out in 1979-1980 divided hydrothermal systems in areas of recent volcanism into two main groups based on temperature (Figure 14):

- Group A: Tufiño, Chachimbiro and Chalupas high temperature areas; and
- Group B: Ilaló, Chimborazo and Cuenca low-temperature areas.

Further studies by the government's Instituto Ecuatoriano de Electrificación (INECEL) indicated an electricity generation potential of 534 MW for the three high-temperature areas. Following the shut-down of INECEL in 1993, a period of exploratory stagnation lasted until 2008. In that year, the Ministry of Electricity and Renewable Energy (MEER) restarted exploration with the aim of developing one or more of the former INECEL geothermal prospects. Exploration drilling was undertaken at the Tufiños-Chiles prospect, where the first geothermal exploration well in Ecuador was completed in May 2009. The Chachimbiro prospect received 1 MUSD of funding for geophysical exploration and siting of deep exploration wells. The National Council for Electricity (CONELEC) commissioned a desk-top study on a 50 MW_e plant at the Chalupas prospect and an overall assessment

of Ecuador’s geothermal prospects. Also, Electroguayas, a part of the National Utility Corporation, funded a geological and geochemical reconnaissance study of the Chacana Caldera and an upgrade report on the Tufiños, Chachimbiro and Chalupas prospects.

6.3 The Tufiño-Chiles prospect

See section 5.4.

6.4 Current utilization and electricity generation

Current utilization of geothermal resources in Ecuador is restricted to direct use for bathing, balneology and swimming pools. Several aquaculture projects (fish hatcheries) await funding.

The installed electricity generation capacity of Ecuador was 4,557 MW in 2008 with a gross generation of 18,609 GWh/yr, of which 51.7% came from hydro power and 44.0% from fossil fuel based power plants. These numbers indicate a capacity factor of 0.47. Ecuador has imported approximately 500 GWh of electricity from Colombia and Peru per year, but that is expected to reverse when new hydro power plants come on line. In 1999, GEA estimated Ecuador’s geothermal electricity generation potential at 420-850 MW, which is 9-19% of the installed capacity in 2008.

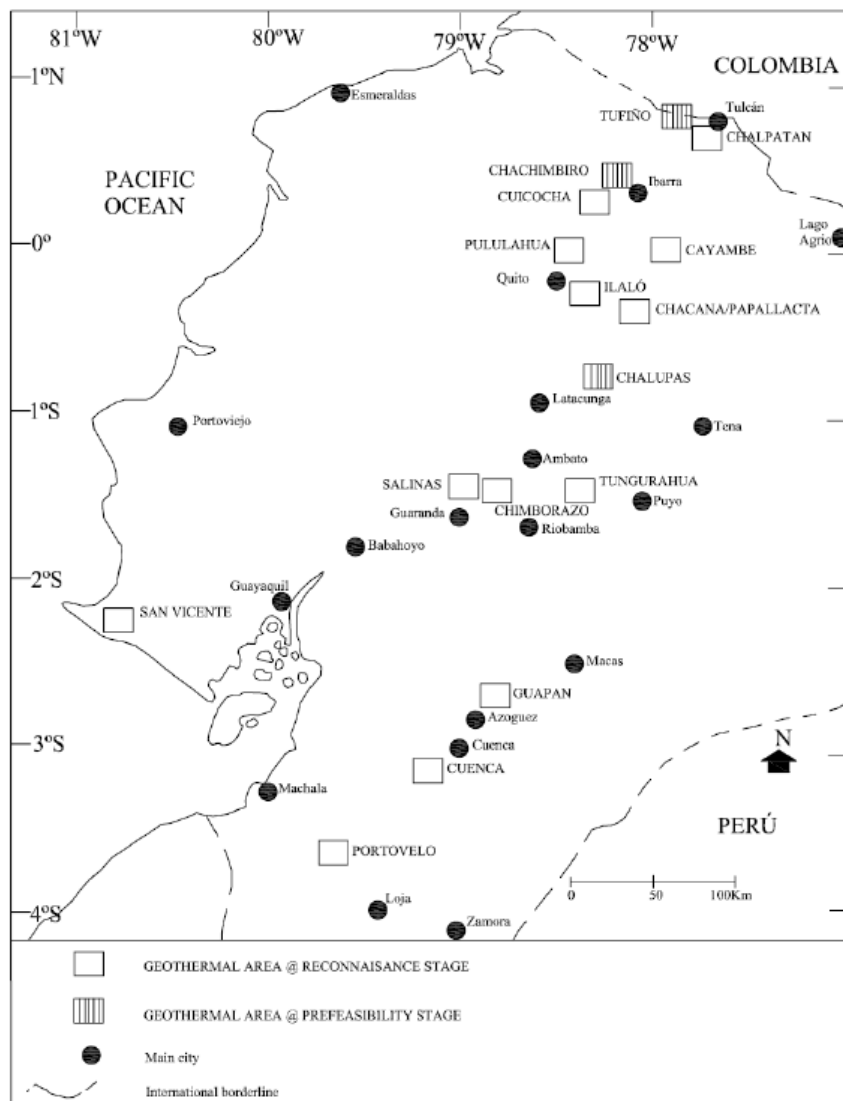


FIGURE 14: Geothermal areas in mainland Ecuador (Beate and Salgado, 2010)

6.5 Outlook

Geothermal resources can help Ecuador achieve self-sufficiency in electricity production as they offer reliable base load power. The government has decided to fund, explore and develop clean, indigenous, renewable energy resources, including geothermal. The first geothermal power plant is expected to be on line in the next 5 to 10 years. The government also intends to further explore and develop direct use for the tourist industry, agribusiness and fish hatching. In reaching these goals, public investment plays a key role.



FIGURE 15: The three geographic regions of Peru

7. PERU

7.1 Geographical/Geological setting

Geographically, Peru is divided into three regions (Figure 15; Figure 16):

- The Coast;
- The Andean mountain chain; and
- The Amazon basin, which accounts for approximately 60% of the land area.



FIGURE 16: Geographical map of Peru
(www.nowpublic.com)

7.2 Geothermal resources (Vargas and Cruz, 2010)

Peru has a vast geothermal potential that is evident in numerous surface manifestations such as hot springs, geysers and fumaroles. In northern and central Peru, high temperature manifestations are the result of the geothermal gradient and infiltrated meteoric water flowing in deep faults, while in the southern part the manifestations are related to active volcanism, and hot spring water is of both meteoric and volcanic origin.

In the Geothermal Map of Peru, recently updated by Vargas and Cruz, the country is divided into six geothermal regions with different temperatures of surface manifestations (Figure 17):

- Cajamarca – La Libertad (28-74°C);
- Callejón de Huaylas (24-60°C);
- Churín (20-73°C);
- Central (20-55°C);
- Eje Volcánico Sur (20-90°C); and
- Cuzco – Puno (24-88°C).

In this context it is worth noting that the boiling point of water at 3,000 m is approximately 90°C. Most of the studies to date have been focused on Eje Volcánico Sur, which has more than 300 volcanic centers. Recent activity has been noted in Misti, Ubinas, Ticsasi, Sabancaya, Huaynaputina, Tutupaca, and Yucamante. The region has more than 300 surface manifestations from hot springs to fumaroles. It is subdivided into three zones based on the quality of resources recognized from preliminary studies:

- Zone A (high importance): Tutupaca, Calacoa, Maure, Laguna Salinas, Chachani and Chivay;
- Zone B (medium importance): Puquiao, Parinacochas and Orcopampa; and
- Zone C (low importance): Catahuasi, Coropuna, Caylloma and Mazo Cruz.

Some companies have started geothermal exploration projects in Eje Volcánico Sur.

In 2011, the Ministry of Energy and Mines reported a potential of exploitable geothermal energy capacity of 3,000 MW (ThinkGeoEnergy, 2011). This is considerably higher than the estimate of Gawell et al. (1999), which was in the range 600-1,410 MWe.

7.3 Past and current utilization

The use of geothermal manifestations for entertainment and balneology in Peru goes back to pre-Inca and Inca periods (Cernik et al., 2010). The pre-Inca Caxamarca culture built an important city by the hot springs that later became known as the Baños del Inca (Inca baths). The place at that time consisted of some buildings that were one of the principal residences of the Caxamarca chiefs, who used the hot springs for healing and the worship of water (Figuroa Alburquerque). As the Incas gained influence in the region, the baths by Cajamarca became one of the principal residences of Inca chiefs prior to the arrival of the Spanish conquistadors. This is where Inca emperor Atahualpa first heard of the Spanish invasion and some sources say that he was aroused from the baths to receive the news. Atahualpa was subsequently captured at Cajamarca.

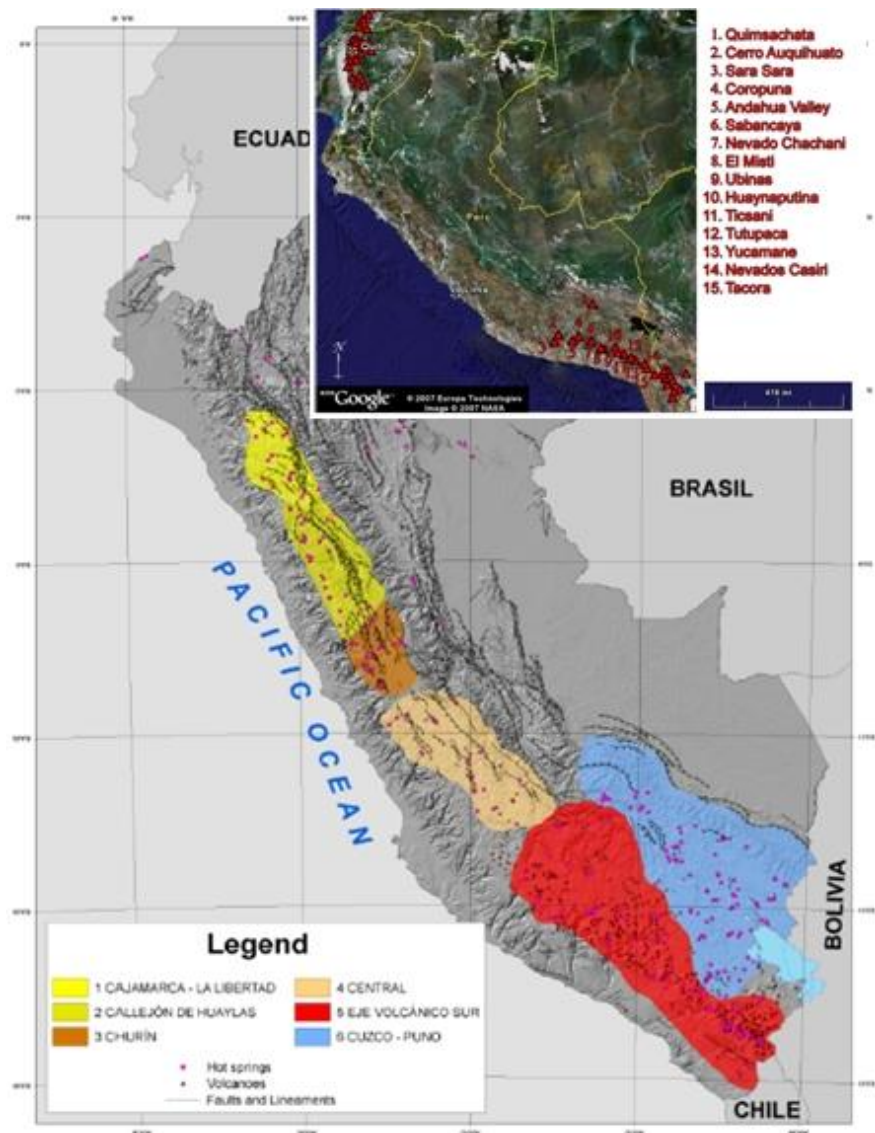


FIGURE 17: Updated geothermal map of Peru (Vargas and Cruz, 2010) and the volcanoes of Eje Volcánico Sur (Europa Technologies; NASA)

Kepinska (2003) notes that a great number of Inca palaces and temples were built near natural geothermal ponds and hot springs that were equipped with bathing facilities supplied with hot and cold water through a system of pipelines. Both aristocracy and common people had opportunities to bathe in warm springs.

The utilization of geothermal resources in Peru is still mostly limited to entertainment and balneology at places such as Baños del Inca, Callejón de Huaylas, Churín hot spring, and the Aguas Calientes baths, which are located at the closest access point to Machu Picchu. As such, they play an important role for the tourist industry.

7.4 Electricity generation

Electricity generation capacity in Peru is evenly divided between thermal and hydro, although the latter accounts for around 70% of the actual generation. The generation capacity in 2008 amounted to 7,158 MW and the gross generation was 31,921 GWh which reveals a capacity factor of 0.51 (EIA, 2010). In 1999, GEA estimated Peru's geothermal electricity generation potential at 600-1,410 MW, which is 8-20% of the installed capacity in 2008.

7.5 Recent developments

According to Vargas and Cruz (2010), the Peruvian Geological Survey (INGEMMET) conducted the first geothermal studies in the 1970s. Due to world market trends, a renewed emphasis has been placed on geothermal development and to that end all existing information has been collected in the Geothermal Map, which is intended to help with management decisions to be taken on possible investment in exploration and exploitation.

On March 25th 2010, the Peruvian Ministry of Energy and Mines presented a draft regulation on Law No. 26,848 for public commenting (MINEM, 2010). The regulation is considered necessary to reorganize and develop the various aspects regulating the rational development of geothermal resources to ensure energy supply necessary for economic growth, the welfare of the population and the efficient diversification of the country's energy sources, cautious development of those activities, access and issues related to competition (ThinkGeoEnergy, 2010b). The regulation addresses planning, the acquisition of land, the application of concessions, exploration, exploitation, rights, permits, performance guarantees, taxation, general procedures, and obligations. It is indicative of the intent of the Peruvian government to develop the country's geothermal resources beyond the traditional direct use of natural hot-springs.

Seven concessions have been granted to Mustang Geothermal Corporation at Baños del Inca, Pacla, Ninobamba, Atecata, Coline, Condoroma South, and Condoroma (New York Times, 2011). The company has already started exploration activities at Condoroma, as rural and commercial electrical consumers including the mining industry are in need of additional electrical power sources (PR Newswire, 2011). The Ministry of Energy and Mines has also authorized the exploration of geothermal resources in the regions of Arequipa and Cuzco by Hot Rock Peru SA (ThinkGeoEnergy, 2011).

8. FINAL REMARKS

Based on the World Energy Council 2007 Survey of Energy Resources, Fridleifsson and Haraldsson (2011) report a 0.73 capacity factor for geothermal power plants, which is far higher than that of any other renewable power plants. Assuming this average factor in the four countries reviewed in this paper and a geothermal generation potential that is midway between the GEA low and high estimates from 1999, except for Chile where the generation capacity is assumed to be that reported by Lahsen et al. (2010), leads to the numbers presented in Table 1. US Energy Information Administration data are used for capacity and generation in 2008 and those numbers may vary slightly from other sources. It is clear that geothermal can in all cases contribute significantly to the energy mix of the countries.

In 1999, the Geothermal Resources Council estimated average carbon dioxide emissions from geothermal power plants to be 0.08 kg/kWh, while the emissions from fossil fuel plants were: coal 0.97, petroleum 0.71, and natural gas 0.47 kg/kWh of carbon dioxide respectively (Bloomfield and Moore, 1999). This compares with 0.12 kg/kWh for geothermal power plants reported by Bertani and Thain (2002). From these numbers it is clear that using geothermal resources to generate electricity in place of fossil fuel based thermal power plants can avoid substantial CO₂ emissions.

TABLE 1: Comparison of installed capacity and generation in 2008 to estimated geothermal potential

	Cap. factor		Gen. capacity		Generation		Geoth. vs. 2008	
	Total 2008	Geoth	Installed 2008	Geoth potential	Total 2008	Geoth potential	Generation capacity	Generation
	-	-	MWe	MWe	GWh	GWh	%	%
Bolivia	0.47	0.73	1,454	885	5,982	5,659	61	95
Chile	0.52	0.73	13,145	16,000	60,281	102,317	122	170
Colombia	0.43	0.73	13,410	1,035	51,015	6,618	8	13
Ecuador	0.49	0.73	4,189	635	18,061	4,061	15	22
Peru	0.51	0.73	7,158	1,005	31,921	6,427	14	20

The United Nations University Geothermal Training Programme (UNU-GTP) can support the countries of South America in strengthening the skills of experts who are tasked with the responsibility of carrying out geoscientific exploration, utilizing and managing geothermal resources. Since its inception in Iceland in 1979, the programme has graduated 482 Fellows from 50 developing countries (Georgsson and Fridleifsson, 2012). The Fellows have obtained both a broad overview of the major geothermal disciplines as well as committing to in-depth studies in one or more of the 9 available lines of specialization: geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, environmental studies, chemistry of thermal fluids, geothermal utilization, and drilling technology. Many of the Fellows bring with them data from home to analyze during the nearly 3 month long project work, which entails the writing of a report that is included in the annual publication *Geothermal Training in Iceland*. The individual reports are available on the UNU-GTP website (www.unugtp.is). In this way, strong groups of geothermal experts have been established in many developing countries over the years. A selected number of Fellows who have shown outstanding performance in their 6 month studies, have been offered the opportunity to further their geothermal studies at the University of Iceland towards an MSc degree, and a few have been enrolled in PhD programmes.

Since 2006, the UNU-GTP has offered almost annual Millennium Short Courses in cooperation with LaGeo S.A. de C.V. in El Salvador for the Latin America region (Georgsson and Fridleifsson, 2012). The courses are the contribution of the government of Iceland towards the United Nations Millennium Development Goals and are intended to strengthen the skills of participants in specific geothermal disciplines, as well as providing a venue for experts in the region to meet and compare books. These Short Courses are often the first step for candidates to take towards further studies at the UN University Geothermal Training Programme.

Geothermal energy has been an under-developed energy source in South America, but it has the potential of providing reliable base load electricity, reducing greenhouse gas emissions, lessening reliance on imported energy, bringing electricity to the rural poor and possibly lowering electricity prices. The exploitation of geothermal resources can thus help raise the standard of living in the countries along the Andean mountain range, while also contributing to the UN Millennium Development Goals and a better worldwide environment.

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