

An Important Role of Neo-Granites as the Deep-seated Geothermal Reservoirs and Their Heat Sources

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Abstract

The deep-seated geothermal systems are being clarified in more detail with progression of exploitation in some geothermal fields such as The Geysers in USA, Larderello and Monte Amiata in Italy, Tongonan and Palinpinon in Philippines, and Kakkonda in Japan. These fields are reviewed with special reference to plutonism based on previous works. These fields are also compared each other from the viewpoint of geographical position, geological horizon, characteristics of shallow and deep reservoirs, cap rock and geothermal fluids and heat source. These study indicates that the Neo-granite plays the role of a potential heat source, and top of Neo-granite can be expected as a potential deep-seated geothermal reservoir in some of these fields. The Neo-granite is used as the same meaning of Quaternary granitic intrusive bodies in this paper.

1. INTRODUCTION

Sumi(1990) reviewed the researches on the heat source rocks of geothermal fields in Tohoku, Japan, and pointed out the important role of high level young batholiths as heat source for active geothermal systems.

Harayama(1992) reported the youngest exposed granitoid pluton on Earth from the Pliocene-Quaternary Takidani Granodiorite in the Japan Alps, central Japan. This Granodiorite is a pluton (13x4 km) situated along a major axis of the Japan Alps that was intruded into late Pliocene age (2.4 Ma) volcanic rocks. Rb-Sr, K-Ar and fission-track dates on coexisting minerals from the pluton are 1.9-0.8 Ma.

Muraoka(1993, 1994) described the common characteristics of shallow-depth neo-granitoid plutons found in Mutnovsky, The Geysers, Tongonan and some other Japanese fields.

Gianelli and Puxeddu (1992) have compared the geological frameworks between Larderello (Italy) and The Geysers (USA) geothermal fields, and pointed out that both are located in regions underlain by Pliocene-Quaternary silicic batholiths emplaced in shallow levels of the crust during a late orogenic stage of extensional tectonics following a polyphase compressional stage.

The author will review the geothermal setting of these well studied geothermal fields from the viewpoint of young plutonism, and consider the roles of these plutonism for active geothermal systems.

2. NEO-GRANITE IN SOME GEOTHERMAL FIELDS

2.1 NEO-GRANITE IN THE GEYSERS, USA

Thompson(1989) described the felsite distribution in The Geysers as follows. The Franciscan rocks at The Geysers are intruded by a silicic batholith informally called "felsite". The felsite is a composite intrusion that has been encountered over an area of at least 30 square miles and may underlie the entire field. The limited ages for this felsite range from 0.9 Ma to 2.4 Ma (Schriener and Suemnicht, 1980; unpublished age dates). Compositions including granite, granodiorite, and quartz, monzonite have been encountered in drill holes. The felsite complex has an elongate dome shape with a linear axis that trends northwest-southeast through the heart of the field.

Gunderson(1989) proposed the schematic model of pre-exploitation Geysers reservoir based on the distribution of oxygen isotopes and non-condensable gas in steam. The emplacement of a small silicic batholith caused nearby contact metamorphism and initiated fluid circulation in Franciscan graywacke. The fluid was of meteoric origin, and circulation was most intense in what is now the southeastern part of the producing field where the batholith is shallowest. After the liquid-dominated system has established spatial and isotopic characteristics, the hydrothermal system boiled down to become vapor dominated. In response to this boil down,

vapor-dominated "heat pipe" became the predominant mechanism of vertical heat transport.

Hulen and Nielson(1993) reported on geology of The Geysers felsite. The felsite is a composite igneous body comprising at least three major intrusive rock types; (1) biotite rhyolite porphyry, (2) orthopyroxene-biotite granite and (3) hornblende-pyroxene-biotite granodiorite. The rhyolite porphyry and granite are geochemically similar to overlying extrusive rhyolites of the Clear Lake volcanic field, but are too old to have been contemporaneous magma (>1.3 vs. 1.07 Ma). The granodiorite and an overlying Clear Lake extrusive dacite are temporally (about 1 Ma) and geochemically alike, and therefore possible magmatic and volcanic equivalents. Hydrothermal alteration and mineralization (dominantly tourmaline, quartz, orthoclase and albite) in the uppermost felsite and overlying metamorphic hood zone are concentrated in the northwest and southeast The Geysers. Felsite-hosted alteration and vein mineralization are partially controlled by hydrothermal breccias, potentially excellent steam-bearing conduits throughout the field.

2.2. NEO-GRANITE IN THE LARDERELLO, ITALY

Batini et al.(1985) reported the deep structure, age and evolution of the Larderello-Travale geothermal field as follows. A main seismic reflecting horizon (K), occurring in the depth range 3-6 km of this field, probably consists of fractured levels, sometimes filled with hot fluids and/or authigenic minerals present at the contact between granites and the overlying basement, which is seen in drill cores to have undergone a Hercynian metamorphism followed by a late Hercynian thermal event. After a polyphased Alpine metamorphism, a new thermal event then gave origin to the geothermal field and produced corundum and chialtolite in mica schist, leucogranitic dikelets and the resetting of metamorphic biotite ages to values in the range 1.6-3.5 Ma. The different thermal regime in different wells easily explains the variations in the apparent ages of biotite, which is still partly open to ^{40}Ar and ^{87}Sr volume diffusion.

The K-horizon is explained differently as a kinematically active rheological boundary which separates a brittle upper unit from a ductile lower unit in the upper crust by Cameli et al.(1993).

Gianelli et al. (1988) made the geological model of a young volcano-plutonic system in the geothermal region of Monte Amiata (Tuscany, Italy). Geological, geophysical and petrological data point to the presence of a granitic body below this area. A broad area of about 900-1300 km² centered on Mt. Amiata volcano shows a regional uplift of the Pliocene beds to 950 m a.s.l. The uplift began during the lower Pliocene, with a regression of the Pliocene sea from an uplifted area. The temperature distribution below the Piancastagnaio field shows an updoming of the isotherms, forming a thermal high, probably present since the earliest stages of interaction between geothermal fluids and country rocks. Seismic reflection data reveal the continuous and widespread occurrence of a reflecting horizon (K) of the "bright spot" type all over the geothermal region. This horizon is present at a depth of 5-6 km. By analogy with Larderello, it is interpreted as a fracture interval filled with hot fluids, contact metamorphic minerals and hydrothermal minerals generated in the uppermost part of the granite and the basal levels of the wall rocks. By integrating geophysical and geological data, a two dimensional gravimetric model of the volcano-plutonic system of Monte Amiata is proposed, with the following features: roof depth = 5-6 km, $T=820^{\circ}\text{C}$, $d(\text{magma})=2.15 \text{ g/cm}^3$, $d(\text{wall rock})=2.8 \text{ g/cm}^3$, shape of the intrusion is lens shaped or mushroom-like with possible thickening and roots just below Piancastagnaio. This model fits well with gravimetric data, which show a negative anomaly in correspondence with the uplifted area.

Baldi et al.(1993)described the geothermal fields of central Italy as follows. All the elements which characterize the Tuscan geothermal fields lead to the conclusion that their "roots" are attributable to magmatic intrusions of an essentially acid-anatectic type. On the basis of the available data, it is not possible to make definite conclusions about the age of these magmatic bodies. However, the very high rock temperatures measured at relatively shallow depth, together with the above consideration on the rheological characteristics of the rocks and the trend of the seismicity, lead us to believe there is a quite recent, if not active, "magmatism". The structural and phenomenological characteristics of the Latian geothermal fields are substantially different from those of the Tuscan ones. The geothermal anomalies of these fields are clearly located in areas of volcano-tectonic collapse. Furthermore, these anomalies fade more quickly than the Tuscan ones, in a radial way, and thus appear more isolated from each other.

2.3 NEO-GRANITE IN THE TONGONAN AND PALENPINON, PHILIPPINES

Lovelock et al.(1982) proposed a hydrothermal model of the Tongonan geothermal field, and described the map showing generalized top of the Mahiao diorite and isotherm at a depth of 900m below sea level.

Reyes (1990) summarized the petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment as follows. Philippine geothermal systems occur in the vicinity of large Holocene calc-alkaline volcanic complexes. Wells drilled in these areas encountered multiple intrusions; the latest dikes are the subsurface manifestations of the youngest heat source. Commonly, at least two hydrothermal regimes are juxtaposed in a single area, with the latest being in equilibrium with the present temperature and chemical regime.

Alcaraz et al.(1994)reported a case for the Nasuji pluton being a composite intrusive complex. In the Palinpinon, Nasuji pluton was divided into 3 separate igneous bodies by K-Ar dating, where each body was dated as 10.5, 5.6 and 1.5 Ma respectively. The boundary between composite bodies yield good productivity.

2.4 NEO-GRANITE IN THE KAKKONDA, JAPAN

Kato and Doi (1993) reported Neo-granitic pluton and later

hydrothermal alteration at the Kakkonda geothermal field, Japan as follows. A neo-granitic pluton ranging from adamellite to quartz diorite exists at 1,950-2,770m depth at the Kakkonda field. The intrusion of the pluton is younger than 4.9 \pm 1.0 Ma. The metamorphosed area covers over 2.0x2.5 km². The pluton underlies about 700-1,000m below the biotite isograd and about 600m-700m below the cordierite isograd. There are productive fractures in the pluton, on surface of the pluton and in the metamorphosed rocks. Contraction caused by cooling of the magma is one of the main reasons of the formation of the fractures. The pluton is fresh, however there is a little hydrothermal alteration along the fractures. The hydrothermal minerals distribute in the metamorphic rocks. Wairakite distributes extensively in the 230-250 °C zone, and is characteristic in that zone. It distributes below the biotite isograd. These facts tell that the pluton is a part of the heat source and that the pluton has started cooling by hydrothermal convection.

Doi et al.(1993) reported the K-Ar age of neo-granite and formation age of the Kakkonda geothermal system as follows. Hornblende(well 19); 0.34 \pm 0.37, 0.15 \pm 0.36 Ma, Biotite(well-13); 0.16 \pm 0.06, 0.21 \pm 0.06 Ma, Biotite(well-19); 0.21 \pm 0.04, 0.20 \pm 0.04 Ma, K-feldspar(well-19); 0.14 \pm 0.02, 0.14 \pm 0.02 Ma.

Sugihara et al.(1994) presented the relationship between hypocenter distribution of microearthquakes and a Neo-granite body in the Kakkonda in Japan. His cross section shows that hypocenters concentrate above the Neo-granite indicating the location of shallow and deep geothermal reservoirs, and hypocenters of induced microearthquakes by pressure build-up after the shut down of production wells range along the side of granitic body indicating the pass of ascending geothermal fluids. The temperature of the uppermost part of this Neo-granitic intrusion is about 350°C. This temperature is close to the transition between brittle and ductile deformation, even though it is affected by flow stress and strain velocity. These relationship seem to be expected in other geothermal fields. Especially, around the Larderello in Italy, sharp seismic reflection is identified as K-Horizon around 5 km in depth, and interpreted as top of the granitic pluton or the boundary between brittle and ductile zone in the upper crust.

Table 1. Comparison of features of neo-granite

	The Geysers (USA)	Larderello (Italy)	Tongonan, Palinpinon (Phil.)	Kakkonda (Japan)
composition	granite, granodiorite, Qz monzonite, porphyry	granite	diorite(Tongonan) Ho Qz monzonite(Pal.)	adamellite, tonalite, Qz diorite
Distribution & Morphology	>80 km ² (-3 km) elongated dome shape	>40 km ² (-5 km) elongated dome shape	>17 km ² (-1.8 km) elongated dome shape	>2 km ² (-1.5 km) elongated dome shape
Age	0.9-2.4 Ma, 1.3, 1.0 Ma	resetting Bi age; 1.6-3.5 Ma	unknown, 10.5, 5.6, 1.5 Ma	0.34, 0.2, 0.15, 0.14 Ma
other features	hydrothermal breccia for steam-bearing conduit	seismic reflecting horizon (K) at 3-6 km depth	with calc-alkaline volcanism multiple intrusions	the pluton is fresh wide heat anomalous zone
potential heat source	felsite intrusion & magma reservoir	acid-anatectic magma below the K-Horizon	Young intrusive bodies & magma reservoir	Neo-granite & magma reservoir

Table 2. Comparison of features of goothermal systems.

	The Geysers (USA)	Larderello (Italy)	Tongonan (Philippines)	Kakkonda (Japan)
tectonic position	along the San Andreas F. SW of Quaternary volcanoes	Tyrrhenian upheaval Tuscan magmatic province	along Philippine fault volcanic front	Backbone range behind volcanic front
reservoir horizon	thrust packet of greywacke Top of the felsite	Tuscan Nappe (carbonate rock) Basement (metamorphic rock)	up. Plio- Pleistocene Intrusive, Mio-Pliocene	Tertiary top of neo-granite
cap rock	greenstone melange self-sealing zone	Allochthonous Flysch Neoautochthonous clay	Smectite zone	Pliocene siltstone
reservoir charac.	shallow (~240°C, neutral) deep (260~315°C, acidic) pressure drop (3.45-1.03MPa)	shallow (500-1000m in depth) deep (1500-4000m in depth) vapor pressure (7-0.2 Mpa)	shallow (1000m in depth) deep (2000m in depth) liquid dominates system	shallow (<1500m in depth) deep (>1500m in depth) liquid dominated system
heat source	felsite intrusion & magma reservoir	acid-anatectic magma below the K-Horizon	Young intrusive bodies & magma reservoir	Neo-granite & magma reservoir

3. FEATURES OF NEO-GRANITE

Subsurface young batholiths identified or estimated in some geothermal fields have similar characteristics, and these features are summarized in Table 1.

All of them are composite intrusion ranging from granite to diorite. The intrusive body in The Geysers is more silicic and potassic than those in the Tongonan, the Palinpinon and the Kakkonda.

The subsurface distribution areas for batholiths are changing from shallow to deep horizons according to their morphological shapes. The size of batholiths in The Geysers and Larderello are larger than those in Tongonan, Palinpinon and Kakkonda, though the former are deeper than the latter. However, all of them have the same shape as elongated dome.

The ages of the batholiths crossed by wells were almost dated as 1-2 Ma or more, but only the neo-granite from the Kakkonda was dated very young as less than 0.34 Ma. Not only this data, but also other dated ages from other fields have to be examined on the degree of thermal resetting of ages after the intrusion of batholiths.

4. FEATURES OF DEEP-SEATED GEOTHERMAL SYSTEMS RELATED TO NEO-GRANITE

Four geothermal systems; The Geysers, Larderello, Tongonan and Kakkonda are compared each other from the viewpoint of tectonic position, reservoir horizon, cap rock, characteristics of shallow and deep reservoirs and heat source (Table 2). This comparison indicates some similarities and differences among them as follows.

The Geysers and Tongonan are situated along big lateral faults, Tongonan and Kakkonda on or behind volcanic fronts, and Larderello and Kakkonda on upheaval zones.

The reservoir horizons of The Geysers and Larderello are pre-Tertiary thrust packet and Nappe, while of Tongonan and Kakkonda are Tertiary or Quaternary formations. However, all of the reservoirs of these geothermal fields are closely related with intrusive bodies.

The cap rocks consist of fine grained sedimentary rocks, hydrothermal alteration zones and self-sealing zone.

The characteristics of reservoirs are divided into vapor dominated systems in The Geysers and Larderello and liquid dominated systems in Tongonan and Kakkonda.

The heat source of these fields are regarded as young intrusive bodies and underlain magma reservoirs.

According to these review and comparison, it can be concluded that the Neo-granite plays the role of a potential heat source, and top of Neo-granite can be expected in some cases as a potential deep-seated geothermal reservoir in many geothermal fields.

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