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WHY NEO-PLUTONS ARE DEEPER IN EXTENSION TECTONIC FIELDS AND SHALLOWER IN CONTRACTION TECTONIC FIELDS

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SUMMARY – Neo-plutonic bodies are often encountered beneath the contraction tectonic geothermal fields in 2-4 km boreholes but are rarely reported from the extension fields. This leads to a hypothesis that tectonic over-stress in the contraction fields amplifies the upper crustal density and magma buoyancy, so that magma rises to a shallow depth. A difference in the density of diamond drill cores obtained from extension and contraction fields demonstrates this hypothesis

1. INTRODUCTION

In the last two decades, many geothed drillholes have penetrated young plutonic bodies in and beneath hydrothermal reservoirs (Muraoka, 1993; Tamanyu, 1995). They play a key role not only as a geothermal heat source but also for geothennal reservoirs (Kiryukhin, 1993; Kato and Sato, 1995). It should be noted that most of them have been reported fiom the contraction tectonic fields. Long-lived magma chambers are also known in the extension tectonic fields, but ordinary geothermal wells of 2-4 km depths have rarely encountered plutonic bodies. This observation suggests that plutons tend to be emplaced at deep levels in the extension tectonic fields and at a shallow depth in the contraction tectonic fields.

To explain the difference of the emplacement depth of plutons between the extension and contraction tectonic fields, this paper proposes a stress constraint hypothesis. This paper tests the hypothesis using core density data fiom geothermal exploration wells in Japan.

2. TWO-TYPES OF MAGMA-TECTONIC SETTINGS OF GEOTHERMAL FIELDS

There are two types of magma-tectonic settings of geothermal fields in the world, extension and contraction tectonic fields. The extension tectonic fields typically form a zone of scattered monogenic volcanoes that may mark where dike swarms intrude into shallow depths. Iceland, Salton Trough, Tuscany, Taupo and Kyushu are well known examples of this type (Table 1). In the Nasjevellir geothermal field, Iceland, several 2 km class boreholes penetrated numerous dikes and the proportion of dike-derived rock reaches 100% in those boreholes below 1.6 km (Franzson, 1995). The contraction tectonic fields usually consist of composite volcanoes that may mark where long-lived magma chambers occur at shallow depths. Representative fields are Philippines, Indonesia, Kamchatka and Northeast Japan (Table 1).

The type of major active fault can be used as a simple criterion to distinguish those tectonic types. Where a major fault type is a normal fault, it is categorized into an extension tectonic field. When a major fault type is a reverse fault, it is categorized into a contraction tectonic field. From this viewpoint, a field dominated with strike-slip type faults is intermediate in nature. However, a field of strike-slip type faults is traditionally included in the contraction tectonics. The Geysers geothennal field is dominant in strike-slip type faults and focal mechanisms also show the strike-slip type pattern (Stanley and Rodriguez, 1995), so that this field is defined as a contraction tectonic field in this paper.

In the last two decades, many geothermal drillholes have penetrated young plutonic bodies in and beneath hydrothermal reservoirs (Lovelock et al., 1982; Yock, 1982; Takeno and Noda, 1987; Thompson, 1989; Gunderson, 1989; Sternfeld, 1989; Doi et al., 1990; Reyes, 1990; Maeda, 1991; Browne et al., 1992; Kiryukhin, 1993; Kato et al., 1993; Kato and Sato, 1995; Hulen and Nielson, 1996; Muraoka, 1993; Muraoka et al, in press). Some of them are shown in Table 1, but other examples are known. Although the age is 5-6 Ma and not necessarily young, a diorite plutonic body plays an important role for reservoir structure in the Sumikawa geothermal field, Northeast Japan (Maeda, 1991). Young plutonic bodies are quite common beneath geothermal fields in Philippines and one of them

Table 1- Comparison of magma bodies beneath geothermal fields between the extension- and contraction-tectonic settings

Regional field	Representativ field	Tectonic settings	Major fault type	Magma pluton	Depth of top of pluton
Iceland	Nesjavellir	**Extension tectonics** Spreading ridge	Normal fault	Lack (dike complex) Ref.(1)	
Salton Trough	Cerro Prieto	**Extension tectonics** Spreading ridge	Normal fault	Lack (dike complex) Ref.(2)	
Tuscany	Monteverdi	**Extension tectonics** Subduction zone	Normal fault Ref.(3)	Low-velocity body Ref.(3)	**7km?** Ref.(3)
Taupo	Ohaaki	**Extension tectonics** Subduction zone	Normal fault	Magnetized body Ref.(4)	**4km?** Ref.(4)
Kyushu	Hachobaru	**Extension tectonics** Subduction zone	Normal fault Ref.(5)	Heat body Ref.(6)	**4km?** Ref.(6)
The Geysers	The Geysers	**Contraction tectonics** Slab windows	Strike-slip fault Ref.(7)	The Geysers felsite Ref.(8)	**1.20km** Ref.(8)
Philippines	Tongonan	**Contraction tectonics** Subduction zone	Reverse fault	Mahiao diorite Ref.(9)	**1.60km** Ref.(9)
Kamchatka	Mutnovsky	**Contraction tectonics** Subduction zone	Reverse fault	Mutnovsky diorite Ref.(10)	**1km** Ref.(10)
Northeast Japan	Nyuto	**Contraction tectonics** Subduction zone	Reverse fault Ref.(5)	Nyuto diorite Ref.(11)	**1.34km** Ref.(11)
	Kakkonda			Kakkonda granite Ref.(12)	**1.95km** Ref.(12)

Reference: (1) Franzson (1995), (2) Elders et al. (1997), (3) Baldi et al. (1995), (4) Soengkono (1995), (5) Sasada (1995), (6) Ehara and Morita (1995), (7) Stanley and Rodriguez (1995), (8) Thompson (1989), (9) Lovelock et al. (1982), (10) Kiryukhin (1993), (11) New Energy and Industrial Technology Development Organization (1992), (12) Kato and Sato, (1995)

is known in the Palinpinon geothermal field.

When we examine tectonic settings of those plutonic bodies, it should be noted that they are exclusively found from the contraction tectonic fields (Table 1). The only exception could be a well at the Ngatamariki geothermal field, New Zealand where one of four boreholes penetrated a diorite plutonic body below a depth of 2.46 km (Browne et al, 1992).

As summarized in Table 1, dike swarms are more common in some extension tectonic fields such as Iceland. However, large plutonic bodies with a batholith dimension are also expected in other extension tectonic fields like the clustered caldera areas in the Taupo Volcanic Zone, New Zealand. Therefore, the rare occurrence of plutonic bodies in extension tectonic fields could be ascribed to the difference in an emplacement depth of plutonic bodies that is deeper than the ordinary depth of geothermal wells. The depth to the top of some plutonic bodies is, in fact, estimated to be 4-7 km in extension tectonic fields (Table 1).

3. STRESS CONSTRAINT HYPOTHESIS

From a geothermal viewpoint, we shall consider the rise of magma to a high level in the crust. Magma may rise (a) in a diapir, (b) in an elastic dike disconnected from a magma source region or (c) in an elastic dike connected to the magma source region. There is a critical difference between magma in a diapir or a disconnected dike, which can only rise if it is buoyant, and magma in a connected dike, which can rise even when it is not buoyant if the source region has a great enough over-pressure (Wilson et al., 1993).

The (c)-type is analyzed in terms of driving pressure, Pd $= P_m - \sigma_t$, where P_m is the magma pressure and σ_t is the tectonic compressive stress normal to the dike face (Rubin, 1990; Reches et al., 1993). Because the vertical (overburden) stress is a standard value to divide compressive or extensive stress and is almost equal to σ_1 in the extension tectonic fields, horizontal compressive tectonic stress σ_t is usually negative in the extension tectonic fields. Therefore, the driving pressure P_d is usually positive in the extension tectonic fields, allowing the magma to propagate to a shallow depth (Rubin, 1990; Reches et al., 1993). This explains a fundamental genesis of the rift-zone magmatism where dike swarms are the most dominant.

The (a)- and (b)-types are exclusively constrained by the buoyancy of magma in the crust. The buoyancy is evaluated by the density contrast between the magma and the surrounding rocks (Muraoka, 1997). Diapiric magma bodies of the (a)-type tend to form large-scale stocks and batholiths and are particularly important as a long-lived magma chamber as well as a potential geothermal heat source. Plutonic bodies described above are mostly categorized into this type. We shall consider the reason why the emplacement depth of diapiric magma is greater in extension tectonic fields than in contraction tectonic fields below.

The density of magma is basically a function of silica and volatile contents (Muraoka, 1997). However, there is a wide variation in magma composition in both extension and contraction tectonic fields, so that this is not the main factor controlling the difference in the emplacement depth between two type tectonic fields.

Another factor is the density of rocks in the shallow crust. At less than several kilometers depth, the density change is sharp, because the porosity of rocks decreases with depth. Pressure or stress exclusively controls the porosity of rocks. For simplicity, we shall consider a typical extension tectonic field with normal faults and a typical contraction tectonic field with reverse faults.

A standard (overburden) stress σ_v is equal to σ_1 in the extension field, whereas σ_v is equal to σ_3 in the contraction field. Therefore, their stress regions are completely separated by a line $\sigma_h = \sigma_v$. This line is calculated from $\sigma_v = \rho_r g z$, where ρ_r is the density of rock as given here to be 2.62 g/cm^3, g is the gravitational acceleration and z is the depth. The ratio σ_1/σ_3 is given to be 1-2 that was measured at 23 locations in Japan (Kanagawa et al., 1986). The stress range of the extension and contraction tectonic regions was drawn using this value in Fig. 1.

Rocks undergo anisotropic stress in general, but an average stress is shown by the intermediate point of each region in Fig. 1. If we assume the average stress to be 50 MPa, it is given as point E for an extension field and point C for a contraction field (Fig. 1). Fig. 1 shows that the same stress value is obtained at twice greater depth in extension fields compared to contraction tectonic fields. This suggests that the density-depth profile is different between extension and contraction tectonic fields.

Based on this consideration, we can construct a stress constraint hypothesis on the difference in the emplacement depths of plutonic bodies between extension and contraction tectonic fields. As is the same for the definition of tectonic fields, the stress regime is a key factor. Because the density of rocks is exclusively controlled by stress, a large tectonic stress in contraction tectonic fields amplifies the density of rocks which promotes the buoyancy of the magma, driving it to a shallower depth. Conversely, the lesser tectonic stress in extension tectonic fields can not drive the magma to a shallow depth.

This hypothesis can be verified when we compare the density of rocks between extension and contraction tectonic fields.

4. VERIFICATION BY CORE DENSITY

We have constructed a geothermal well database system (Yano and Muraoka, 1986). Not all, but a large amount of core data from Japanese geothermal exploration wells are stored in this database system. We shall use the density data measured under the wet-constraint state, because this is the closest to the subsurface natural state.

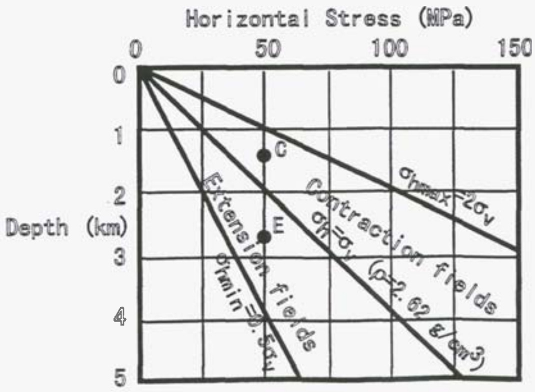

Figure 1- Simplified stress regions of extension and contraction tectonic fields

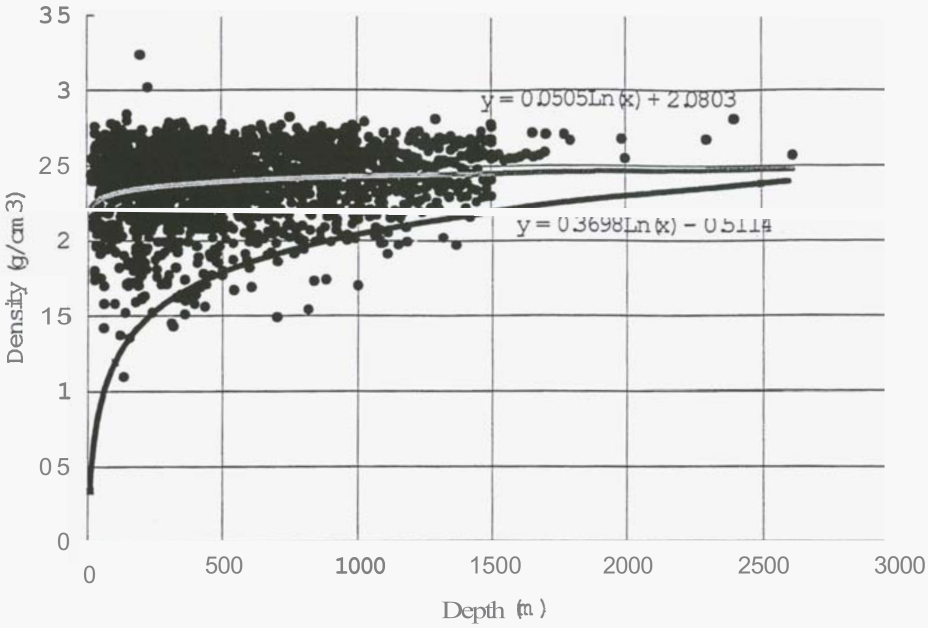

Figure 2- Core density data from the Hohi graben area, central Kyushu, Japan

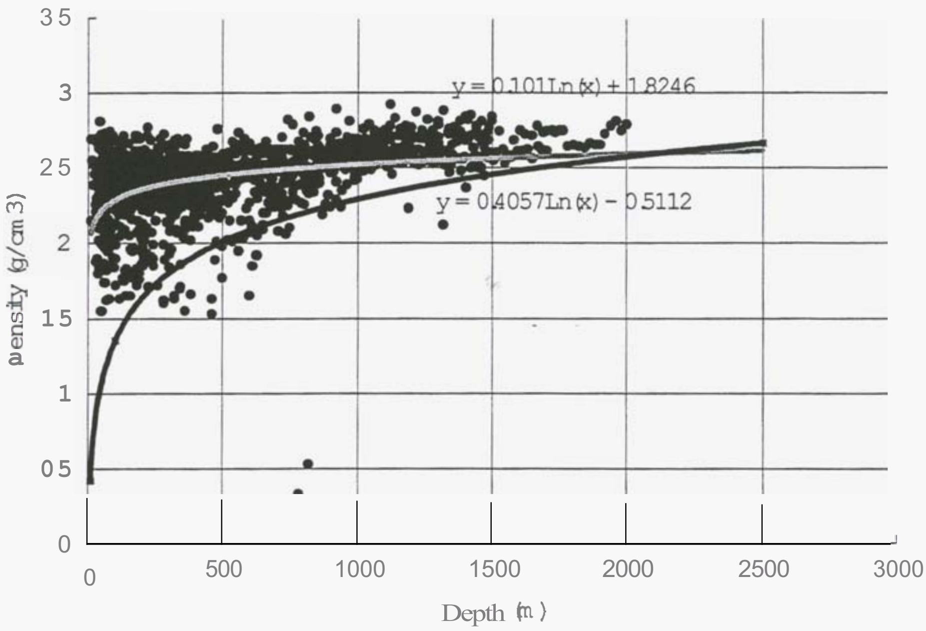

Figure 3- Core density data from the Hachimantai volcanic area, northeast Japan

Core density is compared between two regional geothexmal areas: the Hohi graben area in Kyushu and the Hachimantai volcanic area in northeast Japan. A number of exploration wells have been drilled in these two areas and the tectonic settings are quite clear: the former is an extension tectonic field and the latter is a contraction tectonic field (Sasada, 1995).

Figure 2 shows core density data from 1799 samples and 27 wells in the Hohi graben area. Figure. 3 shows core density data from 1182 pieces and 44 wells in the Hachimantai volcanic area. Clusters in both diagrams are bounded by a linear edge in the higher density side. This margin indicates the density of pure rock materials with less porosity such as basaltic and andesitic lava. On the other hand, clusters in both diagrams are bounded by a logarithmic edge in the lower density side. This margin bounds the field of porous rocks such as normal sediments and pyroclastic rocks. These rocks absorb stress and easily become more dense with increasing stress.

The two curves are drawn in Figures. 2 and 3 respectively: one is a logarithmic approximation in a manual procedure to the lower density margins that are sensitive to stress and the other is a logarithmic approximation for the entire cluster in an automatic procedure. For the manual procedure, curves are roughly fitted to match the relation where the same density value is obtained at twice greater depth in extension fields (Fig. 2) compared to contraction fields (Fig. 3). These curves are consistent with each lower density edge. This accurately satisfies the theoretical consideration. Equations of for the "automatic" curves also indicate that the density given in Figure 2 is more than twice greater depth in Figure 3. These results support the theoretical consideration and the stress constraint hypothesis.

5. CONCLUSIONS

(1) Dike swarms are dominant at shallow depths in extension tectonic geothermal fields, whereas young plutonic bodies are dominant at shallow depths in contraction tectonic geotheml fields.
(2) From a theoretical viewpoint, this observation is explained by the effect of tectonic stress: dike swarms can rise to shallow depths if stress is weak and plutonic bodies can rise to shallow depths if stress is strong because the denser crust amplifies magma diapir.
(3) The latter new hypothesis named the 'stress constraint hypothesis' is demonstrated by the comparison of core density between extension and contraction tectonic fields: the density of the latter fields is systematically larger than in the former.

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