Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

PETROLOGIC CHARACTERIZATION OF THE QUATERNARY VOLCANO-PLUTONIC SYSTEM: THE TAKIDANI PLUTON AND ASSOCIATED VOLCANIC ROCKS IN THE JAPAN ALPS , JAPAN

Masatoshi Bando and Noriyoshi Tsuchiya
Department of Geoscience & Technology, Graduate School of Engineering,
Tohoku University, Sendai 980-8579, Japan

Key Words: Granitoid, Reversely zoned pluton, Quaternary age, Petrology, Geochemistry, Geothermal reservoir

ABSTRACT

The Takidani granitoid rocks (TG) is reported to be the youngest exposed pluton on the Earth (1.9-2.4 Ma), and forms part of a volcano-plutonic complex system with the Pliocene Hotaka Andesites. In this study, petrographic and petrochemical characteristics of the TG, enclaves and Hotaka Andesites are described, together with preliminary pressure estimations for the TG. Overall, TG has a reverse zonal structure, based on the modal abundance of constituent minerals and chemical composition of surface samples. The inner zone of TG is composed of hornblende rich biotite granodiorite (Bi-Hb-Gdt) with whole rock SiO_2 ranging from 66 to 70 wt%, whilst granite and biotite rich hornblende granodiorite (Hb-Bi-Gdt) occur in the outer zone. In the eastern and western parts of the pluton, an apparent exception to the reverse zonal structure is evident. At the edge of the eastern zone, porphyritic granodioritite (P-Gdt) occurs that has a SiO_2 content of 68-71 wt% with porphyritic granite (P-Grt: 70-73 wt%) closer to the core of the intrusion. In hornblende rich biotite granite (Bi-Hb-Grt) located in the western part of the TG, SiO_2 content increases from 68 wt% to 71 wt% approaching the inner zone. Thus, in the eastern and western parts of the pluton, a normally zoned chemical structure is formed. Accordingly, the genesis and emplacement process of the Takidani pluton has been characterized by multiple magma processes i.e. with extended in situ crystallization of reversely stratified magma in the marginal zone. A reverse zonal chemical structure of TG might be major evidence for an underlying stratified magma chamber.

1. INTRODUCTION

The Pliocene and Quaternary was a time for widespread emplacement of granitoid intrusives, with young granitoids found all over the world (Gianelli *et al*., 1988; Hill *et al*., 1992). Recently, Quaternary granite has been intersected by boreholes in the Kakkonda geothermal area in northern Japan. The K-Ar age of the pluton minerals is younger than 0.24Ma, (Kanisawa *et al*., 1994; Doi *et al*., 1998), so it is the youngest yet found granite. The Kakkonda Granite was encountered in boreholes at depths where the measured temperature is over 350 ℃(Kanisawa *et al*., 1994).

Clearly, young granitoids are effective host rocks for deep geothermal reservoirs. It is difficult, however, to collect deep granitic rocks in-situ. Therefore, the study of exposed young granite is necessary in order to provide useful basic information to evaluate other potential deep geothermal reservoir. The TG is a practicable analogy, as a case-study of a deep geothermal reservoir because of the following reasons : ① The wide exposure of the pluton allows the vertical and lateral textural variation to be readily determined.② Emplacement process may be considered on the basis of a straightforward cooling model, due to the absence of any evidence of recrystallization.

2. GEOLOGICAL SETTING

TG is located along one of the major axis of the Japan Alps, with the Norikura volcanic chain being one of the active volcanic belts in Japan. TG is distributed over an area of $21km^2$ (13 km long and up to 4 km a wide), and has a 1220m vertical exposure from 1450 m to the contact with the Hotaka Andesites at 2670 m above sea level (Harayama, 1992)(Fig.1). It is possible to investigate spatial modal and chemical variations within the TG. The Takidani pluton intruded the late Pliocene (2.4Ma) Hotaka Andesites on its eastern contact. The pluton intruded Mesozoic basement, and Paleogene granitic rocks on the western contact, and is covered by the Quaternary volcanic rocks on its southern part (Harayama, 1994). TG is reported to be the youngest exposed granitic body on the Earth. The solidification and exposure age were determined in the range of 1.9-2.4 Ma and 0.1-0.65 Ma respectively (Harayama, 1994).

3. EXPERIMENTS

The following experiments were carried out on the TG, enclaves included in TG, and the Hotaka Andesites:

- Modal analyses
- Full petrographic description, including textural characteristic of constituent minerals
- Whole rock chemical analysis (major and trace elements) using X-ray fluorescence techniques
- Chemical composition of hornblende and plagioclase in TG using electron probe microanalyzer, primarily for application of the Al-in-hornblende geobarometer
- PSHA (Principal Strain Hysteresis Analysis) for preliminary pressure estimation

4. RESULTS

4.1 Modal Analyses and Petrography

TG was classified into granite and granodiorite based on the results of modal analysis (Fig.2). According to textural characteristics, and modal content, TG was further subdivided into six categories (Fig.3). They are:

① Porphyritic granodiorite (P-Gdt): Euhedral plagioclase (42-53 vol %) and hornblende chiefly occur as a phenocrysts predominately, in a fine-grained matrix.
② Porphyritic granite (P-Grt): Fine-grained groundmass with minor plagioclase (30-41 vol %), quartz and hornblende phenocrysts.
③ Hornblende rich biotite granodiorite (Bi-Hb-Gdt): The mineral assemblage consists of euhedral plagioclase, euhedral-subhedral quartz, anhedral potassium feldspar (7-22 vol %), biotite, hornblende (2-11 vol %) , and minor magnetite. A medium-grained equigranular texture is observed.
④Biotite rich hornblende granodiorite (Hb-Bi-Gdt): This Rock has the same texture and mineral assemblage as Bi-Hb-Gdt, but greater modal amount of potassium feldspar (15-24

vol %) and l hornblende less than 3 vol %.
⑤Hornblende rich biotite granite (Bi-Hb-Grt): This lithofacies has a similar mineral assemblage as Bi-Hb-Gdt. It has, however, a greater modal amount of potassium feldspar (16-30 vol %) than the Hb-Bi-Gdt, with hornblende also more abundant (2-6 vol %). Medium to fine-grained equigranular texture was observed.
⑥ Biotite rich granite (Bi-Grt): Although the mineral assemblage and texture is similar to that of Hb-Bi-Gdt, the rocks were categorized as granite because of the greater modal amount of potassium feldspar compared with Hb-Bi-Gdt.

Overall, the TG has a reverse zonal structure based on its lithofacies distribution (Fig.3). Hornblende rich granodiorite (Bi-Hb-Gdt) occurs in the inner zone of the pluton, and granite (Bi-Hb-Grt and Bi-Grt) and biotite rich granodiorite (Hb-Bi-Gdt) occur in the outer zone. An apparent exception to this trend is found in the eastern part of the TG where P-Gdt occurs at the edge of the pluton and P-Grt further away from the contact.

TG hosts dark enclaves which are divided into two types. One Type (M) is inferred to have been derived from magma because of the circular-ovoid shape and occurrence of reaction rims. The other type(H) may be derived from the Hotaka Andesites, since they have an angular shape and no visible reaction rim. Most of the enclaves identified in the field are of the former type.

The Hotaka Andesites is composed chiefly of andesitic to dacitic welded-tuff, diorite porphyry stock, and collapse breccias.

4.2 Whole Rock Chemical Composition

A range of SiO_2 content (66~76wt%) and lateral variations have been determined across the TG. As a general trend, the TG shows a reverse zonal structure, based on its major element whole rock chemistry. A high SiO_2 content was determined in the outer zone (Bi-Grt: 72-76wt%/Hb-Bi-Gdt: 69-74wt%), which decreases towards the inner part of the exposed TG (Bi-Hb-Gdt: 66-70wt%). In contrast, a variation to this trend is evident in the eastern part of TG, as shown in Fig.4. P-Gdt is characterized by lower SiO_2 content (68-71wt%) than P-Grt (70-73wt%). In the western part of the TG, SiO_2 content increases from 68 wt% in the outer (Bi-Hb-Grt) facies to 71 wt% in its innermost part.

Other major oxide components of TG vary with SiO_2 content, and follow the general pattern of Japanese granitoid rocks (Aramaki *et al.*, 1972). Variation of K_2O against SiO_2 content is shown in Fig.5(a). The straight line in the figure indicates the average variation trend of Japanese granitoids (Aramaki *et al.*, 1972). Slightly high K_2O content was determined in P-Grt. TG is categorized into I-type granite, based on its whole rock major element chemistry, with analysis plotting in the I-type field on the A/CNK diagram (Fig.5(b)).

Ba content increases, albeit with some scattering with increasing SiO_2 content (Fig.5(c)). The Bi-Grt and Hb-Bi-Gdt lithofacies are enriched in Ba, whilst there is an apparent depletion of Ba in P-Grt.

Rb concentration is a great in rocks with higher SiO_2 content (Fig.5(d)). A slightly greater Rb concentration is indicated in P-Grt, compared to Bi-Grt and Hb-Bi-Gdt, which have almost the same SiO_2 content. In contrast, P-Gdt is slightly less depleted in Rb compared to the other rock types. In spite of lower SiO_2 content, Rb is generally high in the enclaves (M).

Sr concentration decreases systematically with an increase of SiO_2 content (Fig.5(e)) except for the enclave(M). Sr content of P-Gdt shows a slightly enriched trend while slightly less abundance is identified in P-Grt.

TG, Hotaka Andesites and enclave (M) show a similar trend, with respect to incompatible trace elements abundance, which are normalized to primitive mantle (Taylor and McLennan,1985) (Fig.6). In this figure, representative samples of each facies are plotted. On the basis of their similar trace elements patterns, TG, Hotaka Andesites and enclaves (M) are suggested to have a close genetic relationship with each other, and their source material.

4.3 Chemical Composition of Hornblende and Plagioclase

The Al-in-hornblende geobarometer (Schmidt, 1992), based on the chemical composition of hornblende and plagioclase, indicates that the TG was emplaced at a pressure of < 3.4 kbar.

4.4 PSHA

A PSHA experiment after Yamaguchi *et al.*,(1990) was performed on samples collected from the western part of the TG (Bi-Hb-Grt). On the basis of the results, microcracks in rocks located in the western TG were inferred to have occurred at the lithostatic pressure in the range of 32 MPa to 44 MPa.

5. DISCUSSION AND CONCLUSIONS

On the whole, the Takidani pluton has a reverse zonal structure i.e. more leucocratic lithofacies (Bi-Grt and Hb-Bi-Gdt) are distributed in the marginal zone of the pluton, with high SiO_2 content also identified. The outer zone of the pluton is characterized by P-Gdt, P-Grt and Bi-Hb-Grt lithofacies, with a SiO_2 content that indicates normal zoning, discordant with the overall trend of reverse zoning.

The best interpretation to resolve the occurrence of normal zoning in the outer zone, is provided by "in situ crystallization" (Langmuir,1989). According to this model, heat is lost along the margin of the magma chamber, and crystal growth occurs, with intercumulus liquid being efficiently expelled from the partially solidified zone. Subsequently, more evolved liquid is returned the ' interior ' of the magma chamber. The abundance of K_2O content in P-Grt (Fig.5(a)) supports this model. Furthermore, the trace element distribution in P-Gdt and P-Grt (Fig.5(c,d,e)) i.e. Rb depletion and enrichment of Sr in P-Gdt compared to P-Grt is evidence for in situ crystallization. This relationship was caused by a low and high partition coefficient of Rb and Sr respectively, in feldspar, with crystal/melt fractionation of feldspar having occurred between these two facies. Plagioclase phenocrysts abundance in P-Gdt may also support this hypothesis. Based on the normally zoned variation in SiO_2 content (Fig.4), in situ crystallization is inferred to have occurred not only in the eastern part but also in the western part (Bi-Hb-Grt) of the pluton.

Reverse zonal structure determined for the TG is inferred to be produced by a stratified magma chamber. The inner and outer zones of the pluton were formed by less evolved magma and more evolved magma respectively. Furthermore, extended in situ crystallization occurred along the roof and cooler wall of the evolved magma chamber. Thus, a normally zoned structure was formed in the western and eastern areas. The unusual zonal structure of the pluton, characterized by an overall reverse zonal structure and normal zoning in marginal zones, considered to be formed as a consequence of multiple magma processes.

Based on the application of the Al–in–horbnblende geobarometer and results from the PSHA experiment, hornblende was inferred to have crystallized at less than 11.5 km depth. Microcracks in the western part of the TG occurred at 1.3-1.8 km depth. These results could be the indicators for pressure estimation.

The reverse zonal structure of the TG might be good indication of an underlying stratified magma chamber. The description of petrologic characterization of the exposed pluton, and the preliminary pressure estimation, contribute to our understanding of potential host rocks for deep geothermal reservoir.

ACKNOWLEDGEMENTS

We would like to express our gratitude to Dr. Y. Motoyoshi and Miss K. Seno for their kind guidance on XRF. We thank to Mr. I. Hino (Tohoku Univ.) for preparing thin sections. We wish to thank Dr. T. Sawada Hotaka Sedimentation Observatory, Kyoto Univ. for kind help during field work. This work was financially supported by JSPS (RFTF 97 P00901).

REFERENCES

Aramaki,S., Hirayama,K. and Nozawa,T.(1972). Chemical composition of Japanese granites, part2. Variation trends and average composition of 1200 analyses. *J.Geol.Soc.Japan*, Vol.78, pp.39-49.

Langmuir,C.H. (1989). Geochemical consequences of in situ crystallization. *Nature*, Vol.340, pp.199-205.

Doi N., Kato O., Ikeuchi K., Komatsu R., Miyazaki S., Akaku K., and Uchida T. (1998). Genesis of the plutonic-hydrothermal system around Quaternary granite in the Kakkonda geothermal system, Japan. *Geothermics*, Vol.27, pp.663-690.

Gianelli,G., Puxeddu,M., Batini,F., Bertini,G., Dini,I., Pandeli,E. and Nicolich,R. (1988). Geological model of a young volcano-plutonic system: The geothermal region of Monte-Amiata (Tuscany, Italy). *Geothermics*, Vol.56, pp.719-734.

Harayama,S.(1992). Youngest exposed granitoid pluton on Earth: cooling and rapid uplift of the Pliocene-Quaternary Takidani Granodiorite in the Japan Alps, central Japan. *Geology.*, Vol.20, pp.657-660.

Harayama,S.(1994). Cooling history of the youngest pluton in the world –The Plio-Pleistocene Takidani Granodiorite (Japan Alps, central Japan) –. *Mem.Geol.Soc.Japan*,Vol.43, pp.87-97. *

Hill,E.J., Baldwin,S.L. and Lister,G.S. (1992). Unroofing of active metamorphic core complexes in the D' Entrecasteaux Islands, Papua New Guinea. *Geology*, Vol.20, pp.907-910.

Kanisawa,S., Doi N., Kato O. and Ishikawa K.(1994). Quaternary Kakkonda Granite underlying the Kakkonda geothermal field, Northeast Japan. *J.Petrol.Mineral.Econ. Geol.*, Vol.89, pp.390-407. *

Schmidt,M.W. (1992). Amphibole composition in tonalite as a function of pressure: an experimental calibration of the Al-in hornblende barometer. *Contrib. Mineral. Petrol.,* Vol.110, pp.304-310.

Taylor,S.R. and McLennan,S.M.(1985). The continental crust: its composition and evolution. Blackwell Science Publication London., pp312.

Yamaguchi,T., Oikawa,Y., Sato,Y., Kuriyagawa,M., Temma, N. and Kobayashi, H. (1990). Determination of in-situ stress state by DSCA. *Proc. 8th Japan Sympo. on Rock Mech.*. pp.303-308. *

* in Japanese with English abstract

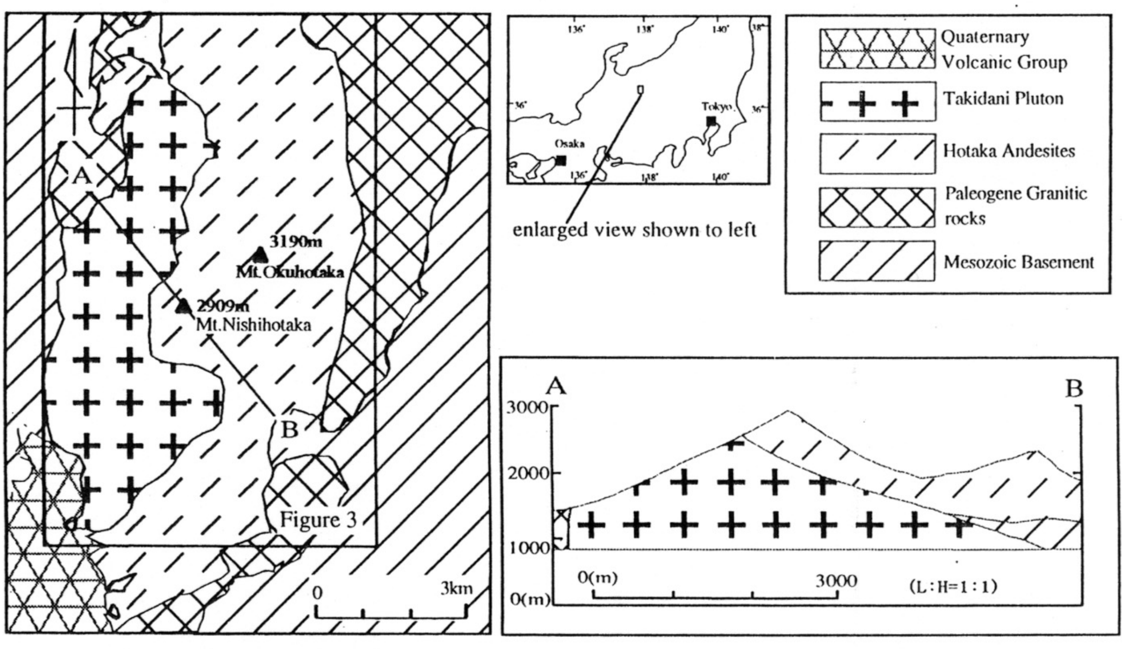

Figure 1. Generalized geological map and cross section of Takidani area (Simplified after Harayama,1992)

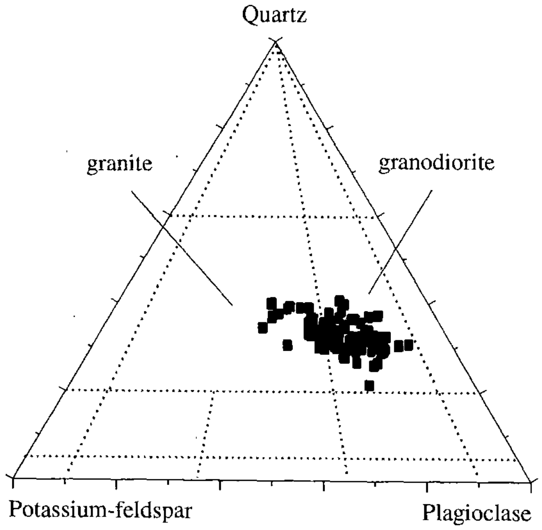

Figure 2. Modal analyses (Based on the IUGS modal classification and nomenclature of the plutonic rock)

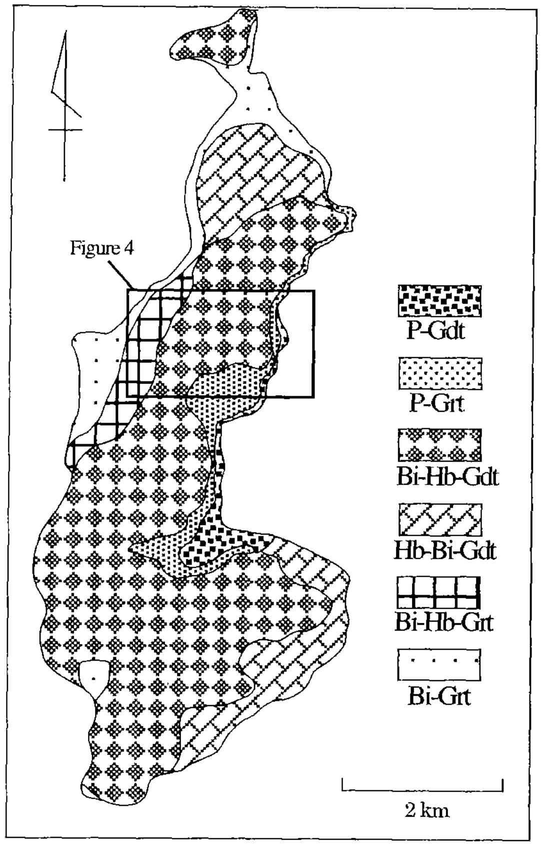

Figure 3. Lithofacies map of TG

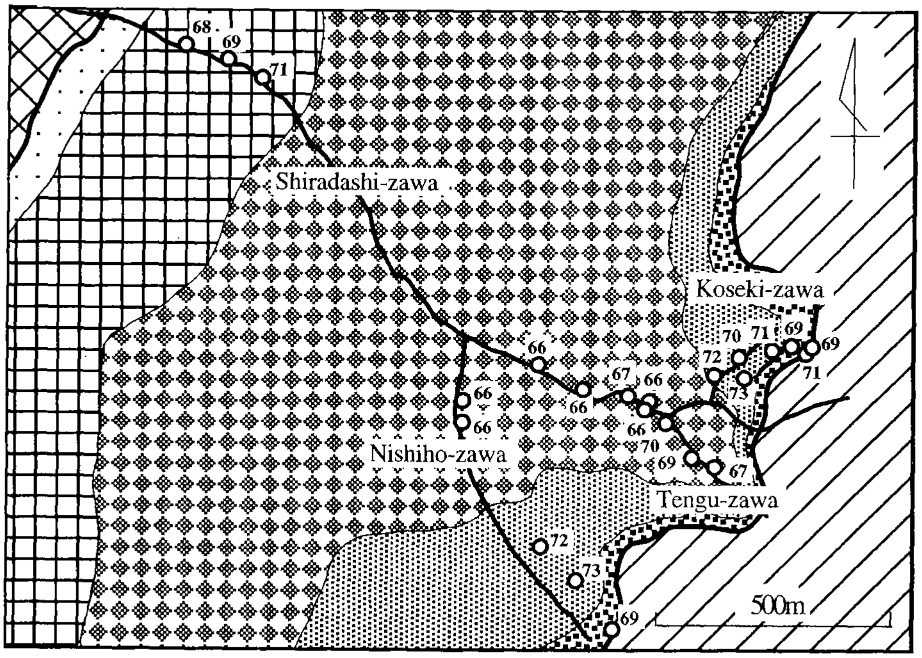

Figure 4. Variation of SiO_2 content along the Shiradashi-zawa. Labels in the figure are SiO_2 content in wt%. The legend for lithofacies is the same as Fig.3

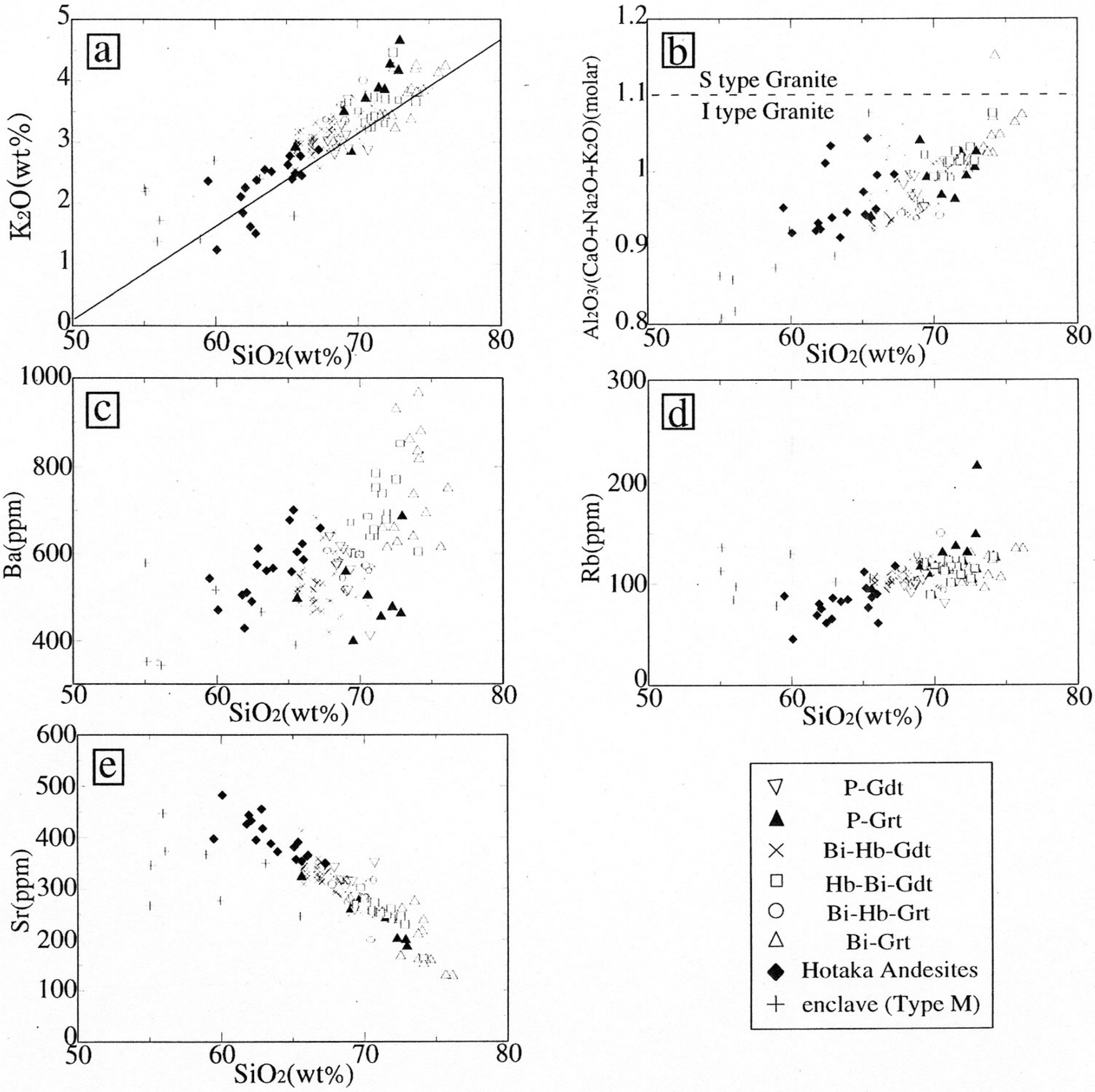

Figure 5. Major oxide and trace elements variation diagrams, see text for description of rock classification

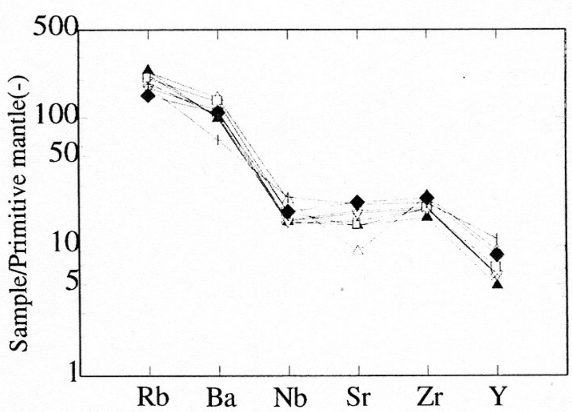

Figure 6. Incompatible trace elements patterns normalized to primitive mantle (after Taylor and McLennan,1985). The legend for lithofacies is the same as Fig.5