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SILICA CONTENT AND GAMMA RAY LOGS IN VOLCANIC ROCKS

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Abstract

Chemical analyses of 254 rock samples from Iceland are used to establish a relationship between the natural gamma ray intensity (expressed as API gamma ray units, or API GU) and the silica concentration of Icelandic rocks (% SiO_2). For each sample, the gamma response is calculated based on concentrations of K, Th, and U, using linear equations established by Belknap (1959). The SiO_2 concentration in this sample population is shown to be linearly related to the K, Th, and U contents. Combining these equations, we obtain the following linear relation: API GU = $(2.63 \pm 0.10)*SiO_2 - (102 \pm 6)$. This result agrees with a previous calibration where actual gamma ray logs were compared with chemical analyses of cores and cuttings (Stefansson et al. 1982). The relation obtained makes it possible to express the natural gamma ray logs as percentage of the SiO_2 in the Icelandic rocks. Furthermore, as the matrix thermal conductivity of volcanic rocks seems to correlate with their silica content, it might be possible to obtain continuous profiles of the thermal conductivity from the gamma ray logs together with a suitable porosity log.

Introduction

Different concentrations of the radiogenic elements, uranium, thorium, and potassium, in various geological formations make it possible to use natural gamma ray logs (GRL) to map different geological units in wells. The GRL has been in use for some 60 years and is considered one of the simplest logs presently in use. As most of the wells in the world have been drilled into sedimentary rocks, the interpretation methods applied to GRL are based on the radiogenic properties of sedimentary rocks. The classical approach is to use the GRL to distinguish between pure sandstone and shale. Interpretation of GRLs in igneous rocks has received less interest.

Natural gamma ray logs have been used systematically in Iceland for the last 20 years. Early in this period, it was demonstrated that a relation exists between the intensity of the GRL and the chemical composition of Icelandic crystalline volcanic rocks (Stefansson et al., 1982). An approach was proposed, where the GRL could be expressed as the concentration of the SiO_2 of the rocks. These results were mainly based on a comparison of a detailed GRL and extensive analyses of the continuous core obtained in the IRDP research borehole in Reydarfjördur in Eastern Iceland (Flower et al., 1982) together with a similar study of one well in Krafla, Iceland.

At present, the National Energy Authority of Iceland (Orkustofnun) is carrying out an extensive research programme on the properties of Icelandic reservoir rocks, including petrophysical (Stefansson., 1997), petrochemical, and petrological (Franzson et al., 1998) studies. Orkustofnun participates in the Nordic heat conduction project (Middleton et al., 1998). Detailed chemical analyses of some 250 rock samples from Iceland have been carried out as a part of this research programme. These analyses provide an opportunity to recalibrate, in an independent way, the intensity of the GRL as a function of the chemical composition of the rocks. The present paper describes the new determination of the relation between the GRL (in API GR units) and the concentration of SiO_2 (in %). Results obtained with the new calibration method are in agreement with previous results (Stefansson et al., 1982).

Classification of Icelandic rocks

Icelandic rocks are divided into petrographical provinces according to their chemistry and they are systematically correlated with the active volcanic zones. The provinces are closely related and it may be difficult to distinguish between basaltic types in hand specimens from different localities. The rock classification is therefore primarily based on chemistry and secondly on mineralogy. The nomenclature of igneous rocks has been based on different methods of classification. The most widely accepted method for classification is based on the concentration of the main constituents, that is more basic (richer in Fe, Mg, Al, Ca) to more acidic (richer in Na, K, SiO_2). By using the alkali and silica contents, three main basaltic differentiation trends are obtained, that is tholeiite-, transitional- and mild-alkalic basalt trends. The more evolved the rock is, the richer it is in silica and alkali components. Sodium and potassium increase with silica and their amount in the rock constitutes the rock type index. The terminology most widely used in Iceland and adopted here is shown in Fig. 1.

Geochemical variations in Icelandic rocks

Fig. 2 shows the correlation between K_2O and SiO_2 of the samples used for the calibration in this paper. The best fit line through the data points is also shown in the figure. There is considerable scatter in the data, but there is a clear positive correlation between the parameters.

The positive correlation between Th and SiO_2 is presented in Fig. 3. The graph for thorium is similar to that of potassium. It is clear from the figure that the samples are mainly of two types, one cluster of data points for basalt with a silica content of about 50% and one cluster for rhyolite with a silica content of about 75%. The scatter is considerable, especially for the rhyolite.

Fig. 4 shows the correlation between uranium and SiO_2 for the samples used for the calibration. There is larger scatter in this graph than in Figures 2 and 3. This is most likely due to higher mobility of uranium than for potassium and thorium.

In spite of the fact that the data points in Fig. 2-4 show considerable scatter, it is clear that there is a positive correlation between the elements K, Th, and U on the one hand and the concentration of SiO_2 on the other hand. Therefore, the geochemical variations in the Icelandic rocks suggests that there should be a positive correlation between the natural gamma ray intensity emitted from the rocks and the silica content.

Calibration of GRL in SiO_2 units

The specific intensity of gamma rays from extended rock formations can be considered a linear function of the amounts of uranium, thorium, and potassium present in the rocks (Belknap et al., 1959):

$$A = A_U * C_U + A_{Th} * C_{Th} + A_K * C_K \quad (1)$$

where

A is the specific activity of the rock
A_i is the specific activity of the elements U, Th, and K respectively and
C_i is the concentration (mass fraction) of the same elements.

For all practical purposes in well logging, it can be assumed that the source material is uniformly distributed throughout the rock and that the radiogenic elements are in radioactive equilibrium. The specific activities of the elements are (Belknap et al.,1959):

A_U = $2.8 * 10^4$ photons / sec gram U
A_{Th} = $1.0 * 10^4$ photons / sec gram Th
A_K = 3.4 photons / sec gram K

If the concentration of U, Th, and K is known for a (rock) material, the gamma ray intensity can be calculated from equation (1).

Natural gamma ray logs are usually calibrated in API gamma ray units (API = American Petroleum Institute). This intensity unit is traceable to a test pit in Houston in Texas, where a specially made block of concrete with the following composition:

24	ppm Th
13	ppm U
4	% K

has been defined as environment emitting 200 API GU (Belknap et al., 1959).

Equation (1) and the concentration of the radiogenic elements in the test pit gives that

200 API GU = $72 * 10^{-2}$ photons / sec gram

This means that the gamma ray intensity in API GU can be calculated from the chemical analyses of the rocks. We have used chemical analyses of 254 rock samples from Iceland to calculate the gamma ray intensity in API GU. The result is given in Fig. 5 where the gamma ray intensity is shown as function of the silica content (% of SiO_2).

A linear fit through the data points gives the following equation:

$$\text{API GU} = (-102 \pm 6) + (2.63 \pm 0.10) * SiO_2\ (\%)$$

The correlation coefficient for the line is 0.86.

The previous calibration (Stefansson et al., 1982) was based on direct comparison of gamma ray logs in two wells with the determination of the SiO_2 in the core in one case, and cuttings from the well in the other case. The best fit equations obtained for the wells were:

$$\text{API GU} = (-108 \pm 18) + (2.7 \pm 0.3) * SiO_2$$

for well KJ-16 (cuttings)

and

$$\text{API GU} = (-144 \pm 11) + (3.6 \pm 0.2) * SiO_2$$

for the IRDP well (core)

There is a good agreement between the two calibration methods. The calibration line obtained from the chemical analyses is almost identical with the line obtained for well KJ-16. As two different and independent calibration methods are giving similar results, it is assumed that the relation between the API gamma ray intensity and the silica content of Icelandic rocks is reliable.

Determination of thermal conductivity from GRL and porosity logs

The influence of porosity on thermal conductivity of volcanic rocks is poorly known. Stefansson (1997) showed that for a limited number of basaltic samples from Iceland and published data on rock samples from California and Mexico, the geometrical average seemed to give the best description of the effect of porosity on thermal conductivity. There is, however, large scatter in the available data and a special Nordic project is presently being carried out in order to determine unambiguously the effect of porosity on the thermal conductivity of volcanic rocks (Middleton et al., 1998).

It was also suggested by Stefansson (1997) that the matrix thermal conductivity of volcanic rocks might be described by one parameter only, the silica content of the rock. A possible relation between these parameters is given by Stefansson (1997) and is reproduced here as Fig. 6. If this hypothesis turns out to be valid, it is clear that a unique relation can be established between the GRL and the matrix thermal conductivity of volcanic rocks. Together with a suitable porosity log (neutron-neutron, sonic or gamma-gamma) it would be possible to determine a continuous profile of the thermal conductivity in a well drilled into a volcanic rock pile. If such relation can be established, it would open up new dimensions in heat flow studies in volcanic regions.

Conclusions

A new calibration method, which relates the intensity of the gamma ray logs (GRL) with the chemical composition of Icelandic rocks, is described in the paper. The method is based on the definition of the API gamma ray unit together with chemical analyses of 254 rock samples from Iceland. The results obtained are in excellent agreement with a previous calibration where actual GRL in two wells in Iceland were compared with determinations of SiO_2 of core or cuttings from the actual wells.

If the matrix thermal conductivity of volcanic rocks can be described by the silica content of the rocks, it may be possible to obtain continuous profiles of the thermal conductivity in wells from GRL together with a suitable porosity log.

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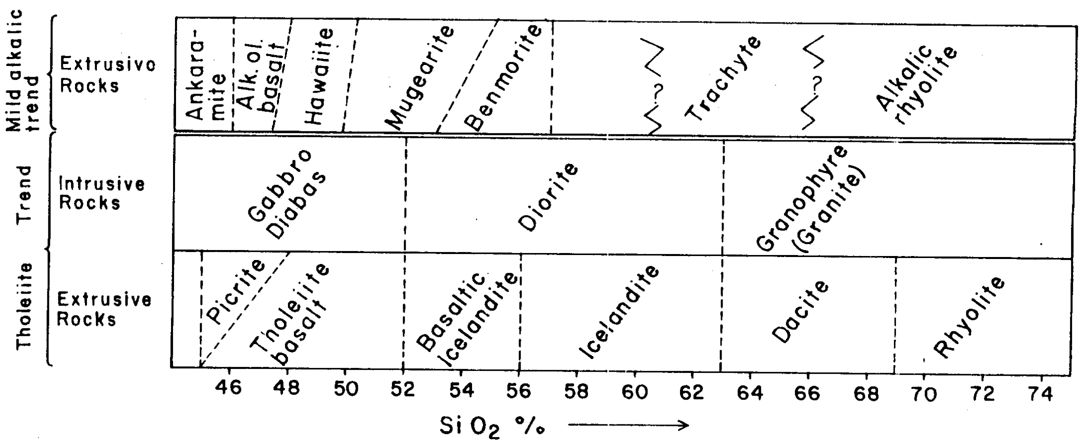

Figure 1. Schematic figures showing the terminology of Icelandic rocks.

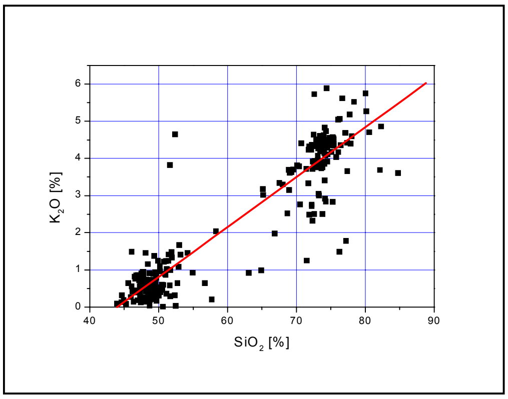

Fig. 2 Correlation between potassium and silica

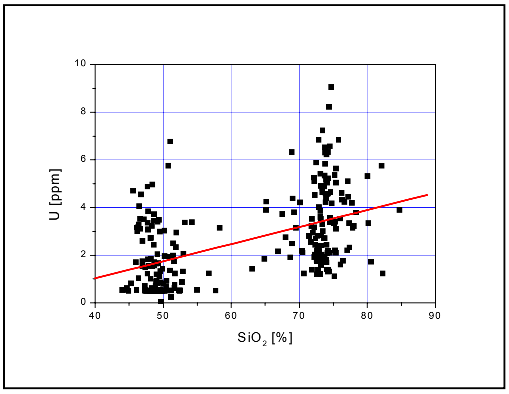

Fig. 4 Correlation between uranium and silica

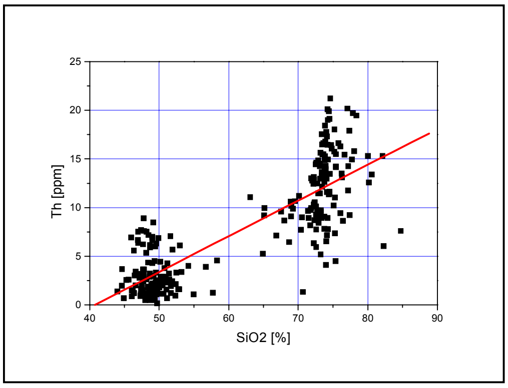

Fig. 3 Correlation between thorium and silica

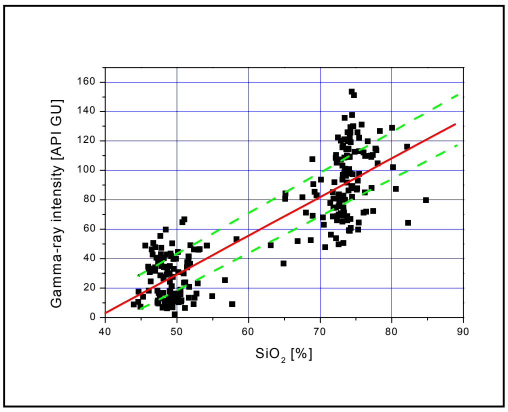

Fig. 5 Linear relationship between gamma ray intensity and silica content. The dashed lines show the limits of one standard deviation.

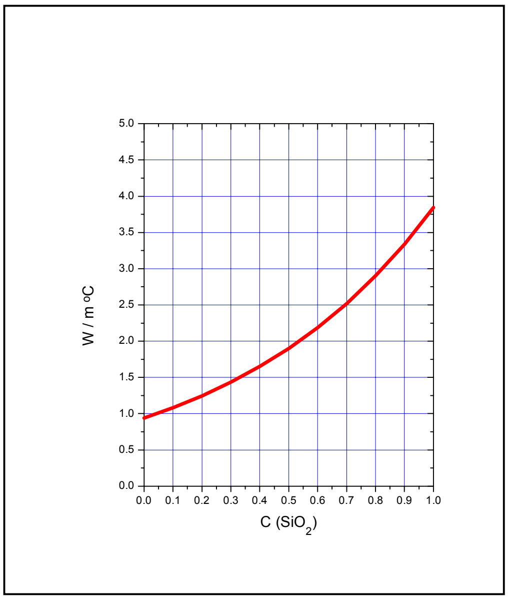

Fig. 6 Possible relation between thermal conductivity and concentration of silica in volcanic rocks