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The Stages of Volcanic Rock Petrophysical Property Alteration During the Earth's Evolution

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Abstract

A petrophysical database of effusive rocks including more than 4000 samples has been established at the Department of Engineering and Ecological Geology at the Moscow State University. The database includes samples of various ages from different tectonic units of the earth and contains 20 petrophysical parameters as well as petrographical and mineralogical characteristics.

The alteration of effusive rock properties has been studied in connection with various factors such as mineral and chemical composition, rock structure, age, depth, burial and tectonic histories. The main peculiarities of effusive rock formation and alteration have been described. The relationship between petrophysical properties has been studied.

The following regularities concerning volcanic rocks' petrophysical properties have been obtained. Progressive increase of density, as well as values of acoustic, elastic and mechanical parameters along with reduction of porosity are observed from modern to ancient effusive rocks (in the sequence Q-Cz-Mz-Pz-Prt). Quaternary rocks are the most heterogeneous by their physical and mechanical characteristics. Property dispersion gets lower towards ancient rocks. Density, acoustic, elastic and mechanical parameters depend on the type of effusive rock and get lower in following succession: basalts, andesit-basalts, andesites and dacites.

Different tectonic units - rifts, active continental margins, foldbelts and platforms – are characterized by different conditions of rock formation, burial history and secondary alteration, and accordingly the petrophysical properties of rocks are different as well.

1. Introduction

It is well known that igneous rocks compose the earth interior and cover large areas, and are even widespread in other planets. The type of igneous rock, forming as a result of magma rising and flowing on the surface and cooling is called effusive rock. Effusive rocks are unique because they bring us information about the earth interior. We can see the formation of effusive rocks at modern volcanoes. Effusive rocks are formed mainly within rifts and island arcs, rarely within foldbelts and platforms. The main types of effusive rocks are basalts (SiO_2 45-54%), andesites (SiO_2 54-63%), dacites (SiO_2 > 63%). After impact of secondary processes (weathering, metamorphism), effusive rocks give rise to the metamorphic rocks as well as the material for the sedimentary rock formation. Effusive rocks are unique by their petrophysical properties: porosity ranges from 0.3 to 70 %, velocity of longitudinal waves varies from 1.5 to 7 km/s, strength (compressional) changes from 1 to 600 MPa.

During the two last decades the Department of Engineering and Ecological Geology at the Moscow State University has carried out sampling and investigation of volcanic rocks in connection with fundamental scientific problems as well as engineering-geological practical tasks. More than four thousand samples of effusive rocks have been collected. The collection includes samples from Proterozoic to Quaternary age. It contains samples from all main tectonic units of the earth such as rifts, active continental margins, foldbelts and platforms (Table 1). Some of the samples have been donated by scientific institutions. The samples have been taken from drill-holes as well as from the surface or from the oceanic bottom.

Careful petrographical investigations and petrophysical measurements allowed us to establish a database of volcanic rock properties. Statistic software has been used for the database. The following petrophysical properties have been defined for the majority of the samples: bulk and specific density, total and effective porosity, hygroscopic moisture, velocity of longitudinal waves in dry and water-saturated conditions, rigidity, strength (compression) for dry and water-saturated samples, breaking strength and magnetic susceptibility. Several determinations of each property have been made for each sample and average values have been calculated. For a portion of the samples the following have also been determined: velocity of transversal waves, modulus of elongation, Poisson’s ratio, acoustic anisotropy, study of genetic storage (memory) using the Kaizer effect (this method determines levels of maximum and minimum stresses, which influence upon the rocks during their geological life) and thermal properties – thermal capacity (specific heat) and thermal conductivity.

Petrophysical properties have been analyzed along with composition and structure of the rocks. All samples have been studied in thin sections. X-Ray and thermogravimetric analyses, chemical analysis, scanning microscopy, microprobe, morphological analysis of pore-space and luministic microscopy have been made for some of the samples.

Table 1. Characteristics of the samples in the database.

AGE	Tectonic structure	Regions of sampling	Amount of samples
Modern eruptions	Island arcs	Kamchatky peninsula: volcano Kluchevskoy, Tolbachik, Bezimiany and others the New Zealand	**400**
Quarternary **(Q)**	Rifts Island arcs Foldbelts Platforms ?	the Red Sea rift, region Bouvet Island - Atlantic Ocean, region Hess's depression - Pacific Ocean Kamchatsky peninsula, the Caucasus, v. Etna (Italy) Spitsbergen Island Iceland, the Antarctic	**1695**
Cenozoic **(Cz)**	Island arcs Foldbelts	Kamchatka peninsula (N,₽) the Caucasus (N,₽)	**780**
Mesozoic **(Mz)**	Island arcs Foldbelts Platforms	Kamchatka peninsula (Cr) the Caucasus (Cr,J), the Crimea (J) Siberia (T, P-T), Russkaya (T1)	**750**
Paleozoic **(Pz)**	Foldbelts Platforms	the Ural (O,S,D), the Altay (Cm,D) Kazakhstan Russkaya (D)	**200**
Proterozoic **(Prt)**	?	Karelia	**105**

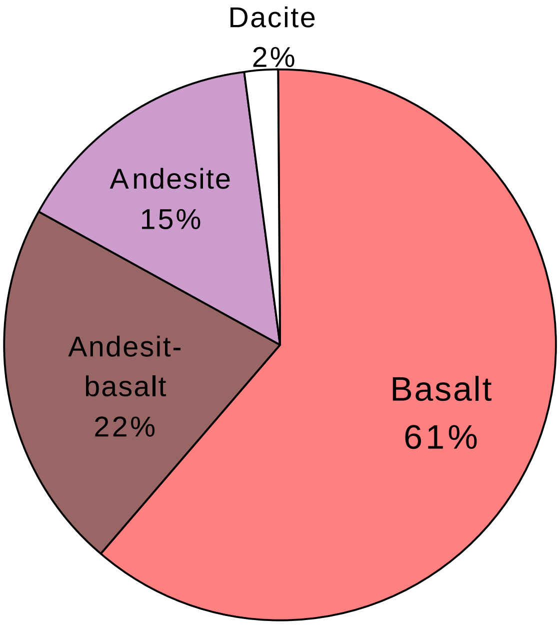

Figure 1. Portions of the main effusive types in the database.

The database covers all main types of effusive rocks such as ultrabasic rocks and basalts, andesite-basalts, andesites and dacites. Figure 1 illustrates the portions of various types of rocks in the database. Basalts predominate over others. Detailed petrographic analysis shows that one portion of the rocks is fresh whereas another is metamorphically altered.

Effusive rocks differ by their textures. The main textures are following: vitrophyric and hyalopilitic (volcanic glass content is higher than 50%), intersertal (25-50% volcanic glass), ophitic (without volcanic glass), sheaf-like fibrous (typical for oceanic basalts), poikiloophitic (typical for plateau basalts). The structures are different as well: porous, massive and amygdaloidal. This great variety of composition and structure of effusive rocks is the reason of great property dispersion: porosity ranges from 0.3 to 67 %, velocity of longitudinal waves varies from 1.5 to 7 km/s, strength changes from 1 to 600 MPa.

Using the database we attempt to answer the following questions: how do the properties change during the geological history, what is the petrophysical difference between various tectonics structures, between various types of volcanic rocks, what are the main factors controlling volcanic rock properties, how do petrophysical parameters correlate with each other? And what is the nature of rock properties?

2. Property alteration along with the age

Figure 2 shows the alteration of the main properties such as density, porosity, velocity of longitudinal waves and strength with the age from Modern to Proterozoic rocks.

Each point on the diagram represents the average property value for a given age: Proterozoic, Paleozoic, Mesozoic, Cenozoic, Quaternary and Modern. Progressive increases of density, velocity and strength and reduction of porosity are observed from modern to ancient effusive rocks. The main reason is gradually filling of pore space by secondary minerals during the burial history.

Figure 3 shows the change of magnetic susceptibility with age. Progressive decrease of magnetic properties is observed, likely as a result of titan-magnetite destroying and transformation into sphene. The exception of total regularity is Cenozoic rocks exhibiting the highest magnetic susceptibility which will require additional investigation.

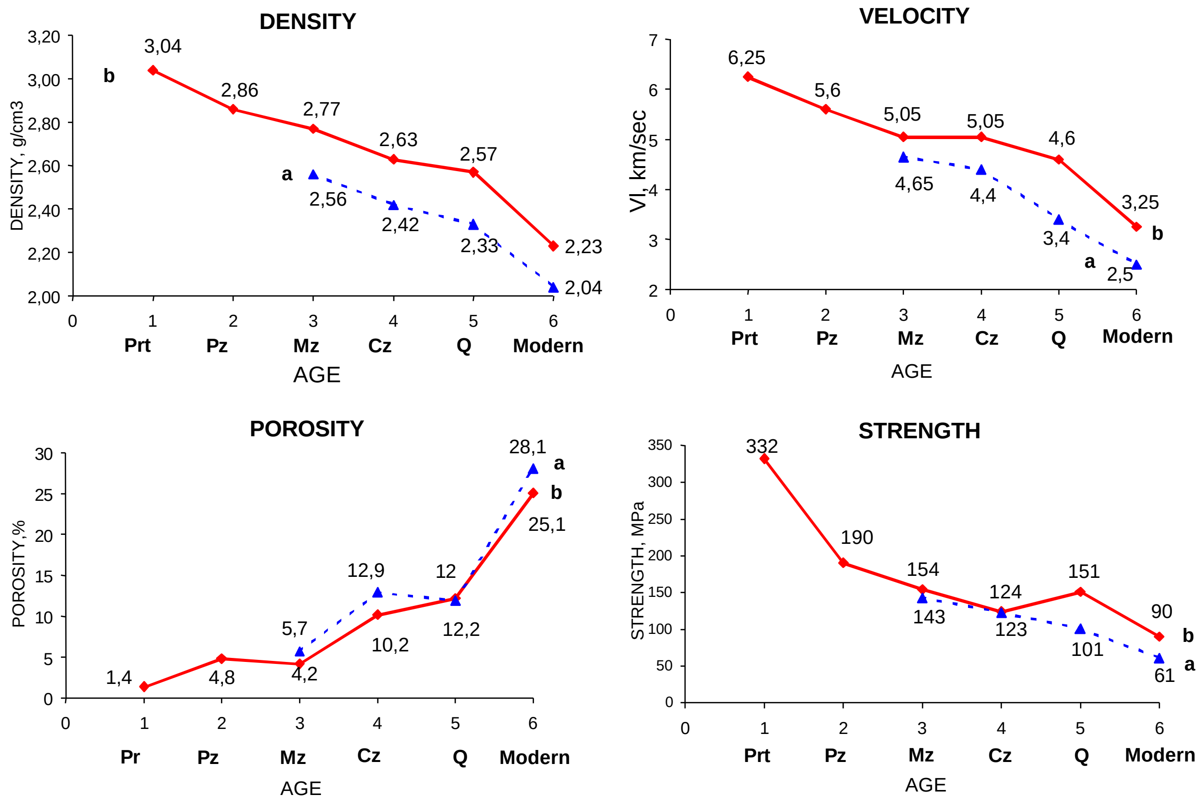

Figure 2. The alteration of effusive rock petrophysical properties with the age, a - andesites, b – basalts.

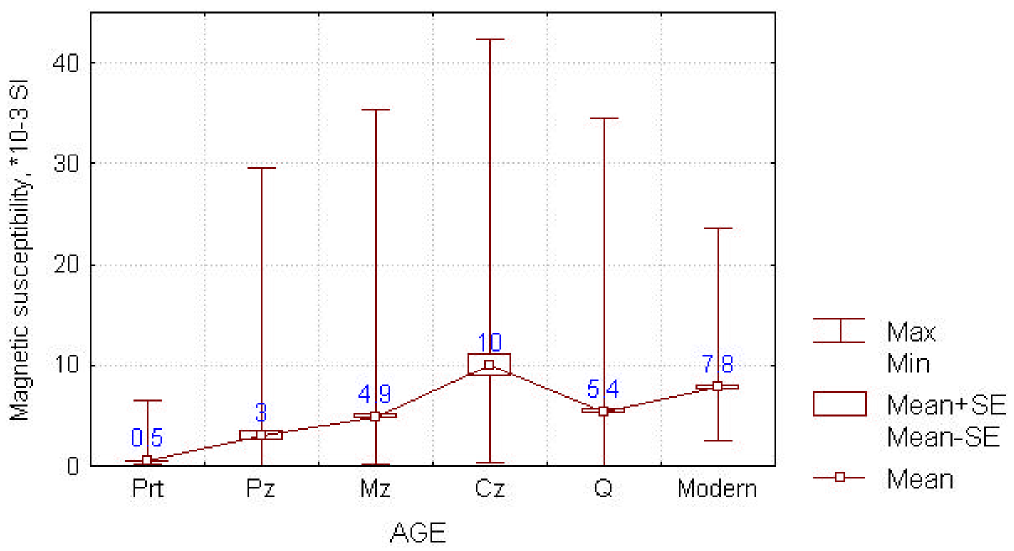

Figure 3. The alteration of basalt's magnetic susceptibility with the age.

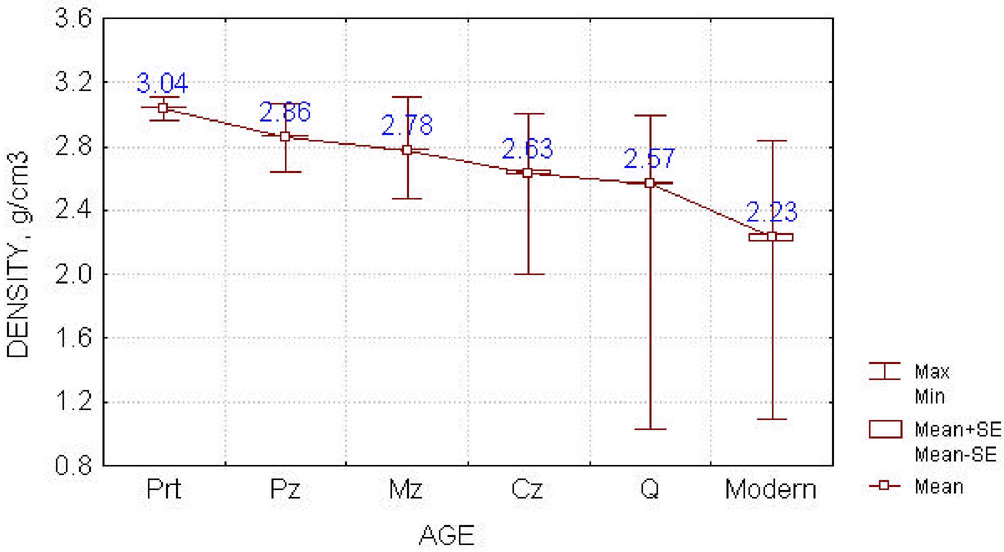

Figure 4. The change of density dispersion with the age.

One can see as well that properties depend on the type of volcanic rock (Figure 2). The two curves on each plot characterize the two main types of effusives such as basalts and andesites. Basalts are denser and stronger in comparison with andesites. It is observed that density, velocity and strength get lower in following succession: basalts, andesit-basalts, andesites and dacites.

Undoubtedly dispersion of property values is great even within one given age or one given type of rock. Quaternary basalts are the most heterogeneous. They are characterized by the widest property dispersion. Totally, dispersion gets lower towards ancient rocks (Figure 4).

3. The main stages of formation and alteration of effusive s petrophysical properties

3.1. Quaternary effusive rocks

Lava effuses on the surface, gets cold and hard, and transforms into effusive rocks. As a rule these rocks are characterized by porous structures and fresh minerals. Depending on lava gas content and conditions of lava cooling, primary porosity ranges from 2 up to 67 %. Pore size varies widely as well, sometimes reaching several centimeters. Density and strength of young effusives are controlled by porosity and varies widely. These traits are peculiar to the majority of Quaternary and Upper Neogenic effusives.

Modern effusive rocks are distinguished from other Quaternary rocks by extremely high porosity, and low density, strength and velocity of longitudinal waves.

A strong correlation between porosity and strength is observed for modern basalts. But there is no correlation between porosity (density) and velocity of longitudinal waves for modern basalts. Even for dense and low-porous rocks, velocity values often are as notable as 2-3 km/s (Ladygin & Nikitin, 1980). The low velocities have been determined to be caused by microfracture networks. These microfractures are invisible in thin section but clearly observed in luministic microscope if saturated by oil. They are observed as well by scanning microscopy (Figure 5).

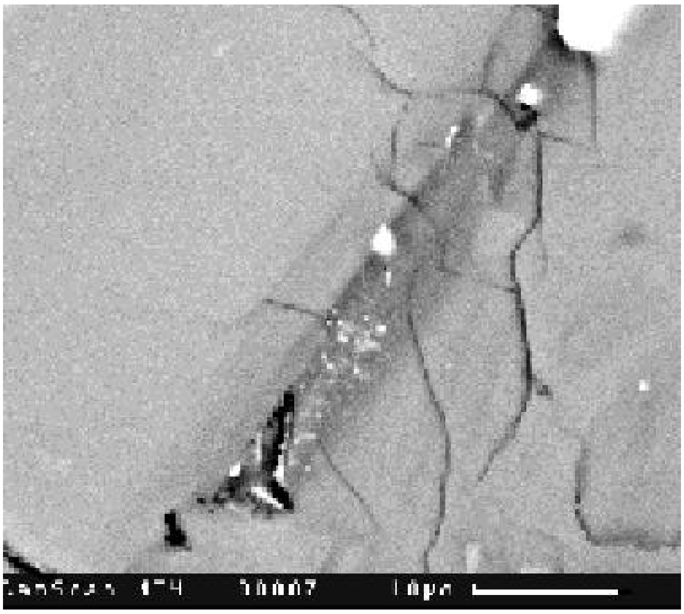

Figure 5. Microfractures in modern basalt from Kluchevskoy volcano (Kamchatka). Scanning image.

An indirect evidence of these microfractures is an increase of velocity by 1-2 km/s after saturation by water. We suppose microfractures are forming during lava cooling. Then, as a result of relaxation processes, microfractures close during about 10 thousand years. There are no such microfractures in older basalts. When the microfractures disappear, the result is an increase of velocity up to 4-5 km/s and appearance of a correlation between porosity and velocity.

A study of the relationship between strength and porosity shows that strength depends not only on porosity, but is controlled as well by pore size, shape and distribution. Pairs of samples having equal porosity but different strength have been considered and studied using morphological analyses of pore space. The first pair is characterized by low porosity as 4 %. High strength (300 MPa) is observed for samples with small regularly distributed pores whereas strength is only 150 MPa for samples with irregularly distributed pores. The second pair is characterized by porosity around 12-13%. Both samples have similar pore space but fractures within the second sample decrease strength from 150 to 40 MPa. The third pair of samples has as high porosity as 24%. Structures with round pores are stronger (80 MPa) in comparison with structures with rough pores (40 MPa).

3.2. Ancient effusive rocks

As a rule, during geological history, initially fresh and porous effusive rocks undergo significant changes. First of all effusive rocks undergo devitrification of volcanic glass. Then under the influence of regional low-grade metamorphism, primary pores are filled by secondary minerals. This results in primary porosity decreases and disappearance. The pore structure transforms into an amygdaloidal one. Figure 6 illustrates one amygdule using a scanning microscope. It is a plateau basalt of Mesozoic age from the Siberian platform (Russia). The pore is filled by several minerals: pumpellyite, chalcedony, chlorite and some others (Spiridonov *et al.*, 2000). As a result of pore filling, the rock became denser. Porosity as a rule is less than 5-10%. Velocity of longitudinal waves increase significantly, while strength increase slightly.

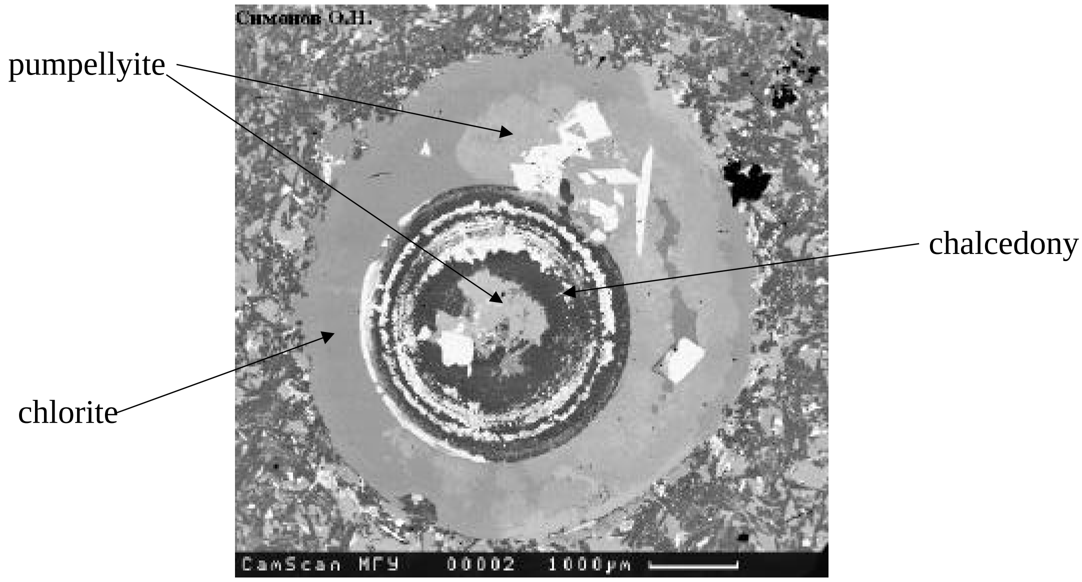

Figure 6. The amygdule in plateau basalt from Siberian platform (Russia). Scanning image.

Subsequent metamorphic alteration of volcanic rocks results in a change of primary components such as volcanic glass and olivines, and then plagioclases, pyroxenes, and their substitution by secondary minerals. The main facies of regional low-grade metamorphism are zeolitic, prehnite-pumpellyitic and pumpellyite-actinoltic (secondary minerals are chlorite, calcite, zeolites, prehnite, smectite, quartz, albite, epidote).

Thus, a change of pore-space structure are observed during the geological history. Primary pores and microfractures are closed and secondary porosity is formed. Secondary porosity consists of a porosity of secondary minerals and inter-crystalline pores. Secondary pores are of small size. Total porosity as a rule is less than 5 %.

The change of porous structure has been studied through a petrophysical parameter (Q_{vp}). This parameter shows how many percent the velocity of longitudinal waves increases after saturation of the sample by water:

$$Q_{Vp}= \{(V_{pw}-V_p)/V_p\}*100 \quad (\%),$$

where V_p - velocity of longitudinal waves for dry samples, V_{pw} - velocity of longitudinal waves for water-saturated samples.

As a rule, a high Q_{Vp} value indicates microfractures and open pores. Values about nought is evidence of a dense structure with small pores. A negative value indicates clay or other loose secondary minerals, which re-compact contacts within rocks under water saturation. This parameter gradually gets lower during geological history decreasing from 30-40% (and even 100 % in modern basalts) to 0 % towards ancient rocks.

Totally, effusives get denser (2.8-3.0 g/cm^3) and stronger (more than 200 MPa) under metamorphic processes and are characterized by high velocities from 5 to 7 km/s. Sometimes petrophysical properties values reduce, but it is some specific cases, for example, as a result of intensive hydrothermal process impact, especially zeolitization or argillization.

In contrast to Quaternary volcanites, the petrophysical properties of ancient rocks are controlled mainly by secondary mineral composition.

4. Petrophysical properties of quaternary basalts from different tectonic units

The total mechanism of rock property formation and changes has been considered above. However, different tectonic units are characterized by different conditions of rock formation and secondary alterations. They differ by depth of magma chamber, chemical composition of magma, conditions and speed of lava cooling. Accordingly, petrophysical properties of rocks should be different as well.

A detailed study of Quaternary basalts from rifts, active continental margins, foldbelts and platforms shows differences in petrochemical types, mineral composition and textures was carried out (Table 2).

Average porosity is similar for all quaternary basalts and ranges from 10 to 13 %, while porosity dispersion differs significantly. Basalts from active continental margins are notable by the highest porosity dispersion from 2 to 65 %. Porosity of rift basalts varies widely as well – from 0.5 to 45 %. This fact is evidence of unstable gas content of magma within rifts and active continental margins. Basalts of platforms and foldbelts are more homogeneous. Porosity varies mainly from 5 to 25%. So gas content is more stable and totally lower.

In spite of similar porosity, other petrophysical properties are different. The reduction of strength and velocity of longitudinal waves are observed in the following sequence: rifts, platforms, foldbelts and active continental margins (Figure 7). Basalts from active continental margins and foldbelts are more magnetic in comparison with platforms and rifts.

Conclusion

1. Progressive increase of density, velocity and strength, and decrease of porosity and magnetic susceptibility are observed going from modern to ancient effusive rocks.
2. Quaternary basalts are the most heterogeneous. They are characterized by the widest property dispersion that is the result of a wide porosity range. Property dispersion gets lower towards ancient rocks.
3. Petrophysical properties depend on types of effusive rock. Density, velocity and strength get lower in following succession: basalts, andesit-basalts, andesites and dacites.
4. Different tectonic units are characterized by different conditions of rock formation and secondary alteration and accordingly petrophysical properties of rocks are different as well. Average porosity is similar for all quaternary basalts while other properties are different. Strength and velocity of longitudinal waves decrease in following sequence: rifts, platforms, foldbelts and active continental margins. Basalts from active continental margins and foldbelts are more magnetic in comparison with platforms and rifts.

References

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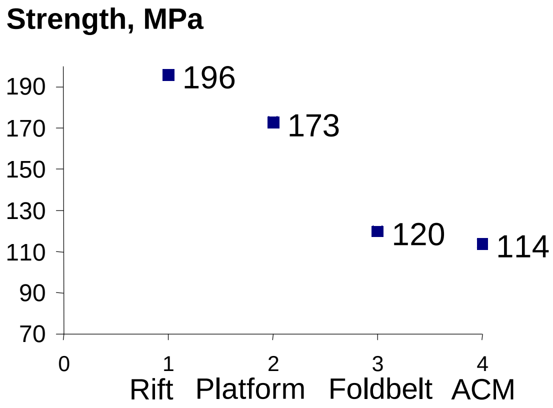

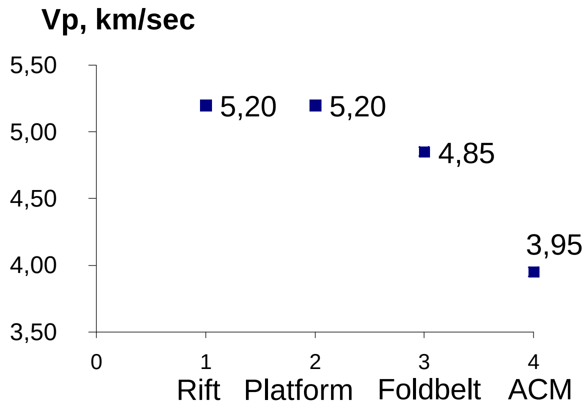

	Rifts	**Platforms**	**Foldbelts**	**Active continental margins**
Conditions of eruption	submarine	submarine and subaerial	subaerial	
Petrochemical type	normal alkaline tholeiitic basalts	subalkaline	normal alkaline calc-alkali	
Mineral composition	pyroxene, plagioclase, olivine, volc.glass	olivine (5-10%), clinopyroxene - augite (5-15%), plagioclase - an,lab (<5%) volc. glass 60-80% xenolith	plagioclase, pyroxenes - clino and ortho olivine volc. glass (0-80%)	
Main types of texture	sheaf-like fibrous hyalopilitic ophitic	hyalopilitic vitrophyric	ophitic, intersertal, hyalopilitic	intersertal, hyalopilitic ophitic
Porosity,%	<u>11</u> 0,5-45	<u>10</u> 3--25	<u>12</u> 5--25	<u>13</u> 2--65
Sp.den g/cm^3	2,99	3,03	2,93	2,92
Vp, km/sec	5,2	5,2	4,85	3,95
χ*10^{-3} SI	3,3	2,3	9,8	8,9
Amount of samples	233	218	50	330

Figure 7 and Table 2. Petrophysical properties of quaternary basalts from different tectonic units of the earth.