Dynamics of magmatic systems as revealed by quantitative textural measurements of igneous rocks from SE-Birjand (East of Iran)

Amir Eskandary* , **Sadraddin Amini** , **Nasrin Farahkhah**

1) Department of Geology, Faculty of Science, Tarbiat Moallem University, Tehran, Iran
Amir.eskandary157@yahoo.com

Abstract

Textural analysis techniques were used to quantify key aspects of the crystal population, including crystal size distributions (CSD), crystal shape (S) and spatial distribution patterns (SDP) and to discuss physical processes ongoing in the magma chamber. CSDs of plagioclases were determined from micro diorite- quartz diorites of 120 km southeast of Birjand. The CSDs lie in 3 similar groups. All CSDs are curved, concave up and coincident but differing in their maximum crystal size, amount of curvature and concavity. Shape of crystals changed from tabular crystals (with I, L>2) to more equant forms (with I, L<2) with change of CSDs. The SDP of plagioclase crystals as seen in the R value against porosity diagram, are clustered and the trends of data in this diagram consistent with overgrowth trend due to textural coarsening and or asymmetric growth. A dynamic model is proposed for the origin and observed evolution of textures in these rocks. Crystallization of plagioclases started following emplacement of dacitic magma at a depth of at least 5km. Nucleation was probably heterogeneous that causes early clustering of crystals. A steep, straight CSD developed by nucleation and growth. This process was interrupted by the injection of mafic magma into the chamber, or convective overturn of hotter magma. The magma temperature rose until it was buffered, initially by plagioclase solution and later by crystallization. Under these conditions textural coarsening (Ostwald ripening) of plagioclase following CN (Communicating Neighbors) model occurred: crystals smaller than critical radius (or size) dissolved to feed larger crystals. The CSD became less steep and extended to larger crystal size. A repetition of this cycle has generated the observed family of CSDs but the step number of cycle was different for each of three groups of CSDs. During these periods, Shape and SDP of crystals are changed also. Results complement petrographic evidence and geochemical modeling of magma mixing in studied rocks.

Key words: *Birjand, magma mixing, textural coarsening, crystal size distributions (CSD)*

Introduction

The origin of rocks is commonly determined by quantitative studies of intensive parameters, such as chemical composition. Recently, the quantification of rock texture (=microstructure) has become important because important petrologic processes like nucleation, growth and textural coarsening (Ostwald ripening) do not change the overall chemical compositions (e.g. Marsh, 1988, 1998; Higgins, 2006). The texture of rocks can be quantified by measuring such parameters as size, shape, orientation and position of common components, e.g. crystals, pores and fractures (e.g. Jerram et al. 1996; Higgins, 2006). Here, we have investigated the origin of textural diversities in the collection of the rocks with relatively similar chemical composition by quantitative measurements of the plagioclase crystals to open clues into magma chamber processes**.**

Study area is located 120 km to SE of Birjand, and along of Birjand-Sarbisheh-Doroh road. Geologically, this region occurs in Sistan suture zone (Tirrul et al, 1983) and is a wing of east Iran coloured mélange (Fig 1). This study focused on the division of rocks younger than ophiolitic complex (Fig 1). Based on field investigations, petrographic evidences and chemical classifications, these rocks are the shallow level intrusive rocks with quartz diorite-micro diorite composition with dominant texture of porphyritic and glomeroporphyritic. Some of the textural characteristics such as presence of mafic enclaves, xenocrysts with reaction rims, oscillatory zoning, sieve textures, corroded and embayed quartz grains show evidence of disequilibrium between the crystals and melt and indicate magma mixing as recharge of more mafic and hot magma into open- system magma chamber. Inspection of trends in the Harker diagrams and other binary diagrams in addition to geochemical modeling according to lungmuire et al (1978) and De paolo (1981) equations also confirm the magma mixing hypothesis (Eskandary, 2009).

Methods

The texture of the plagioclases was examined both qualitatively and quantitatively (see below) following Higgins (2000, 2006) methods. In both cases the first step was the creation of a binary image of plagioclase distribution. Thin section of eight rock samples imaged with digital camera and Images pasted together electronically (e.g. Fig 2). Images were then transferred to a vector drafting program (CorelDraw). There the crystals were outlined on the screen using a mouse. Crystals that intersect in the plane of the section, but are clearly two separate crystals were outlined and translated to separate them. The crystal outlines were then filled and exported as tiff files for further processing (Fig. 2). The binary plagioclase images described above were quantified using the program ImageJ, a java version of the well-known program NIHImage. This program calculates dimensions of a best-fit ellipse to the crystal outlines and its orientation and position (centre of each crystal). Intersection size data were converted to true crystal size distributions (CSDs) using CSDCorrections 1.3 (Higgins, 2000, 2002a). The shape of crystals were calculated for drawing of CSDs (see below) and a roundness parameter of 0.3 (close to parallelepiped) was choosed. CSD calculations are not very sensitive to the weak fabrics observed here, especially for sections cut orthogonal to the foliation; hence a massive fabric was used. Intervals with fewer than two crystals were eliminated from the diagrams, as they are not precise.

Crystal size distributions (CSD)

The most common quantitative textural measurement is the crystal size distribution, or "CSD". CSD analyses are a quantitative measure of the number of crystals of a mineral per unit volume within a series of defined size intervals. CSD data were plotted on a diagram of ln (population density) versus size (L=longest dimension) following marsh (1988) (Figs). The CSDs lie in 3 similar groups. All CSDs are curved, concave up and coincident but differing in their maximum crystal size, amount of curvature and concavity (Fig 3).

Kinking or curvature in the CSD plot profile has been attributed to processes such as crystal accumulation and removal (Marsh, 1998), compaction (Boorman et al., 2004), mixing of crystal populations or multiple magmas (Higgins, 1996; Jerram et al., 2003) textural

coarsening (Higgins and Roberge, 2003). both crystal coarsening and compaction-driven recrystallization Higgins (2002b).
Textural coarsening is the process by which small crystals dissolve at the same time as larger crystals are growing, so that the overall surface energy is minimized (Voorhees, 1992). It occurs when the temperature of the system is maintained close to the mineral liquidus. Under these conditions the nucleation rate is zero, but the growth rate is significant. Higgins (1998) showed that coarsening following the Communicating Neighbours model of Dehoff (1991) will lead to increases in characteristic Length and this model is more appropriate for geological systems.
Based on combination of geochemistry and other textural analysis, we ascribed these textural diversities to periods of magma mixing, textural coarsening and simple nucleation and growth of crystals following proposed model of Higgins and Roberge (2003) but with some revisions. This hypothesis further examined with other results in next sections.

Quantifying the crystal shape

Shape is best examined in three dimensions, but for regular crystals with more or less uniform shapes intersection data can be used to estimate overall shape. The crystal shape is generally expressed in terms of the ratio of short: intermediate: long (S: I: L) for a bounding parallelepiped or best-fit ellipsoid where S =1 (Higgins, 1994, 2006).
It is desirable to determine the habit or shape of the crystal population for a number of reasons. Firstly, the aspect ratios (S: I: L) are used to convert 2D crystal size measurements into predicted 3D crystal size distributions. Secondly, Shape or habit of crystals is controlled by physicochemical conditions of crystallization, thus quantitative measurements of crystal shapes can reveal aspects of crystallization environment.
It is possible to determine a 3D crystal shape from 2D crystal sections, providing the 3D shape of all the crystals is the same using the width length information from the 2D data (Higgins 1994; Garrido et al. 2001). Morgan & Jerram (2006) produced a spread sheet which can be used to statistically compare 2D shape measurements to the best fit 3D shape. For parallelepipeds (Higgins, 1994) and triaxial ellipsoids (Higgins, 2006) the mode of intersection width/intersection length (2D aspect ratio) is equal to the ratio S/I. It is not easy to determine precisely the ratio I/L from intersection data of randomly oriented crystals (Higgins, 2006a). I/L has been estimated from the statistical parameters of the intersection length/width distribution (Higgins, 1994; Garrido et al., 2001) and by modeling (Morgan & Jerram, 2006). A more pragmatic approach can be used by observation of plagioclase crystals with (010) plane parallel to the plane of sections (Higgins, 2006). The crystal shapes in this study were determined with methods mentioned above and choosed aspect ratios for simplicity and visualization have plotted on a zingg diagram (Fig 4). The results have showed that the shape of plagioclase crystals in samples are weakly tabular to equant ($I \approx L$, I, $L<2$). Furthermore, there is a shift from tabular to more equant forms as well as increment the maximum length of crystals in different sections.
There are many factors that change the crystal morphology such as undercooling, degree of supersaturation, mechanical movement of magma (stirring), advection (relative movement between the crystal and the growing medium), viscosity, diffusion rate, chemical potential gradient and textural coarsening (Lofgren, 1974; Kouchi et al, 1986; Higgins, 1996, 1998,

2006; mock and jerram, 2005; Higgins and chandrasekharam, 2007; Vernon, 2004; Jerram and martin, 2008).

Analysis suggests that plagioclase crystals in our samples were formed under conditions with low undercooling, slow growth rate and high diffusion rate. They were formed in environment which low advection and the low mechanical movement of magma and chemical potential gradient were established. Also, textural coarsening process might be affected on shift of crystal shapes from tabular to more equant forms and reduction of aspect ratio with addition of maximum length of crystals.

Quantifying the spatial distribution pattern of crystal populations (SDP analysis)

Analysis of the spatial distribution pattern (SDP) of crystals in thin section provides a measure of how clustered, random or ordered a distribution of particles is, and can be used to distinguish touching from nontouching crystal frameworks (Jerram et al, 1996, 2003; Mock et al, 2003). A technique to quantify the SDP of crystals in thin section was introduced by Jerram et al. (1996, 2003). The spatial distribution pattern is characterized by a parameter called R, which represents a ratio of the mean nearest neighbour distance (NND) of all particles in a sample area to the predicted mean NND for a random distribution of points with the same population density, and is given by

$$R=\frac{rA}{rE}$$

Or

$$R=\frac{2\sqrt{\rho}}{N}\sum r$$

Where rA is the mean NND of the sample, rE is the mean NND in a random distribution of points with the same population density, r is the NND of a particular grain, N is the number of grain centres measured, and ρ is the density of the observed distribution. Porosity is used as a measure of the volume fraction of grains in a sample and is defined as the modal abundance of other phases present (including other minerals, glass and vesicles). A plot of R vs. porosity may then be used to compare how the SDP varies for different textures.

The R value was calculated using the method described in Jerram et al. (1996, 2003), and the total modal abundance of other phases present in the sample (determined by point counting), was used to define a Porosity. Jerram et al. (1996) also modelled how the R value would vary with changing porosity as a result of mechanical compaction, overgrowth and with grain-size variation or sorting (see insert in Fig. 5). Values of R for rock samples were plotted against porosity and all samples fall within clustered field (Fig. 5). The results show that plagioclase crystal arrangement is clustered because of heterogeneous nucleation in three dimensional spaces of studied igneous rocks. The trends of data in this diagram correspond with overgrowth trend due to asymmetric growth (Jerram et al, 1996). Also, textural coarsening has the potential to affect the R value of a rock and this process was suggested for R value trends in studied rocks (Eskandary, 2009).

Conclusions

Using modern petrographic studies and quantitative textural measurements, some of the physical processes that governed shallow level intrusion formation in study area modeled as repeated cycles of crystal nucleation and growth, injection of basic magma and following textural coarsening that finally ended by nucleation and growth of fine groundmass crystals. The model, justify the observed and measured diversities on size distribution, spatial distribution pattern and shape of plagioclase crystals as mentioned above. These results are not achieved by other qualitative petrographic and quantitative chemical analysis. However, textural analyses are not enough to conclusions and the best results acquired when integrating them with geochemical modeling and microgeochemical analysis.

References:

- Boorman, S., Boudreau, A. & Kruger, F. J. 2004. The Lower Zone-Critical Zone transition of the Bushveld Complex: a quantitative textural study. Journal of Petrology 45, 1209-1235.

-Cashman, K.V., and Marsh, B.D., 1988. Crystal size distribution (CSD) in rocks and the kinetic and dynamics of crystallization II: Makaopuhi Lova lake. Contributions to Mineralogy and Petrology, 99, 292-305.

- Dehoff, R. T., 1991. A geometrically general theory of diffusion controlled coarsening. Acta Metallurgica etMaterialia 39, 2349-2360.

- DePaolo, D.J., 1981. Trace element and isotopic effects of combined wall rock assimilation and fractional crystallization. Earth and Planetary Science Letters 53, 189-202.

- Eftekhar Nezhad, J., Alavi Naini, M., Behroozi, A. (Geological survey of Iran), 1990. Explanatory Text of the Gazik Quadrangle Map 1:250,000 200pp

- Eskandary, A., 2009, Geochemistry and petrology of tertiary magmatic rocks and listvenites in SE Birjand, unpublished thesis, Tarbiat Moallem University of Tehran, 200P

- Garrido, C. J., Kelemen, P. B. & Hirth, G. 2001. Variation of cooling rate with depth in lower crust formed at an oceanic spreading ridge; plagioclase crystal size distributions in gabbros from the Oman Ophiolite. Geochemistry, Geophysics, Geosystems 2, 2000GC000136.

-Higgins, M.D., 1994. Determination of crystal morphology and size from bulk measurements on thin sections: numerical modeling. American Mineralogist, 79, 113-119.

- Higgins, M.D., 1996. Magma dynamics beneath Kameni Volcano, Thera, Greece, as revealed by crystal size and shape measurements. Journal of Volcanology and Geothermal Research, 70, 37-48

Higgins, M.D., 1998. Origin of anorthosite by textural coarsening: quantitative measurements of a natural sequence of textural development. Journal of Petrology 39, 1307–1325.

- Higgins, M.D., 2000. Measurement of crystal size distributions. American Mineralogist, 85, 1105-1116

- Higgins, M. D. 2002a. Closure in crystal size distribution (CSD), verification of CSD calculations and the significance of CSD fans. American Mineralogist, 87, 160–164.

- Higgins, M. D. 2002b. The role of textural coarsening in the development of the Kiglapait layered mafic intrusion, Labrador, Canada: a crystal size distribution study. Contributions to Mineralogy and Petrology, 144, 314-330.

- Higgins, M. D. 2006. Quantitative Textural Measurements in Igneous and Metamorphic Petrology. Cambridge University Press, Cambridge.

- Higgins, M. D. AND Chandrasekharam, D. 2007. Nature of Sub- volcanic Magma Chambers, Deccan Province, India: Evidence from Quantitative Textural Analysis of Plagioclase Megacrysts in the Giant Plagioclase Basalts. Journal of Petrology, 48, 885-900

- Higgins, M.D., and Roberge, J., 2003. Crystal size distribution (CSD) of plagioclase and amphibole from Soufriere Hills volcano, Monteserrat: evidence for dynamic crystallization/textural coarsening cycles. Journal of Petrology 44, 1401-1411

- Higgins, M.D., and Roberge, J., 2007. Three magmatic components in the 1973 eruption of Eldfall volcano, Iceland: Evidence from plagioclase Crystal size distribution (CSD) and geochemistry. Journal of Volcanology and Geothermal Research, 161, 247–260

- Jerram, D. A. & Higgins, M.D. 2007. 3D analysis of rock textures: quantifying igneous microstructures. Elements, 3, 239–245.

- Jerram, D. A., Cheadle, M. J., Hunter, R. H. & Elliott, M. T. (1996). The spatial distribution of grains and crystals in rocks. Contributions to Mineralogy and Petrology 125(1), 60-74.

-Jerram, D.A., Cheadle, M.C., Philpotts, A.R., 2003. Quantifying the building blocks of igneous rocks: are clustered crystal frameworks the foundation? Journal of Petrology 44, 2033–2051.

Jerram, D. A., & Martin, V. M., 2008. Understanding crystal populations and their significance through the magma plumbing system. From: Annen, C. & Zellmer, G. F. (eds) Dynamics of Crustal Magma Transfer, Storage and Differentiation. Geological Society, London, Special Publications, 304, 133–148.

- Kouchi, A., Tsuchiyama, A. & Sunagawa, I. 1986. Effects of stirring on crystallization of basalt: texture and element partitioning. Contributions to Mineralogy and Petrology 93, 429-438.

- Langmuir, C.H., Vocke, R.D.Jr., Gilbert, N.H., Stanley, R.H., 1978. A general mixing equation with applications to Icelandic basalts. Earth and Planetary Science Letters 37, 380-392.

- Lofgren, G. E. 1974. An experimental study of plagioclase crystal morphology: isothermal crystallization. American Journal of Science, 274, 243-273.

-Marsh, B.D., 1988. Crystal size distribution (CSD) in rocks and the kinetics and dynamics of crystallization I. theory. Contributions to Mineralogy and Petrology, 99, 277-291.

-Marsh, B. D, 1998. On the interpretation of crystal size distribution in magmatic systems. Journal of Petrology, 39, 553-599.

- Mock, A. & Jerram, D. A. 2005. Crystal size distributions (CSD) in three dimensions: insights from the 3D reconstruction of a highly porphyritic rhyolite. Journal of Petrology, 46, 1525–1541.

- Mock, A., Jerram, D. A. & Breitkreuz, C. 2003. Using quantitative textural analysis to understand the emplacement of shallow-level rhyolitic laccoliths: a case study from the Halle Volcanic Complex, Germany. Journal of Petrology 44, 833-849.

- Morgan, D. J. & Jerram, D. A. 2006. On estimating crystal shape for crystal size distribution analysis. Journal of Volcanology and Geothermal Research, 154, 1–7.

-Tirrul, R., Bell, I.R., Griffis, R.J., and Camp, V.E., 1983. The Sistan Suture Zone of eastern Iran. Geol.Soc.Am.Bull 94, 134-150

- Vernon, R. H., 2004. A practical guide to Rock Microstructure. Cambridge University Press, Cambridge.

- Voorhees, P.W., 1992. Ostwald ripening of two-phase mixtures. Annual Review of Materials Science. 22, 197–215.

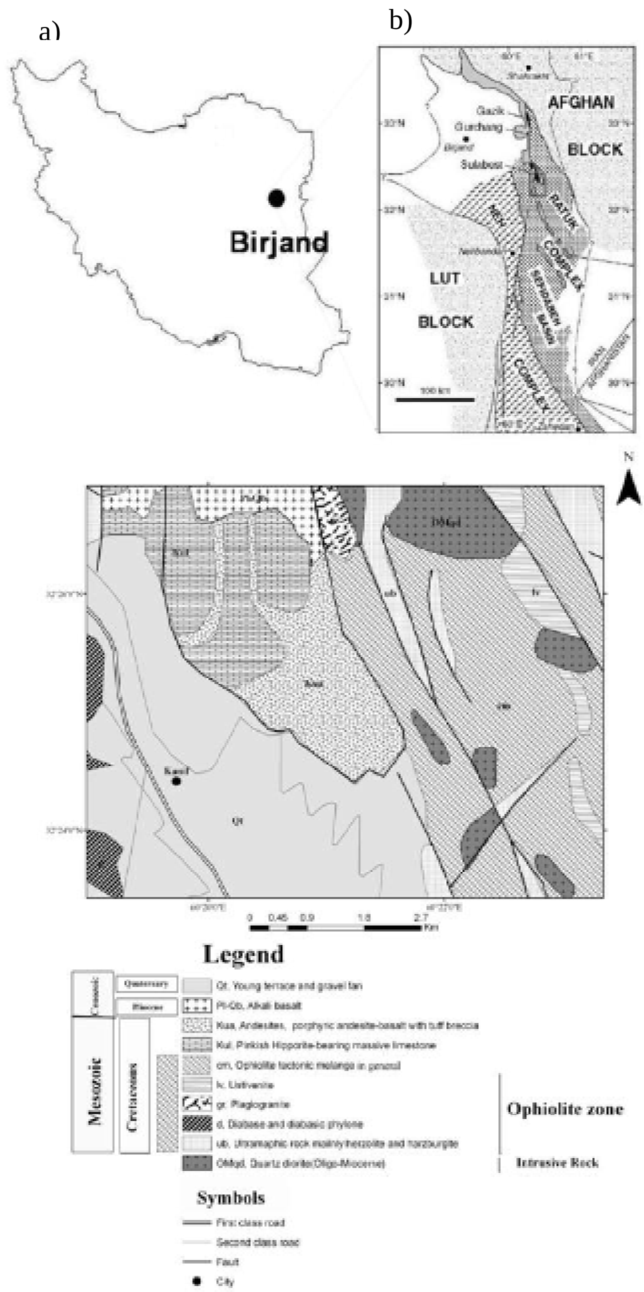

Fig 1: a) General location of study area in East of Iran and SE of Birjand City. b) The Sistan suture zone of eastern Iran and its major subdivisions (modified from Tirrul et al., 1983). Grey-shaded areas within the Ratuk Complex are outcrops of ophiolitic rocks (the Birjand Ophiolite). The rectangle is the studied area. C) Simplified geological map of study area (modified from 1/100000 geological map of Purang (Geological Survey of Iran, 1386)

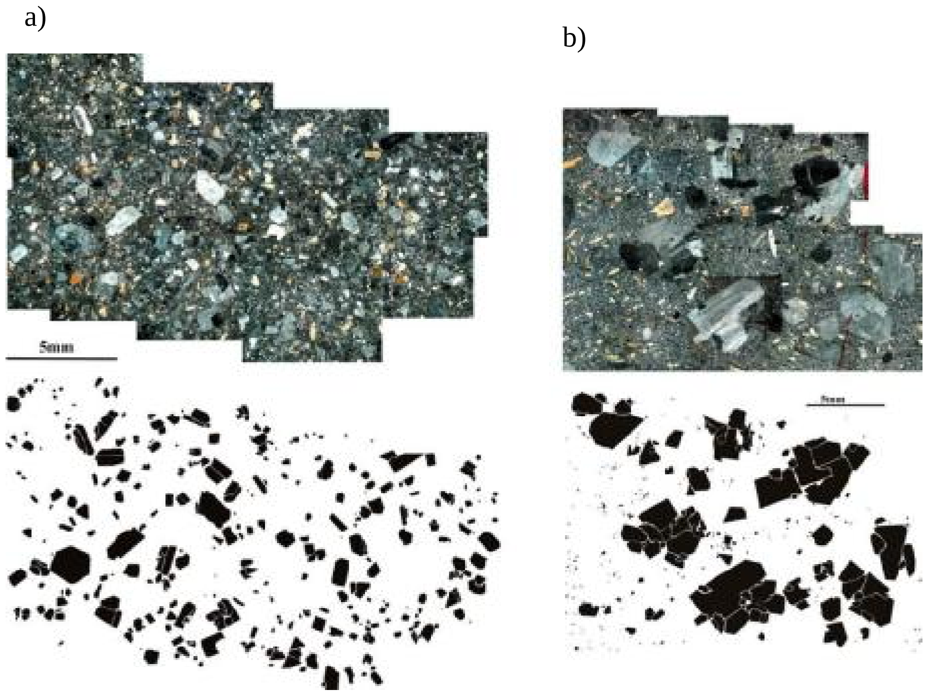

Fig 2: Examples of microscopic and digitized images of thin sections used in this study a) Microscopic image of thin section of KHD2 and digitized outlines of plagioclase crystals (below). b) Microscopic image of thin section of KHT8 and digitized outlines of plagioclase crystals (below). Note to increasing size of crystals from KHD2 to KHT8 (both samples are in the same scale.

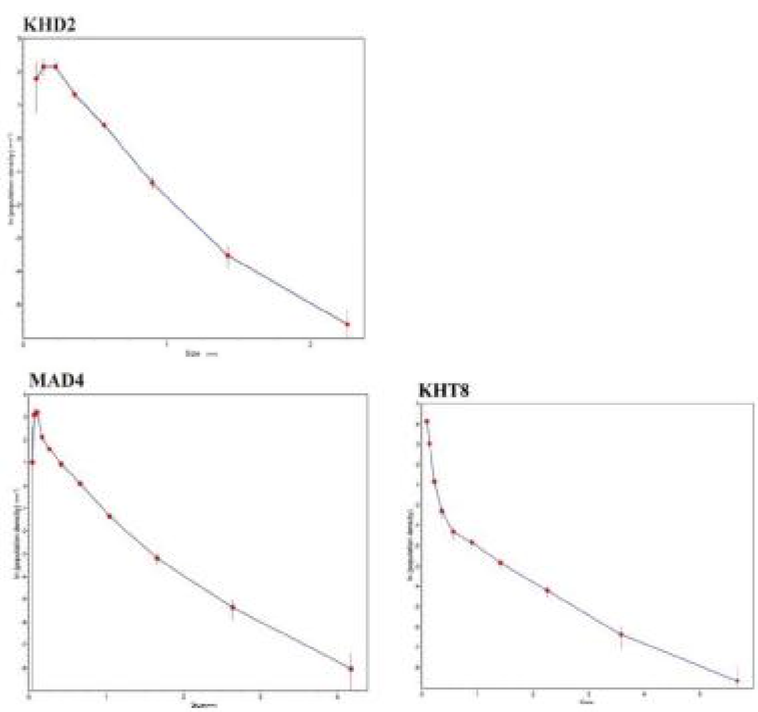

Fig3: Examples of CSD diagrams. ID of samples is shown in upper part of diagrams.

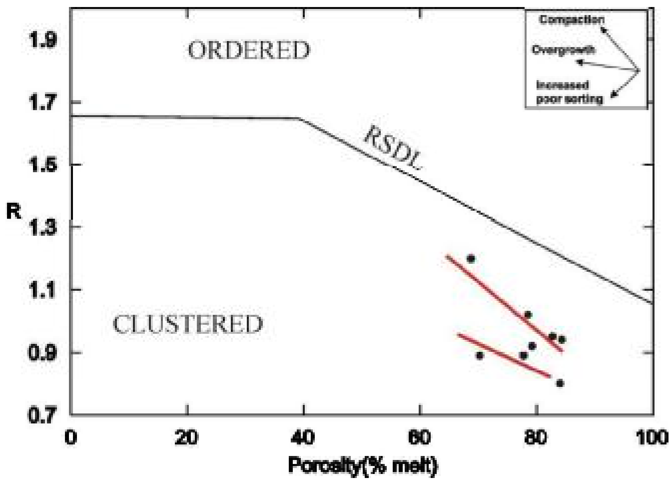

Fig 4: Plot of R value against porosity and location and trends of eight samples (see in text for detail)

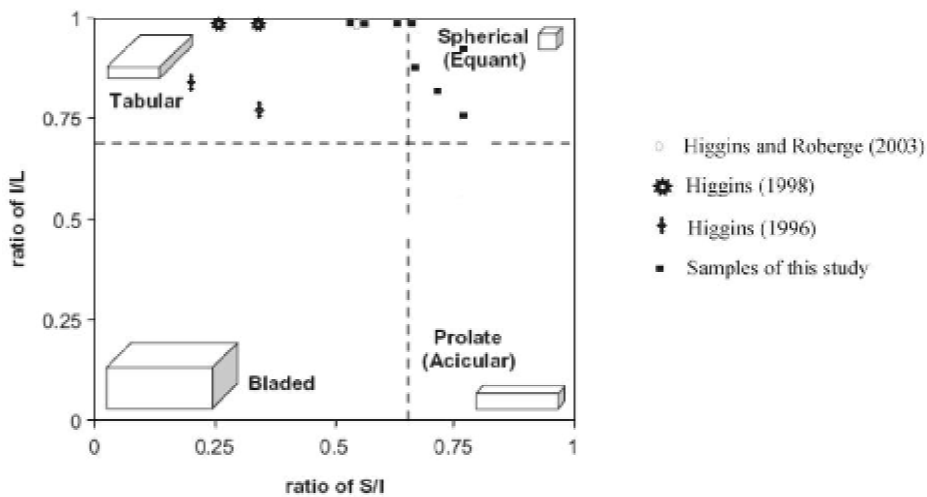

Fig 5: Zingg diagram (I/L against S/I) for studied samples and some of other studies