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Reply to comment on "Closure in crystal size distributions (CSD), verification of CSD calculations and the significance of CSD fans"

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Geochemists have long been aware of closure in chemical analysis (e.g., Chayes 1960). The purpose of my 2002 paper was to point out that closure also occurs in crystal-size distribution analysis (CSD; Higgins 2002). In both geochemistry and CSD analysis closure can lead to meaningless correlations, but carefully designed studies can easily avoid this situation and yield significant results. In my paper, I developed some very simple equations that are applicable to all CSDs, whatever their shape (Eqs. 1, 2, and 6). This is the context for the phrase "applies to all CSDs" that is quoted by Pan. I later developed equations that can only be applied to straight CSDs that extend to all crystal sizes, zero to infinity (Eqs. 3 and 4). These cannot be applied to all CSDs. The phrase "any process that changes the slope of the CSD must also change the intercept" quoted by Pan applies only to straight CSDs. Pan seems to have confused these two approaches.

Consider a family of different samples each having a *straight* CSD and the same volumetric proportion of the phase in question. Different samples can have different slopes to their CSDs. This result is significant and indicative of the processes that have produced the rock texture. However, the slopes of the CSDs of these samples are correlated to their intercepts. Hence, either the slope or the intercept gives information on the geological history of the sample, but the correlation between slope and intercept is not significant. For curved or fragmented CSDs (with empty bins) slope and intercept have no meaning, even though closure is still important.

Pan seems to have misinterpreted the nature of a CSD: it is just a description of the numbers of crystals of different sizes in a unit volume, for instance, 10 crystals per cm^3 between 1 and 2 mm long, 5 crystals per cm^3 between 0.5 and 1 mm long, etc. Pan states "Crystal content … is the only variable that determines the shape and position … of the CSD plot … for similar crystal sizes." It is not clear what he means, as a CSD, by its very nature, is a description of the distribution of crystal sizes. In any case the position and shape of a CSD are only controlled by the sizes and numbers of the crystals within a volume—nothing else. Changes in the size of some or all crystals will result in a new CSD. It should also be emphasized that CSDs can be expressed on many different types of diagram, not just the ln (population density) vs. size graph popularized by Marsh (1988).

Pan makes many references to his 2001 paper (Pan 2001) and hence a few words are necessary. In that paper he attempted to show that CSDs suffer from an "inherited correlation" between size and population density, and hence that CSDs are meaningless. He indicated that each CSD is controlled only by crystal content. A short reflection can show that this is not so. A pegmatite can contain 50% feldspar, but have crystals up to 50 cm long. An andesite also can have 50% crystals, but none will exceed 1 cm. The CSDs of these two rocks are completely different, even though their crystal contents are the same. The proposal of Pan (2001) has been discussed recently in two comments (Marsh and Higgins 2002; Schaeben et al. 2002) and the detailed arguments against it need not be repeated here.[1]

Pan correctly identified that '…"verification of CSD calculations" could only verify crystal content…'. This is what was intended. It is easy to make errors in any measurement, especially those that involve a certain amount of conversion of the data. For example, early workers commonly used the Wager (1961) method to convert intersection data to CSDs. This method can introduce errors in the population density of up to a factor of 100 (Higgins 2000). The type of verification proposed in Higgins (2002) can reveal such errors.

Quantitative measurements of texture, such as CSDs, are a powerful analytical technique. Despite their wide application in the field of materials science, few geological studies have been published so far. Hence, it is important to establish now the constraints on the technique, such as closure.

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[1]It should be noted that there was a mistaken reference in my paper to Marsh et al. (2002), which Pan correctly points out should have been Marsh and Higgins (2002).

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