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Compositions of Natural Sillimanites from Volcanic Inclusions and Metamorphic Rocks: A Reply

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I welcome the opportunity to reply to Dr. Zeck's discussion (1972) as I believe this will clarify a number of important points. Also, I am indebted to Dr. Zeck for pointing out the typographical errors in my 1971 paper. To clarify any misunderstanding, I received the samples of the volcanic inclusions from Cerro del Hoyazo, Spain, upon request, from the petrographic collection of the University of Amsterdam (G.U.) which, I understand, were originally collected by Dr. Zeck.

This discussion and reply hinges on the question of whether the sillimanites measured by me (1971) in the Spanish rocks are indeed volcanic in origin (chemically) or are metastable relics of a previous supposed regional period of metamorphism. The 1971 paper was a report on my investigation to see how close natural sillimanites approached Al_2SiO_5 stoichiometry, especially with respect to Al. In the course of the paper, I inferred that these sillimanites from the Cerro del Hoyazo volcanics should show extensive solid solution—if it is physically possible. In polymetamorphic rocks such as these volcanic inclusions most likely are, it is hazardous if not impossible, on the basis of petrographic evidence alone, to assign the time of formation of specific crystals—for example, specific crystals of sillimanite in a multicrystal aggregate—to specific metamorphic periods. Unhappily, in this old problem, no other evidence commonly exists *(eg,* isotope determinations, *etc).* Thus, we are left with questionable interpretative and probabilistic "conclusions."

We do know, in the case of these inclusions, that the last major thermal event in their history was the volcanism and that this event was of sufficiently long duration to form, according to Zeck (1968), glass, plagioclase, sanidine, biotite, corundum, and spinel. The inclusions may or may not have passed through a large pressure gradient, depending on their origins, but we know that at least part of their history in the last high thermal event was at low confining pressures close to the experimentally defined mullite field and, very generally speaking, under somewhat similar conditions to where mullite is found in rocks. Subsequently, the samples were quenched so that the high temperature, low pressure effects were retained, if they existed. Presumably new sillimanite crystals could have formed or old ones equilibrated to new conditions.

Dr. Zeck assumes that the sillimanite measured did not originally crystallize in this last volcanic event in the Al-rich inclusions from the Spanish locale, although he has not seen the specific sections in question nor have I given enough specific petrographic description in the 1971 paper to draw definite conclusions. Admittedly, Dr. Zeck has seen a great deal of the Cerro del Hoyazo material, but nowhere in the discussion does he substantiate his conclusion (above) with specific petrological evidence. The reason that no more descriptive petrological information was included (Kwak, 1971) is that I felt that enough descriptive material about the aluminum silicates had already been published and interested readers could refer to the respective references cited. It was an oversight on my part and this note gives me the opportunity to clarify some specific and important points.

Dr. Zeck has described the sillimanite formed in the inclusions as (1) acicular isolated crystals in the glass base of the lava, (2) acicular crystals, usually assembled in fibrous aggregates although locally coarser grained examples occur in the Al-rich inclusions, and (3) acicular crystals in loose aggregates in fine grained schists and quartzites. Zeck (1968) believes that the type (1) sillimanites "probably are precipitation products of the magma," (p. 128, lines 19–20), type (2) are apparently formed under regional metamorphic conditions, and type (3) are of volcanic origin. Importantly, none of the pelitic inclusions contain any muscovite and all of them

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(79 samples in total) contain sillimanite. Zeck (1968) attributes the type (3) sillimanite to the breakdown of muscovite during volcanism (p. 137) but, strangely, does not conclude a similar origin for at least some of the sillimanite in type (2). In addition, the fact that all the pelitic rocks are sillimanite–bearing suggests some process other than normal regional metamorphism has occurred; in a normal area all pelitic rocks do not contain sillimanite, and some do contain muscovite.

Central to the whole controversy is the regional metamorphic origin of some of the sillimanite and cordierite. Although Dr. Zeck (1968) has completed geological investigations of a relatively large area around the lavas, no sillimanite or cordierite has been observed nor do these minerals seem likely to occur [because] only the low-to-medium metamorphic minerals chloritoid and staurolite have been observed in the surrounding area. Stable chloritoid-sillimanite and cordierite-staurolite assemblages have, as far as I know, not been reported and the original position of the sillimanite and cordierite, if they are formed outside of the volcanic rocks, are in the familiar "unknown position at depth," and at another metamorphic grade to the surrounding rocks. The sillimanite-cordierite assemblage itself suggests a low pressure (and depth) formation and not a deep seated one. Dr. Zeck believes the inclusions represent "anatectic-restite material, syngenetic with, and complementary to, the magmatic melt." No unequivocal evidence supporting this theory has been presented by Dr. Zeck in either his 1968 or 1972 paper. Thus I see no reason why these cannot be formed simply by the partial melting and reaction of original staurolite grade metamorphic rocks (relict staurolite has been observed in some inclusions).

Most of the sillimanites measured were the larger crystals that occur in swarms of fibrolite which have no particular relationship to any other mineral. Number 28 (Kwak, 1971, Table 1) includes an analyzed "clot" of sillimanite and a single large, acicular crystal isolated in the glass-rich dacite lava. The true origin of this single crystal of sillimanite is unknown but it could be expected to equilibrate, at least partly, to the volcanic conditions if the sillimanite-mullite solid solution does occur. The two monomineralic forms, which were found in the same thin section, were lumped together because they were chemically identical.

In number 29 (Kwak, 1971, Table 1) the sillimanite measured grew at the expense of an andalusite crystal. Dr. Zeck believes the sillimanite to have formed during regional metamorphism although other authors in nearly identical situations believe similar sillimanite is volcanic in origin (*i.e.* Brauns, 1911, p. 34). Again we are left with no unequivocal evidence.

In his discussion, Dr. Zeck states that the coarse grain size of the Finkenberg samples (Kwak, 1971, Table 1) is more indicative of a prevolcanic origin. Again, I see no way to resolve this satisfactorily. The original collector of these samples (Dr. H. M. Schürman, personal communication, 1972) believes these sillimanites are most likely volcanic in origin.

The inclusions studied by myself are not greatly different from those of Aramaki (1961) in containing such materials as glass and corundum, and a result similar to his was expected but not found. Unlike Aramaki's inclusion, the mineralogy and textures of those from Cerro del Hoyazo and Finkenberg do not correspond unequivocally to any of the surrounding country rock. Thus "before and after" types of conclusions, such as those which can be drawn from a hornfels area around an intrusion, cannot be drawn.

In conclusion, the geological and textural evidence is not conclusive enough for some of the samples (*i.e.*, No. 29 previously cited) although we definitely know that they have existed in a low pressure-high temperature environment. For most of the samples, the evidence presented seems to me to favor an origin in which sillimanite-mullite solid solution should occur if it were chemically and structurally possible. That the sillimanite crystallized in its external form during low pressure volcanic conditions is theoretically not a necessary pre-requisite for the solid solution to occur, although this is desirable, of course.

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