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Reply to "Comments on Nd – Sr isotopic compositions of lower crustal xenoliths – Evidence for the origin of mid-Tertiary felsic volcanics in Mexico" by K.L. Cameron and J.V. Robinson

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Cameron and Robinson question the meaning of model Nd ages obtained by Ruiz et al. (1988a) for xenoliths from many localities on the easternmost edge of the Sierra Madre Occidental (SMO). This is a legitimate concern because the age of the xenoliths has direct bearing on the genesis of the voluminous silicic ignimbrites of the SMO (Ruiz et al. 1988b). The source of these volcanics is the underlying, and most important issue. Cameron and co-workers have to be congratulated for their pioneering work on the volcanics of the SMO. Besides the careful field work and K/Ar dating by F.W. McDowell's group at Texas (summarized in McDowell and Clabaugh 1979) and P.E. Damon, at Arizona (i.e. Damon et al. 1981), very little petrochemical data existed for this large volcanic province until Cameron started working on the problem of the origin of the silicic volcanics in the late 70's. After detailed field and petrologic studies in the Batopilas area, (Bagby 1979; Cameron et al. 1980; Lanphere et al. 1980; Cameron and Hanson 1982), Cameron and co-workers concluded that most of the SMO volcanic felsic in Chihuahua was produced by crystal fractionation of mantle derived basalt with little or no crustal assimilation, contamination or any other crustal interaction. In a more recconnaissance-type study of volcanic rocks from various places of the Sierra Madre Occidental in northern Mexico (see Figure 1 of Cameron and Cameron 1985), it was concluded that the parental mantle material needed to produce the silicic volcanic rocks of the SMO had Sr and Nd isotopic values near CHUR.

As Cameron and co-workers admitted, their studies were hampered by a complete lack of knowledge of the Mexican lower crust. The suggestion was, however, that the lower crust and upper mantle would be sufficiently different in their isotopic and some chemical compositions and therefore that any interaction between mantle derived and the lower crustal materials would be evident in the final chemical and isotopic compositions of the silicic volcanics. Previous ideas of the composition of the lower crust based on geologic models (Campa and Coney 1983) did not support a very old and isotopically evolved lower crust beneath most of the SMO. The oldest rocks that crop out around the central and southern parts of the SMO are volcanics and sediments from Mesozoic island arcs. Consequently based on accretionary models for the North America Cordillera, it is thought that the lower crust underlying most of the SMO is young island arc material accreted during Mesozoic times. The crust underlying the northern portions of the volcanic province is probably older. The question remained: what are the isotopic and chemical characteristics of this lower crust?

In an effort to better constrain the character of the lower crust, we have been studying lower crustal xenoliths from numerous localities on the easternmost extent of the SMO (Ruiz et al. 1988a, b; Roberts and Ruiz 1989). Among our most significant findings, that relate to the origin of the SMO, was that most of the lower crustal xenoliths had similar Nd and Sr isotopic compositions to those of the mid-Tertiary volcanics. Consequently, interactions between mantle derived magmas and this lower crust would be difficult to document. Furthermore, based on the isotope data there was nothing to preclude that the silicic ignimbrites could be derived from as much as 100% crustal melts. We realize that this amount of crustal melting without any comingling with mantle material in a subduction setting is an extreme case and probably not possible (e.g. Clemens and Vielzeuf 1989). Our point was that documenting the amounts of crustal v.s. mantle material in a MASH type setting (Hildreth and Moorbath 1988) would be impossible for the SMO magmas.

Cameron and Robinson point out that the xenolith population and exposed Grenville-age crust in eastern Mexico are isotopically different and that the exposed crust could not have been the source of the ignimbrites. That is correct. We never argued that the exposed granu-

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lites from eastern and southern Mexico represented any possible source for the mid-Tertiary volcanics. We believe that only the xenolith population may contain samples that represent lowermost crust available for melting or assimilation by mantle derived material. Accordingly, only the xenolith population need be discussed in the context of the petrogenesis of the mid-Tertiary volcanism.

The isotopic compositions of the ignimbrites most closely resemble metaigneous and some metasedimentary xenoliths. Most of the more pelitic paragneisses are isotopically different. The main question is whether the metaigneous xenoliths are cumulates of the mid-Tertiary volcanism or represent older crust. Thus the age and origin of the xenoliths are the central question. Many of the metaigneous xenoliths have trace element compositions that are consistent with a cumulate origin (Roberts and Ruiz 1989). Few samples, however, have unequivocal cumulate textures; this may be due to recrystallization during granulite facies metamorphism. We attempted to constrain the age of the xenoliths with Nd model ages, in spite of the limitations of the method (e.g. Ruiz et al. 1988a), because they are the only pertinent data available. Model Nd depleted mantle ages obtained for the samples range between about 1500 to 550 Ma. A garnet-rich paragneiss with a high 147 Sm/144 Nd ratio of 0.1871 (sample T-18-86) was incorrectly tabulated with a 1.5 Ga model age. Its correct model age is 2.7 Ga, as Cameron and Robinson point out. The error in the tabulation of the age should not detract from the point that this metasedimentary granulite shows clear evidence of melting and has the same isotopic composition as the mid-Tertiary volcanics. There is no doubt that this sample could represent restite from the mid-Tertiary magmatic event. The high Sm/Nd ratio of the sample, probably caused by the abundant garnet, only allows a very imprecise model age.

In northern Mexico, where it is generally throught that the lower crust is "Grenville" in age, we *only* obtained ca. 1400 Ma model Nd ages, for ortho and paragneiss xenoliths from La Olivina and Potrillo. This age is consistent with model ages obtained for exposed "Grenville age" crust throughout Mexico and Texas (Ruiz et al. 1988a; Patchett and Ruiz 1989). In central Mexico some xenoliths also have ca. 1500 Ma ages but most have younger model Nd ages. As we pointed out in our paper, these model ages may indicate that the

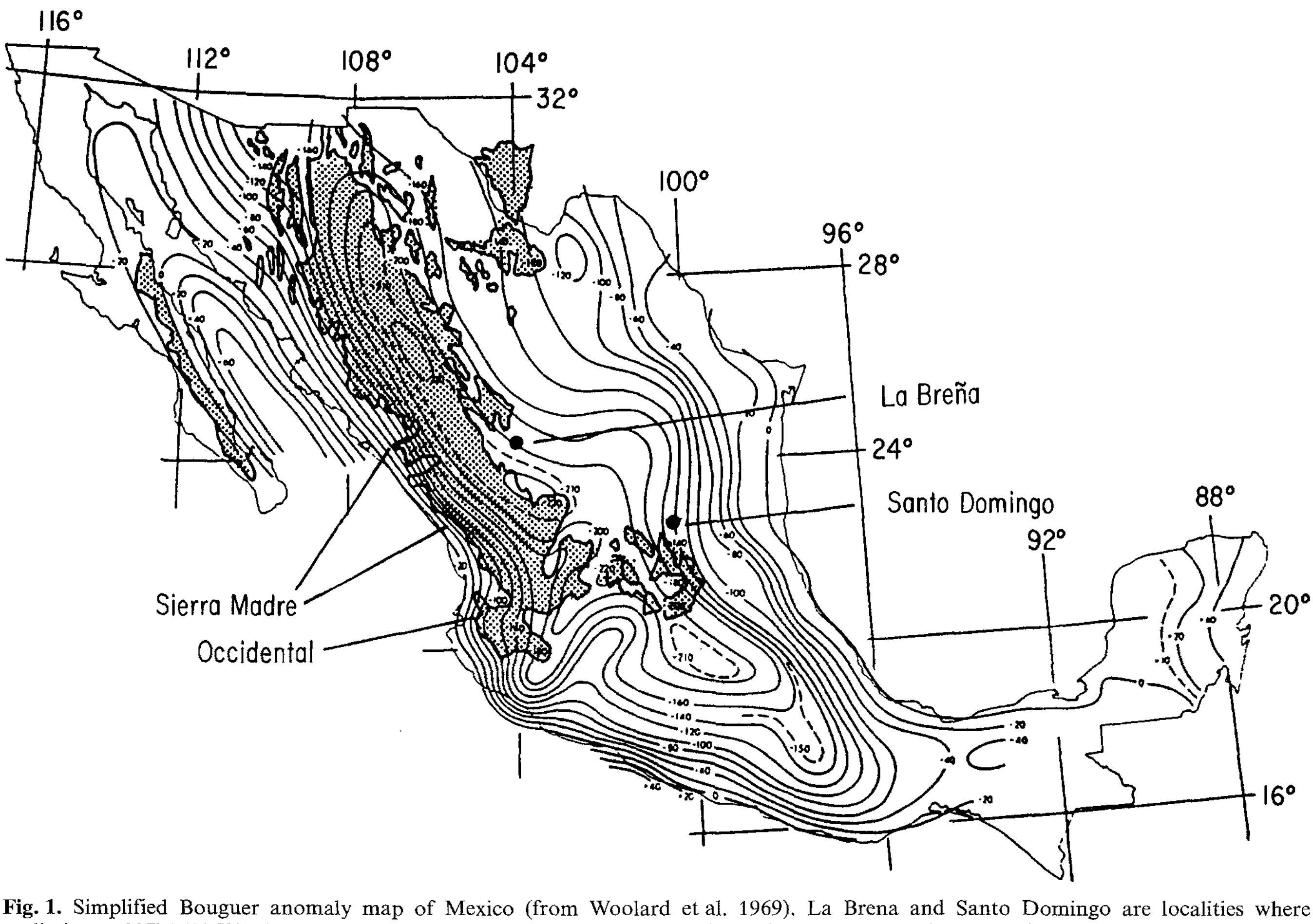

Fig. 1. Simplified Bouguer anomaly map of Mexico (from Woolard et al. 1969). La Brena and Santo Domingo are localities where preliminary 207Pb/206Pb data on zircons from xenoliths (Bowring, Luhr and Poole, personal communication, 1989) indicate a late Paleozoic (La Brena) and Grenville age (Santo Domingo) for the basement. Dotted pattern indicates the major exposures of mid-Tertiary igneous rocks

xenoliths are Paleozoic or younger. Our interpretation of the model ages was based on our limited knowledge of Mexican geology. We are aware that the true crystallization age of the xenoliths is not known and that our ages are model dependent. Our interpretation of the model ages for at least some of the more felsic xenoliths, however, is supported by U/Pb dating. Bowring, Luhr and Pool, personal communication (1989) have dated one xenolith from the Santo Domingo group in San Luis Potosi and one xenolith from La Brena in Durango (Fig. 1). The xenolith from San Luis Potosi gives a preliminary $^{207}Pb/^{206}Pb$ age of ca. 1.1 Ga and the xenolith from Durango an age of ca. 0.550 Ga, entirely consistent with our interpretation of the model ages.

Cameron and Robinson argue that all the model ages from the metaigneous xenoliths reported by Ruiz et al. (1988a) could be produced by fractionation of Sm and Nd during crystal fractionation of mantle derived magmas and that the xenoliths are mid-Tertiary cumulates. Cameron and Robinson further make some calculations that show that with reasonable Kds for Sm and Nd, mid-Tertiary cumulates would have similar model Nd ages as those reported by Ruiz et al. (1988a). The Sm/Nd "isochron" diagram (Figure 4 of Cameron and Robinson) does not add anything to the argument. There is no geological reason why exposures 800 km apart should be plotted on the same line in an 143Nd/144Nd vs 147Sm/144Nd diagram. The 1.6 Ga age obtained for the exposed rocks has no meaning considering the known geologic history of Mexico. Whether xenoliths plot on one line or another is fortuitous.

Although the preliminary U/Pb data of Bowring, Luhr and Pool tend to support our interpretation of the model Nd ages in the case of Mexico, we agree that model Nd ages are difficult to interpret and should be used with extreme caution. We were forced to use the model ages because of the complete lack of geochronological data for the basement of Mexico. For this reason, Cameron's group, (Nimz et al. 1986) have in the past also obtained and used model ages of metaigneous and pelitic xenoliths from La Olivina to conclude that the North American Craton extends to southern Chihuahua.

We think it worthwhile to discuss the origin of the SMO volcanics in the context of the overall plausibility of mantle and crustal origins. In this context the uniqueness or not of the Nd isotope data becomes a side issue, in our opinion. There are many difficulties in deriving the voluminous silicic volcanics from mantle derived materials, without any crustal interaction. Extensive underplating, at least 4 km, is required to produce the silicic volcanics by differentiation (Cameron et al. 1980), because of the amount of mafic mineral/plagioclase cumulates that must be removed from mantle derived basalt to produce the 1 km of dacite/rhyolite volcanics of the SMO.

Available geophysical data (Woolard et al. 1969) do not support this amount of basalt underplating the Mexican crust. Figure 1 shows the large exposures of mid-Tertiary magmatic rocks superimposed on a simplified Bouguer anomaly map of Mexico. Note that the bulk of the Sierra Madre Occidental occurs at the most negative anomalies (ca. −200 mgals). When corrected for topography, large negative anomalies still remain under most of the Sierra Madre Occidental (Woolard et al. 1969). The large negative isostatically compensated Bouguer anomalies are *opposite* to what should be seen if a layer of high density material is underplating the crust (Woolard et al. 1969) and suggests that a large volume of relatively low density material, possibly batholiths, form much of the Mexican crust underneath the Sierra Madre Occidental. While the magmatic differentiation origin for the felsic volcanics requires around 4 km thickness of mafic rocks under the whole SMO, a model where crustal melting is dominant requires only about 1 km of mafic material. This is because the heat capacity of basalt and rhyolite are of the same order, and the crustal rocks melt at lower temperature than that of the incoming mantle derived basalt. Thus the volume of basalt required is only about the same as the volume of rhyolite, which would be about 1 km in thickness over the whole region of the SMO. This was fully discussed by Ruiz et al. (1988b). The gravity data argue against 4 km of mafic rocks, but they probably permit 1 km.

Simple geological plausibility also argues for a strong crustal influence in the felsic magmas. Large amounts of mantle derived basalt at 1100–1300° C transport considerable heat into the lower crust. Simple heat balance suggests that the basaltic magmas are capable of melting intermediate-to-felsic magma from *any* reasonable mafic-to-felsic lower crustal rock complex. If the basaltic magmas are ponded in the lower crust for any length of time, e.g., the time required to produce the differentiation proposed by Cameron et al. (1980), then widespread crustal melting is *unavoidable*. The same applies if the differentiation is reserved for higher crustal levels. In this context it is very difficult to simultaneously avoid both (a) interaction between mantle derived magma and partially melted crust and (b) eruption of crustal melts in their own right. Quite probably both occur and the isotopic signatures of all volcanics become dominated by the crust. Thus simple thermal arguments suggest that the Cameron differentiation model must have a large volume of crustally derived magma to hide if it is to retain credibility.

In conclusion, geophysical, geological and isotope data indicate that the only plausible model for the source of the melts of the SMO is one in which there are interactions between crust and mantle materials in a similar way as in the MASH zone recently suggested by Hildreth and Moorbath (1988) for volcanic rocks from Chile. The resulting material from the MASH zone can undergo extensive differentiation at higher crustal levels to produce more silicic rocks. Cameron's work adequately describes the final differentiation process. However, Cameron and co-workers argue that large amounts of basalt with CHUR isotopic compositions formed the voluminous silicic SMO volcanics with little interaction with the crust. We believe that basalts with isotopic compositions more similar to those found in island arcs interact strongly with the lower crust and subsequently fractionated at higher crustal levels to produce the silicic volcanics. Because the Mexican lower crust is not isotopically very different from the mantle in Sr and Nd, the exact proportions of crust and mantle material in the original melts that produced the silicic volcanics cannot be better quantified. Based on thermal considerations, however, and constrained by the gravity data, large amounts of crustal material, probably greater than 50% of the total, must be involved in the origin of the SMO.

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