Questions About Magnetic Lineations in the Ancient Crust of Mars

Connerney et al. (1) claim to have discovered sea floor spreading–type magnetic anomalies in the measurements of the martian magnetic field done by the Mars Global Surveyor. It is possible that sea floor spreading may have occurred on Mars, but the information that these authors use to demonstrate this does not provide much support for this hypothesis. One advantage of the data under discussion was that three orthogonal components of the field were measured, in contrast with most Earth observations, which are usually of total field magnitude.

Connerney et al. show that the magnetic anomalies on Mars are lineated in an east-west direction. These lineations can be seen over a considerable portion of the southern hemisphere. The report shows four profiles in which the field components perpendicular to the lineation—north-south and vertical—are given, along with block models of the solutions to the vertically integrated magnetizations in these directions. These magnetization diagrams provide a unique opportunity to examine one of the main tenets of sea floor spreading, namely, that the anomalies are caused by reversals of the magnetic field.

The magnetization functions necessary to produce the observed magnetic field are reminiscent of early models of the ocean crustal field in which uniformly magnetized blocks of ocean crust were used. Bott and Hutton (2) found that if the width of the blocks was less than about 0.6 of the height of the observation above the block surface, then instability would occur in the inversion process. Although we know nothing about the magnetization parallel to the lineations, a reversal of the total field will cause a reversal of the projection of the field onto the plane perpendicular to the lineations, which should be reflected by the direction of magnetization within this plane. The inclination of magnetization in this plane is called the effective inclination, which is analogous to marine magnetic anomalies (3). A first test of the reversal hypothesis is, therefore, to see if the effective inclinations are arranged in two groups approximately 180° from each other. From the data presented by Connerney et al., it was possible to calculate the effective inclination in 78 out of the 80 blocks (the other two had low magnetization values for both components, rendering it difficult to make an accurate determination of effective inclination). Figure 1 shows a histogram of the effective inclinations, indicating that there is no grouping. A χ² test gives a value of 10.5 for the 15 groups, each of which has an expected frequency of 5.2, shown by the horizontal line. This value is close to the 50 percent mark for 14 degrees of freedom, showing a random population.

A second test of the reversal hypothesis involves determining the absolute angular change from one block to the next. If reversals cause the magnetic anomalies, then adjacent blocks should frequently have effective inclinations separated by values close to 180°. A histogram of absolute inclination changes is shown in Fig. 2 for the 74 angular changes between adjacent blocks. Adjacent blocks tend to have effective inclinations close to each other, as demonstrated by the best fitting line shown in the graph. There is no tendency for the direction to reverse, that is, to have a change close to 180°.

Connerney, in a personal communication, pointed out that the model magnetization does not allow for any annihilator (a magnetization which produces zero external field) (see [4]). Thus, a further test was done in which an annihilator was added to the magnetization results to see if this might produce directions which are clustered in two groups separated by about 180°, and in which adjacent blocks have directions either close to each other or separated by about 180°. For a uniform spherical shell of finite thickness, the annihilator is any magnetization directly proportional to any internally generated field (5). But since the area of Mars showing lineated magnetization is limited, a simpler annihilator is a uniform magnetization within the uniformly thick slab assumed to generate the magnetic anomalies (4). To investigate whether adding the annihilator would make a difference to the pattern of magnetization direction illustrated in figures 1 and 2, an annihilator of strength 2, 4, or 8 A m⁻¹ was added to the magnetizations. The effective inclination of the annihilator was varied through all effective inclinations in 30° increments. As more of the annihilator was added, greater peaks registered at the effective inclination of the added annihilator (Fig. 1), and the grouping close to zero degrees grew larger (Fig. 2).

In conclusion, the model results presented by Connerney et al. did not support reversals of the martian magnetic field as the cause of the lineated magnetic anomalies found on Mars. This does not necessarily negate a sea floor spreading type of phenomenon in the early history of Mars, but an alternative model is needed to prove or refute this hypothesis.

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References

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Response: Harrison questions the inverse methodology used by Connerney et al. (1) to model Mars crustal magnetism and uses their models to infer the direction of the inducing field, presumably due to an early Mars dynamo. Harrison’s calculated field directions do not fall into two distinct groups representing normal and reversed polarities, as he expects if a reversing dynamo and sea floor spreading combined to form the lineations.

Harrison alludes to a numerical instability in our inverse method, citing Bott and Hutton’s experience (2) with similar models in which instability occurred if the width of magnetized strips was reduced to less than 0.6 times the altitude of observation. Our model strips have a width of one to two times the observation altitude (100 km < z < 200 km), well within the cited range of stability. Bott and Hutton modeled total field magnitudes only, and assumed the direction of magnetization, as is common in modeling magnetic anomalies on Earth, measured in the presence of a much larger background field. We modeled vector observations and made no assumptions regarding the direction of magnetization. Since the stability of a linear system depends critically on the model, assumptions, and observations available, one cannot draw a meaningful comparison between our work and that of Bott and Hutton. Our report provides the reader with sufficient detail regarding the stability of the linear system, deduced from singular value analysis.

One cannot determine the real direction of crustal magnetization or that of the presumed inducing field from our models or observations. This follows from an appreciation of the non-uniqueness of potential field models and from the realization that our models—which use equally spaced, 200-km-wide strips of uniformly magnetized crustal material—cannot adequately represent the complex distribution of crustal magnetization expected in the Mars crust. Our report discussed model non-uniqueness at length and in reference 8 of (1) we explain the concept of the “annihilator” to which Harrison refers. Our report also emphasized the limitations arising from the simplicity of the model, noting that “adoption of different assumptions, say, the number, width, or absolute positions of the uniformly magnetized plates, can result in different magnetizations; our solutions are representative and by no means unique.” Also, “it is expected that the physical dimensions of the sources are considerably more complex than assumed here and that the volume magnetizations are nonuniform, reflecting spatial differences in mineralogy, magnetic microstructure, and history.”

We also cautioned that our model yields an average magnetization over a 200-km-wide band, not simply related to in situ direction of magnetization. We believe that determination of the direction of magnetization in the actual crustal rock, and inferences regarding the primordial inducing field, will require additional constraints or actual sample measurements. In light of the above, we do not believe that Harrison’s calculation of field directions is appropriate.

Our interpretation was considerably less bold than that represented by Harrison. We did not claim to discover sea floor spreading on Mars. We observed that we could fit the Mars Global Surveyor observations with a simple crustal magnetization model characterized by groups of quasi-parallel linear features. Reversals in the direction of magnetization were inferred for both ($J_x$ and $J_z$) components of the magnetization [see figures 2 to 6 of (1)] and we offered four possible explanations for these observations, the most attractive of which, in our view, was the analogy to sea floor spreading on Earth.

Harrison proposes two statistical tests that do not address our interpretation, tests that would likewise fail if applied to sea floor spreading on Earth. We do not claim that average magnetizations would cluster about two directions. One expects a more complicated variation of magnetization over the 4000-km distances and hundreds of millions of years of evolution required to produce such a volume of crust, particularly if one allows for motion of crustal blocks, multiple ridges, transform faulting, and the like (3). His second test, which requires adjacent, equally spaced bands to have alternating magnetization, would fail in any real environment with variable sea floor spreading rates and an aperiodic dynamo reversal history. The outcomes of such tests have no bearing on the observations, models, analyses, and interpretation presented by Connerney et al.

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