NOTE

An Origin for the Linear Magnetic Anomalies on Mars through Accretion of Terranes: Implications for Dynamo Timing

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The proposed existence of magnetic lineations in the Terra Cimmeria and Terra Sirenum regions of Mars was initially explained by Earth-like sea-floor spreading. Here we argue instead that these lineations could have been formed at a convergent plate margin through collision and accretion of terranes. A similar process produced banded magnetic anomalies, similar in geometry and even in size to those in Earth's North American Cordillera. Because only sparse and generally weak anomalies have been detected in the martian northern lowlands, which could constitute an analog to the terrestrial oceanic crust, it is possible that the magnetic field stopped its activity while crustal recycling was still active in Mars.

Key Words: **Mars, surface; tectonics; magnetic fields.**

I. Introduction. The discovery of large expanses of the martian southern highlands crust with strong remanent magnetism and some localized (and generally weak) magnetic anomalies in the northern lowlands (Acuña *et al.* 1999, 2001) has resulted in major revisions to previous ideas concerning martian dynamics. One of the most significant findings of the Mars Global Surveyor (MGS) mission was the east–west trending linear crustal magnetization anomalies of surprisingly great intensity centered in the Terra Cimmeria and Terra Sirenum regions, which can be traced for more than 2000 km (Connerney *et al.* 1999, 2001, Purucker *et al.* 2000, Acuña *et al.* 2001; see Fig. 1). These anomalies have alternating strong and weak magnetic signatures, a pattern which is comparable to much weaker linear magnetic anomalies observed in the Earth's oceanic floor. Thus, this pattern on Mars was proposed to be genetically related to sea-floor spreading in the presence of a reversing dipolar magnetic field (Connerney *et al.* 1999, Nimmo 2000, Sprenke and Baker 2000). Sleep (1994) had already proposed that plate tectonics operated on Mars in the Noachian, although he considered the lowlands instead of the highlands as the ancient oceanic crust.

Several alternative hypotheses have since been proposed to help explain the magnetic lineations, including folding or hydrochemical alteration (Connerney *et al.* 1999), repeated dike intrusions with the locus of intrusion moving with time (Nimmo 2000), and accretion of terranes (Baker *et al.* 2002, Dohm *et al.* 2002, Fairén *et al.* 2002). Even the existence of anomalies may be due to impact demagnetization of a previously globally magnetized crust (Sprenke and Baker 2000, Arkani-Hamed 2001, Hood *et al.* 2002).

Although as of this writing, there is no definitive evidence for ancient martian plate tectonism, here we assume this possibility as a working hypothesis, because of its relevance in relation to the dynamics and evolution of early Mars. In this note we show that the characteristics of the magnetic lineations in Terra Cimmeria and Terra Sirenum can be fairly explained as the result of a process of collision in a zone of crustal destruction, causing continental accretion, like the one that took place in the west coast of North America in Jurassic to early Tertiary time (e.g., Coney *et al.* 1980), which produced a distinctive pattern of magnetic anomalies (Saltus *et al.* 1999). We also discuss the implications of this hypothesis for the temporal evolution of both martian crustal dynamics and magnetic field.

II. Banded magnetic anomalies in north american cordillera and Mars. A pattern of linear and arcuate magnetic anomalies of alternating polarity is found on Earth in the North American Cordillera; it can clearly be seen in the aeromagnetic maps of Alaska (Fig. 2a) and British Columbia (Fig. 2b). There was a great difference in the height at which data were obtained for Earth and Mars: ~300 m for data of North America, 85–170 km for data acquired in MGS aerobraking orbit, and ~400 km for data acquired during the MGS mapping orbit. Nevertheless, the magnetic features on Mars are about one order of magnitude stronger than those of the Earth's continents (Connerney *et al.* 1999), and these high magnetic intensities on Mars suggest materials with remanent magnetization comparable in intensity to that of fresh oceanic basalt on Earth. Even so, the geometry and even the sizes (~100- to 200-km broad) of North American roughly linear anomalies are similar to those of martian lineations (Connerney *et al.* 1999, 2001, Purucker *et al.* 2000) and are interpreted to be the result of sheared terranes, which are accreted to the continent through a process of oblique collision [for an exposition of the accretion process in the North American Cordillera, see Moores and Twiss (1995)]. These accreted terranes have several origins: oceanic crust, oceanic arcs, distal parts of continental edges, rift remainders, or oceanic plateaus (Coney *et al.* 1980).

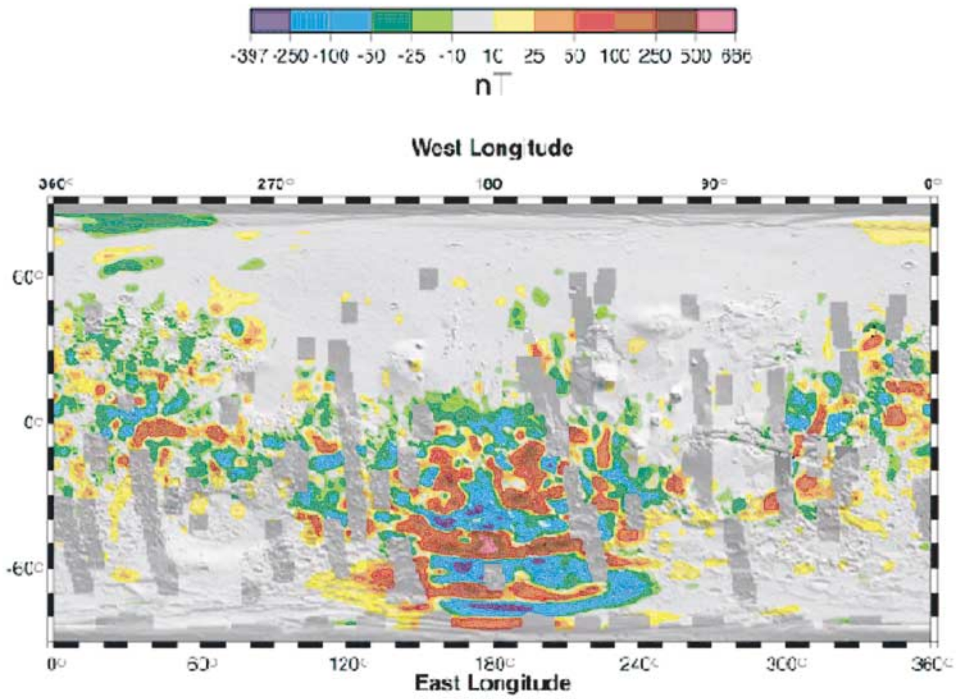

FIG. 1. Radial magnetic field of Mars, overlain on topographic gradient map, from Purucker *et al.* (2000).

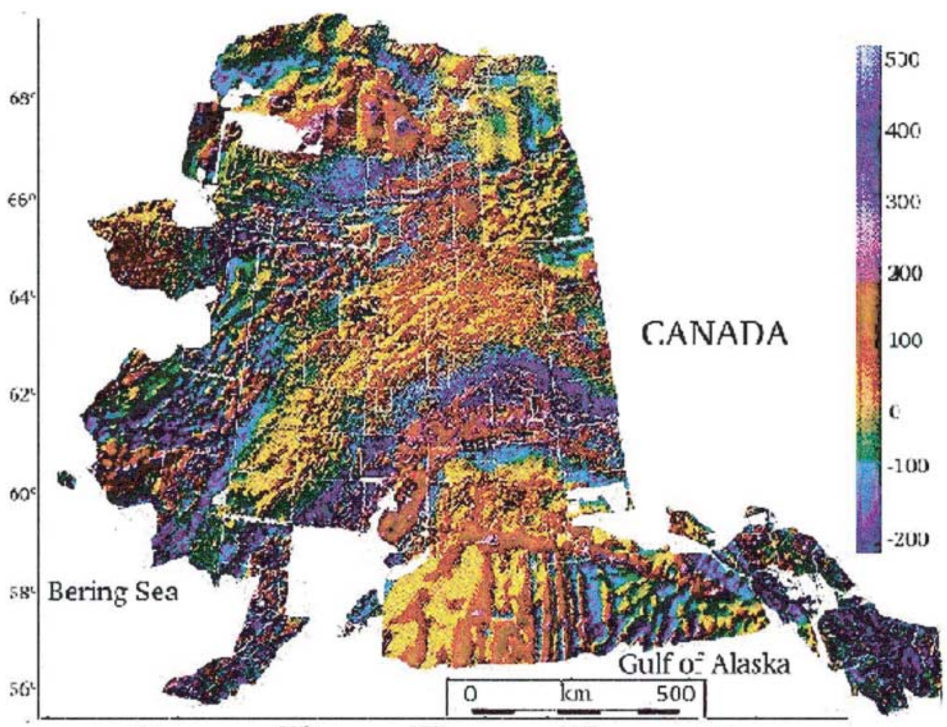

FIG. 2. (a) Composite aeromagnetic map of Alaska that depicts total field magnetic data values (after Saltus *et al.* 1999).

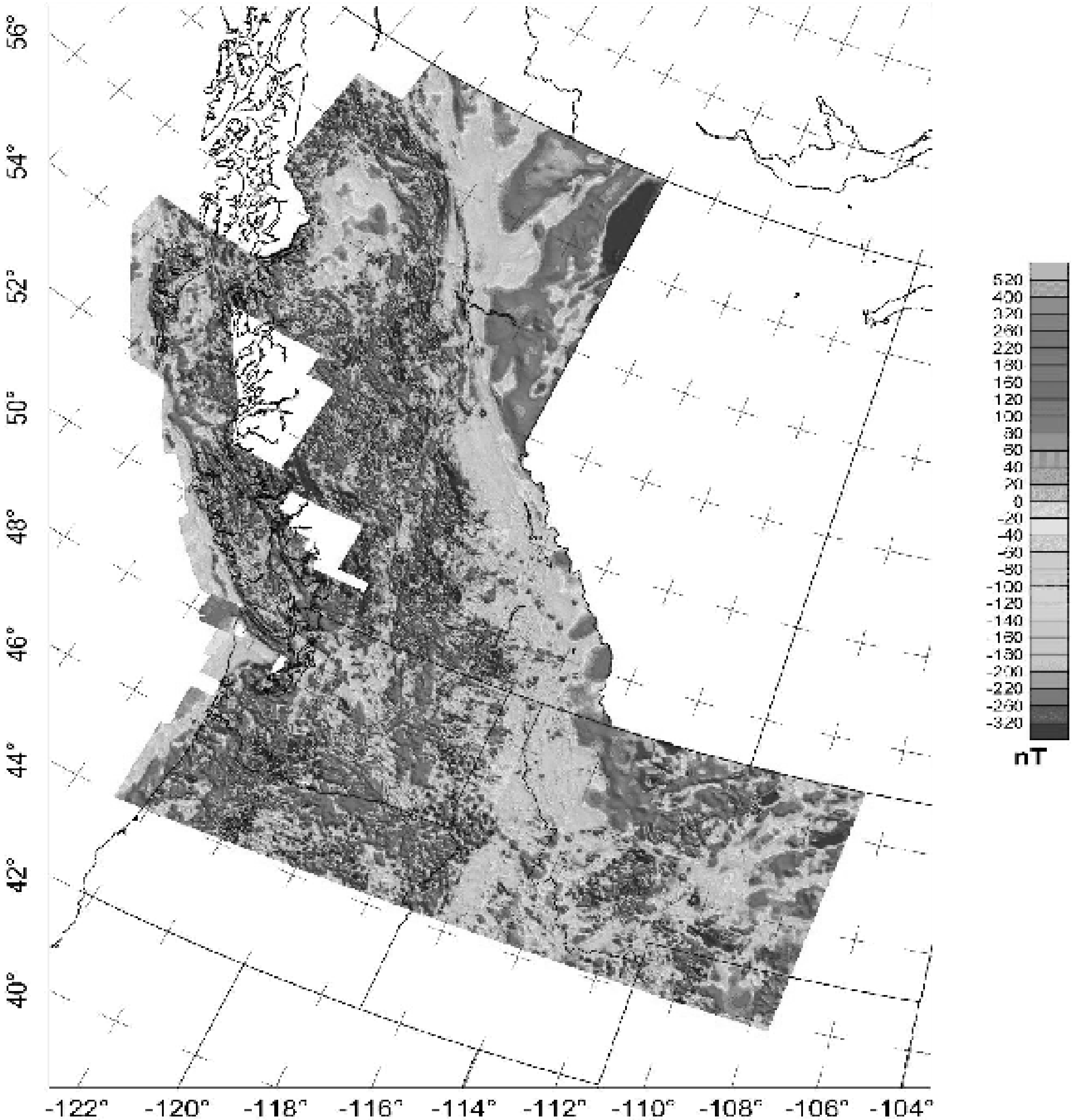

FIG. 2. (b) Aeromagnetic map of the North American Cordillera, over British Columbia, Canada, and Washington, Idaho, Montana, and portions of Oregon and Wyoming, United States (from http://crustal.usgs.gov/namad/images.html).

The sources of the Alaskan anomalies have a significant thickness on a crustal scale (Saltus *et al.* 1999), the same as that proposed for Terra Cimmeria and Terra Sirenum based on magnetization intensity (Connerney *et al.* 1999, Nimmo 2000). Moreover, starting from magnetic features common to several global magnetic maps of Mars, Purucker (2002) suggests that the southern boundary between magnetic and nonmagnetic terranes is sharp for longitudes between 120° and 240°E (corresponding to strongly magnetized crust) and gradational for other longitudes. This could indicate deep-seated discontinuities in the crust (e.g., fault blocks), which is consistent with magnetic linear features of the North American Cordillera that are fault-bounded. Dohm *et al.* (2002) has mapped numerous macrostructures that have similar trends and appear to correlate with some of the anomalies.

Importantly, the magnetic character shown by the southern continental margin of Alaska has been considered (Saltus *et al.* 1999) as a typical example for what is to be expected in any region on Earth that undergoes convergent margin processes. If plate tectonics operated on early Mars, then terrane accretion would be anticipated. Likewise, if this process occurred in the presence of a reversing magnetic field, then a pattern of magnetic anomalies similar to the one observed in North American Cordillera would be expected.

Therefore, the strongly magnetized crust of Mars could be analogous to that interpreted for the North American Cordillera: a jigsaw of continental and oceanic pieces related to a past period of plate tectonics, but to a process of crustal convergence instead of generation. If the martian boundary in Terra Cimmeria–Terra Sirenum is a former convergent plate border, the area southward of the dichotomy would be a zone where fragments of crust would accrete, and their geometry would be defined, as on Earth, by the angle of collision between the two plates. The magnetic linear bands proposed for these regions would thus be sheared terranes, and their northward transition to more round-shaped magnetic features would indicate face-on collision conditions. So, our model of early martian plate tectonics is not entirely equivalent to the one proposed by Sleep (1994), in which the highland–lowland boundary northward of Terra Cimmeria and Terra Sirenum is interpreted as a passive margin instead of a plate-convergence zone.

MGS topography and gravity data indicate that the crust in these locations of strongly magnetized highlands is clearly thicker than that in the lowlands (Zuber *et al.* 2000), which favors the hypothesis of an accretional origin versus that of a sea-floor spreading. Finally, if the accretion model is correct, it has a number of petrologic implications: accreted terrane packages would presumably contain many rock types, such as arc volcanics, silicic plutonics, and metamorphosed sediments. These rock types are not presently known on Mars, and this could be an interesting target for future investigations.

III. Discussion: martian dynamo timing. The absence of magnetization in the Hellas and Argyre basins is an apparent indication that the dynamo was already nonoperative when the forming impacts were produced, and this would imply a minimum age of ∼4 Gyr for the death of the martian magnetic field (Acuña *et al.* 1999, 2001, Arkani-Hamed 2001). However, Schubert *et al.* (2000) proposed an alternative post-Hellas and post-Argyre timing for the martian dynamo, though the characteristics of the anomalies around both these impact basins do not favor this possibility (Arkani-Hamed 2001). If magnetization in Terra Cimmeria and Terra Sirenum was produced in relation to the accretion of terranes, the absence of significant magnetic anomalies in the northern lowlands could have deep implications on the temporal evolution of both the martian dynamo and lithosphere.

In this sense, if the northern lowlands constitute former oceanic floor materials, which originated from sea-floor spreading centers during the time of accretion to the south, then they should have had a similar alternating magnetization pattern as that described for the highlands, because the magnetization process would have affected them in a similar way. However, only minor anomalies have been detected on the martian lowlands and no linear bands have been described (Acuña *et al.* 1999, 2001).

The absence of magnetic lineations in the northern plains could result from several possibilities, including data resolution limits, alteration of magnetized northern plains materials through erosion and hydrothermal processes, or a marked decrease in the time scale for dynamo reversals. The absence of linear anomalies in the northern lowlands could be explained by a termination of magnetic field before the cessation of Mars plate tectonism (Fairén *et al.* 2002, Baker *et al.* 2002). This delay could have been long enough for plate tectonics to generate new, unmagnetized crust in the lowlands until the definitive standstill of crustal recycling. As this process would have been gradual, the localized anomalies detected in some areas of the lowlands could represent weak signatures of the final stages of magnetic field activity. In this sense, it is interesting to stress that the surface of the northern lowlands is clearly stratigraphically younger than that of the highlands (e.g., Tanaka *et al.* 1992, Strom *et al.* 1992), though MGS gravity data seem to indicate that the lowlands basement is roughly contemporary to the highlands (Frey *et al*. 2001, Zuber 2001); therefore, and at least in certain locations, the magnetization of the ancient crust of the lowlands may have survived underlying younger crust (Stevenson 2001, Zuber 2001).

Finally, the absence of magnetization in extended areas of the southern highlands, centered in Noachis Terra, would be due to a demagnetization caused by the impacts that created Hellas and Argyre (Hood *et al.* 2002), although perhaps additional impacts could also be required for this process (Purucker 2002). Alternatively, the nonmagnetized southern regions could represent a primitive martian crust that evolved before the planetary magnetic dynamo began to operate.

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