ARABIA TERRA, MARS: TECTONIC AND PALAEOCLIMATIC EVOLUTION OF A REMARKABLE SECTOR OF MARTIAN LITHOSPHERE

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Abstract. A regional geologic study of Arabia Terra, a densely cratered area of Mars northern hemisphere, has revealed the individuality of this province. This is best expressed by an equatorial belt with a crater age distinctly younger as compared to the northern part of Arabia Terra and to Noachis Terra to the south. We interpret this as an incipient back-arc system provoked by the subduction of Mars lowlands under Arabia Terra during Noachian times. The regional fracture patterns are also best explained in this manner, making it unnecessary to appeal to a rotational instability of the planet, which is not supported by the palaeoclimatic indicators in the area. This model could be the first regional-scale confirmation of Sleep's (1994) hypothesis of a limited plate consumption as an explanation of the martian dichotomy.

Keywords: Mars, tectonics, palaeoclimate, plate tectonics

1. Introduction

Extending roughly from 20° through 280° W and from 50° N to the Equator, Arabia Terra (Figure 1) is the largest ($\sim$12 000000 km^2) expanse of cratered terrain in Mars northern hemisphere. Parts of Arabia Terra have been studied by, among others, Carr and Schaber (1977), Lucchitta (1981, 1984), Schultz et al. (1982), Parker et al. (1989), McGill and Squyres (1991), and Maxwell and Craddock (1995), who mainly emphasised two aspects: glacial features, and the nature of the lowland/upland boundary. Recently Barlow (1995) studied crater degradation in an area north of crater Cassini. No thorough regional study of Arabia Terra has ever been carried out. This area is nevertheless an especially good test bed to callibrate several hypotheses pertaining to some of the big problems of martian geology: the Schultz and Lutz (1988) proposition of large variations in martian obliquity; the 'Martian plate tectonics' conjecture (Sleep, 1994); and the dichotomy origin itself

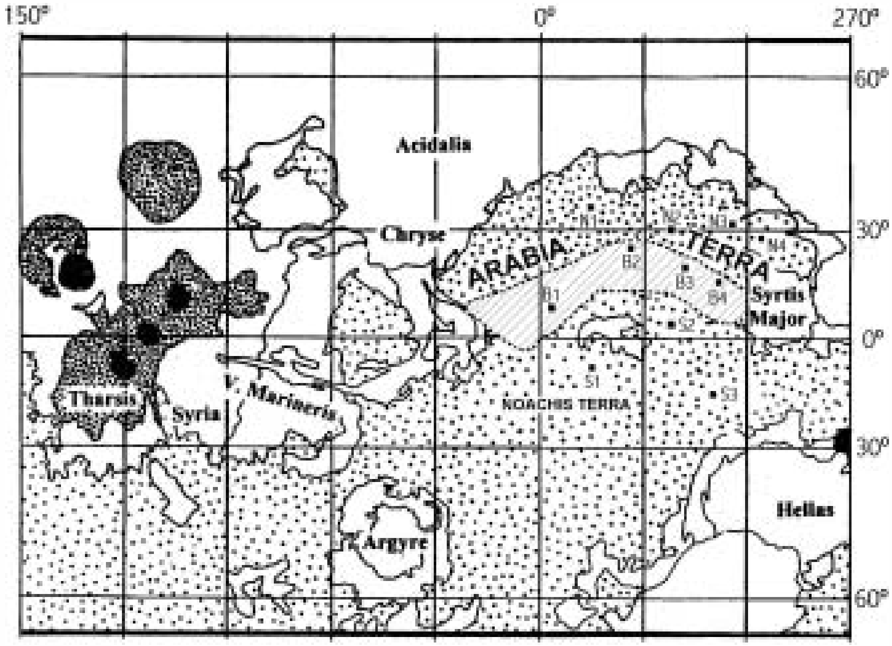

Figure 1. Arabia Terra in a physiographic map of equatorial Mars, 270–150° W. The striped pattern marks the resurfaced belt referred to in the text. The numbered points are the areas where the crater counts have been carried out.

(Wise et al., 1979; Wilhelms and Squyres, 1984; McGill and Squyres, 1991). We will focus these discussions by reconstructing the palaeoclimatology and describing the structures of Arabia Terra, and establishing crater ages that support the individuality of this sector of the Martian lithosphere.

2. Palaeoclimatic Indicators in Arabia Terra

From a morphological point of view, Arabia Terra can be considered a densely cratered volcanic plateau (Greeley and Guest, 1987) perhaps including interbedded sedimentary rocks, with a slight slope to the north. The Mars Digital Terrain Model indicates Arabia has a height of about 3 km above datum near the equator, and then slopes down to about 1 km at its northern edge. Its most important features are erosional valleys (fluvial and/or glacial in origin) considerably modified by periglacial and mass wasting processes, while eolian (and karstic?) shapes are subordinate. Tectonic structures include fault scarps (generally associated in graben) and wrinkle ridges, the graben clearly controlling the layout of the main valleys. The lowland/upland boundary style varies widely along the more than 6000 km which form the northern border of Arabia Terra. In what follows, we will only emphasize morphological features with a possible palaeoclimatic meaning. The reason for this is that some tectonic features (namely the wrinkle ridges) have been attributed (Schultz and Lutz, 1988) to overturns in Mars' rotational axis. Since those rotational instabilities should leave traces in the palaeoclimatic record, they can only be assessed through a discussion on the putative palaeoclimatic indicators.

The origin of the closed depressions (Figure 2B) which abound in the northern reaches of Arabia Terra could require the presence of soluble underground layers. Since the flat bottoms of the depressions (without traces of chaotic terrain on them) seem incompatible with the fusion of permafrost, water solution of rocks could be indicated, with carbonates or evaporites being the best rock candidates (Schaefer, 1990); it should, nevertheless, be noted (Toulmin et al., 1977; Kahn, 1985; Pollack et al., 1987) that the identification of spectral signals for carbonates from Martian orbit have been only tentative up to now. An outcrop which could be composed of sedimentary rocks ('White Rock', a suggested evaporitic formation, Williams and Zimbelman, 1994) lies not far away (at 8° S, 334° W).

The northernmost area of Arabia Terra is a model for fretted terrain (Sharp, 1973), with typical examples of periglacial mass wasting, generating basal debris aprons. Complementary to the fretted terrain are the groups (Cydonia Mensae, Deuteronilus Mensae and Protonilus Mensae) of isolated mesas and buttes (Figure 3) which form the northern fringe of Arabia Terra, and which have been explained (Sharp, 1973) as erosional remnants of the dichotomy. Tectonic effects seem to be the cause of the triangular or, in general, polygonal shape of many of these mesas.

Arabia Terra channels fall in two different classes. The largest ones are fretted channels, which seem to have been carved out of the structural network (Figure 2) by a set of processes among which Baker et al. (1992) list ground ice mobilization, and mass and debris flows. The scarcity of tributaries and of channel flow marks in Martian channels is best explained through sapping (Sharp and Malin, 1975; Baker, 1985, 1990). However, examples are also found of small outflow channels (see again Figure 3) which debouch in the lowlands, disappearing in the dichotomy despite the fact that the regional slope continues steadily to the north. This has been cited (Parker et al., 1993) as an argument for an important water-lain sedimentary cover on the northern lowlands plain. Some channels (Figure 2) feature long, parallel ridges on their bottom, probably formed through mass wasting and glacier flow (Carr and Schaber, 1977; Lucchitta, 1984; Squyres, 1989). More uncertain origins have been attributed to areas of striped ground found near Arabia (Figure 4) usually termed 'thumbprint terrain' (Guest et al., 1977), whose pseudo-folds have been ascribed by Carr and Schaber (1977) to recessional moraines; by Scott and Underwood (1991) to ice-pushed ridges; and by Kargel and Strom (1992) to subglacially eroded channel valleys. The last authors connect these shapes with processes similar to the ones that generate submarine (De Geer) moraines in terrestrial glaciers. The association of this terrain with sinuous ridges comparable

Figure 2. Flat floor ('fretted') channels (A) and closed depressions (B) following the trend of tectonic structures: wrinkle ridges (C) and graben (D). 'Flow' lines parallel to the scarps can be seen in the bottom of some of the valleys (B). Viking mosaic 230 km wide, centered at 40° N 332° W.

Figure 3. Small outflow channels (*A*) disappearing at the dichotomy. Examples of eskers? (B) and mesas and buttes (C) can also be seen in this Viking mosaic centered at 30° N 278° W. Image width, 180 km.

to eskers lends support to this last hypothesis, as well as the scale (hundreds of meters) of the thumbprint terrain, which suggests deposition in deep water (Barnett and Holdsworth, 1974). If those ridges were actually shown to be eskers, a case for a glacier modification of the dichotomy in these areas could be made.

In all, the features of the lowland/upland boundary in Arabia Terra conform to the ocean/lake model put forward, in slightly different versions, by Lucchitta et al. (1987), Parker et al. (1989, 1993), Schaefer (1990), and Baker et al. (1991). And the last results from the laser altimeter onboard Mars Global Surveyor (Smith et al., 1998) also support the ancient ocean hypothesis. Sedimentary progradation, fluvial and glacial erosion and, as can be seen in the following section, tectonic stresses, would later modify this topographic boundary to its present aspect.

3. Tectonic Structures of Arabia Terra

Graben and wrinkle ridges (Figure 5) abound in Arabia Terra, where they are always covered by craters, a fact which implies a very old age for these structures. Scott and Dohm (1990) assign them a Noachian age. Graben show en echelon steps, both right and left, and vary in width from a few kilometers up to several hundred kilometers, although in these last cases there is evidence of erosion, which has widened the original graben by an unknown amount. As can be seen in Figures 3 and 5, both kinds of structures show NW–SE and NE–SW bearings. N–S graben are also developed. When crosscutting relationships are clear, graben always cut wrinkle ridges (Figure 5A and B). These last structures have been interpreted as anticlines above a thrust fault (Plescia and Golombek, 1986; Watters and Maxwell, 1986; Watters, 1988, 1992; Golombek et al., 1991), or as volcanic extrusions (locally, dikes) intruded along graben (Hartmann and Wood, 1971; Scott, 1989). While some authors (Scott, 1989; Maxwell, 1989) propose a tensile origin for wrinkle ridges, the comparison with similar terrestrial structures (for instance, in Plescia and Golombek, 1986, Figure 3) leads most planetary scientists to interpret them as compressional.

Regarding the origin of graben and wrinkle ridges in Arabia, Scott and Dohm (1990) indicate that they follow the trend of the highland/lowland boundary, although they do not explicitly propose a genetic relation of the structures with it. Other sections of the upland/lowland boundary also show graben along the boundary trend, but there is no other set of such regular and closely spaced wrinkle ridges (excepting those associated with Tharsis) in any other region of the dichotomy, a fact that does not suggest a causal relationship between both features. When proposing that the highland/lowland boundary is the rim of a giant impact basin, Wilhelms and Squyres (1984) mention several features that their hypothesis could explain, but the geometry of the tectonic structures south of the boundary is not among them. Moreover, Chicarro et al. (1985) discard on a statistical basis any

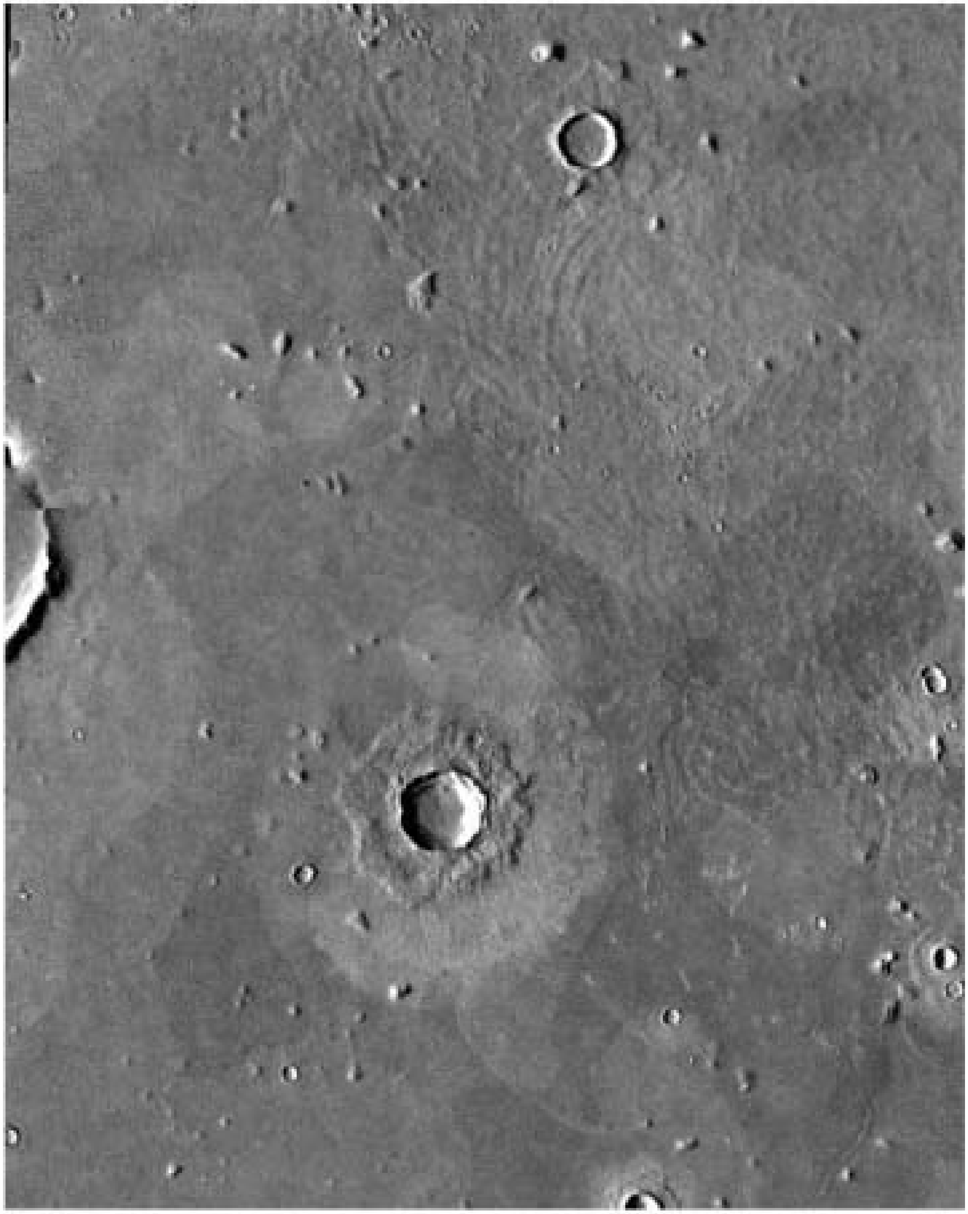

Figure 4. Thumbprint terrain on Utopia Planitia, near the border of Arabia Terra. The figure is a part, 120 km wide, of the Viking mosaic centered at 35° N, 272° W. (A) marks a putative esker, a feature which could support the subglacial hypothesis for the thumbprint terrain origin; but see discussion in the text.

Figure 5. Wrinkle ridges and graben in Arabia Terra. At A and B, wrinkle ridges are cut by graben. This figure is a part of the Viking mosaic centered at 35° N, 307° W. Mosaic width 280 km.

impact basin influence on a number of Martian wrinkle ridges, including the Arabia Terra ones.

The only general hypothesis advanced so far for the origin of Martian wrinkle ridges not associated with basins or domes is the one by Schultz and Lutz (1988), after which one or more chaotic overturnings of the Martian rotational axis would have subjected the whole Martian lithosphere to tangential stresses. Chaotic variations in planetary obliquity (Laskar and Robutel, 1993) have been a fashionable idea recently, and Mars is the best place in the Solar System for testing this hypothesis. If the planet had suffered drastic alterations in obliquity (as Jakosky and Carr, 1985 [25°–45°], Bills, 1990 [up to 51°], and Laskar and Robutel, 1993 [up to 60°] suggest), its climatic zonation would be blurred, with arid and glacial indicators superposed. In Arabia Terra and surrounding areas, the contrary is the case: as has been shown, the landscapes with glacial and periglacial marks are situated consistently at high latitudes (35°–45° N). On the other hand, the putative evaporitic deposits of "White Rock" (Williams and Zimbelman, 1994) are located at 8° S 335° W, and we have located at least one other possible similar outcrop (Figure 6) closer still to the present Equator, at 3° S, 336° W. Therefore the regional evidence does not contain support for important variations of Mars obliquity, although it is acknowledged that only the local palaeoclimatic record has been studied. In any case, it should be pointed out that this provisional conclusion does not hold only for recent times, since Williams and Zimbelman (1994) have

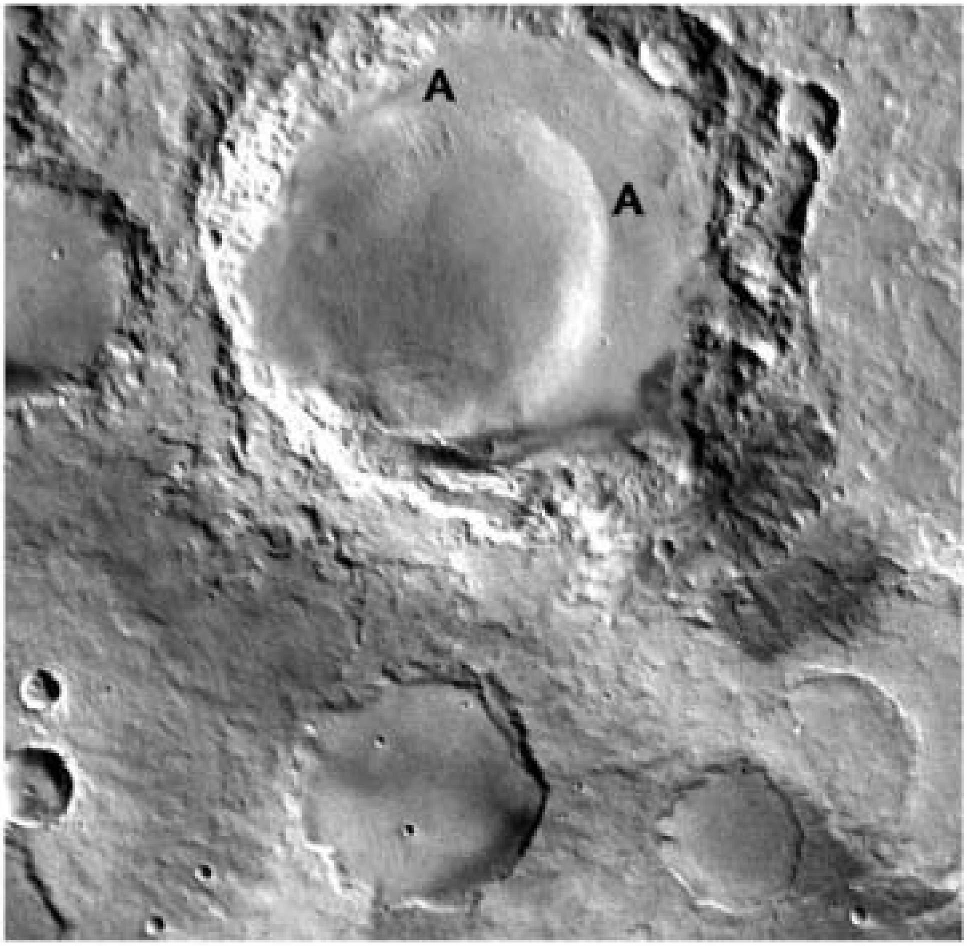

Figure 6. A high albedo deposit (A) blankets the bottom of a crater at 3° S, 336° W in a part, 125 km wide, of the Viking mosaic centered at 5° S 337° W. Compare with Figure 1 of Williams and Zimbelman (1994)

shown that the evaporites' (?) source area is interlayered with volcanics which, on the basis of crater counts, can be confidently ascribed to very old Martian crust. Finally, it must be added that Grimm and Solomon (1986) do not find the theoretical tectonic signatures that should be present on Mars if true polar wander had taken place.

Briefly, we find no solid arguments for the graben and wrinkle ridges of Arabia Terra being associated with one or more large impact basins or with abrupt changes in planetary obliquity. While similar structures do exist in Tharsis (the graben of Alba and Tantalus Fossae, or the wrinkle ridges of Lunae Planum, for instance), it should be stressed that they can be explained as consequences of the construction of the dome itself (Grimm and Solomon, 1986; Smith et al., 1998). The absence of such a volcanic construct in or near Arabia Terra calls for a different explanation.

4. Arabia Terra as a Geologic Unit

In the 1 : 15 000 000 geologic map of Mars' eastern hemisphere (Greeley and Guest, 1987), Arabia Terra is divided among seven main geological units. The mapping criteria are chronological (crater density), structural (presence of ridges), or geomorphological (dissection by channels). The outcrops of one of the units (the 'Subdued crater unit', Npl_2), defined as one with craters partially covered by lava flows or sediments, form a discontinuous corridor which runs from the Equator at 360° W to 20° N, 330° W, by the crater Cassini, thus partially separating the northern part of Arabia Terra from the rest of the cratered highlands. But a careful examination of the Viking mosaics of this area permits us to define a continuous belt of relatively less cratered terrain separating the northern part of Arabia Terra from the rest of the heavily cratered highlands. This belt is even reflected in the Shaded Relief Map of Mars Eastern Region (USGS, Map I-1618). A sketch of this corridor is drawn in Figure 1, and Figure 7 features a tract of the belt.

To confirm this hypothesis, we performed several crater counts on this unit, as well as on northern Arabia Terra and on Noachis Terra, the cratered highland to the south. The results are plotted on Figure 8. Crater counts on Arabia Terra, the belt, and Noachis Terra, are first shown by groups (Figures 8A–C), and then compared (Figure 8D) to highlight the differences between the crater retention age of the equatorial belt and the ones deduced for the neighbouring terrains. Our presentation follows the recommendations of Hartmann (1973) and the Crater Analysis Techniques Working Group (1978). The surface areas over which the counts were conducted measured between 28 000 and 87 000 km^2. Both Viking images and Viking mosaics (all with similar resolutions, between 151 and 256 m/pixel) were used in the counting. The numerical data of the counts are listed in Table I.

The main deduction obtained from the counts is that the belt is defined by a fairly homogeneous, sparse crater population, while Arabia Terra and Noachis Terra show similar, high crater retention ages. Crater density differences, nevertheless, are minimal to nil in the diameter range up to 10 km, while they are well marked from 10 km upwards, and statistically significant in the range between 20 and 40 km. No craters bigger than 50 km have been found in the more than 200 000 km^2 counted in the belt. Following Barlow (1988, 1995) and Hartmann (pers. comm.), we explain the coincidence of the cratering curves for small diameters as the result of crater obliteration, mainly by dust sedimentation but also by volcanism and ejecta cover.

As for the differences in frequency of bigger craters between the belt and the highlands to the north and south of it, we think they require a more significant process. We propose that an important resurfacing event took place in an equatorial,

Figure 7. Sparsely cratered terrain between Arabia and Noachis Terra. Viking mosaic, 230 km wide, centered at 25° N 342° W.

curved corridor almost 4000 km long and 600 to 800 km wide in Arabia Terra. It is interesting to note that the belt shape closely follows the shape of the northern border of Arabia Terra itself, as can be seen in Figure 1. From the belt surface aspect, with broad flat plains without noticeable volcanic constructs, we surmise that the resurfacing event was most probably a fissural volcanic episode.

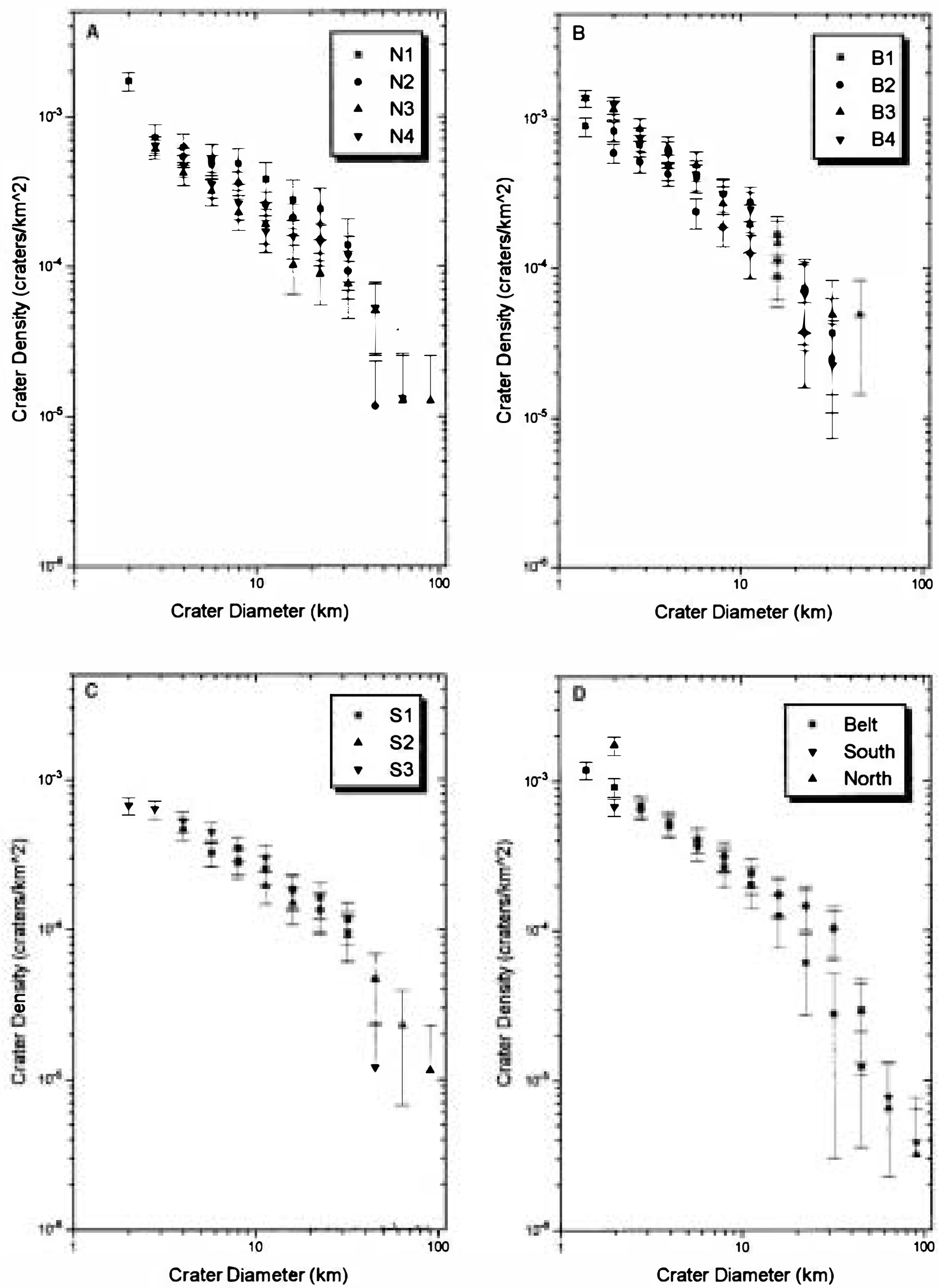

Figure 8. Crater counts plots. A is a plot of the four counts performed at northern Arabia Terra (points N1 to 4 in Figure 1). Similarly, B and C are plots of the counts at the resurfaced belt (points B1 to 4) and at Noachis Terra (points S1 to 3). D is a combined plot of the means of each of the units, for a comparison of crater densities.

TABLE I

Characteristics of the crater counts

Count	Image	Coordinates	Surface (km^2)	Resolution
N1	Viking 529A25	33° N 346°	28 900	151 m/pixel
N2	Photomosaic MI30N322	30° N 322°	85582	231 m/pixel
N3	Photomosaics (*)	25° N 305°	78680	231 m/pixel
N4	Photomosaic MI30N292	30° N 292°	75950	231 m/pixel
B1	Viking 369S05	10° N 355°	53 954	206 m/pixel
B2	Photomosaics (*)	25° N 335°	79370	231 m/pixel
B3	Viking 339S23	20° N 318°	40 738	179 m/pixel
B4	Viking 339S50	16° N 311°	44460	187 m/pixel
S1	Photomosaic MI10S342	10° S342°	86330	231 m/pixel
S2	Photomosaic MI05N322	5° N 322°	87 153	231 m/pixel
S3	Viking 393S01	14° S 312°	83324	256 m/pixel

* These crater counts were made using a combination of the photomosaics around those locations.

5. Discussion: Plate Tectonics Traces in Arabia Terra?

This linear volcanic episode could suggest an important regional event of lithospheric tension. The only hypothesis explaining important tangential tectonic stresses on Mars (unrelated to domes or basins) has been put forward by Sleep (1994), who advocates a limited two-plate tectonics which would have been at work for a short interval in the northern third of the planet. The stage of lithospheric mobility on Mars came to a stop when the lowlands ridge collided against Tharsis and Arabia Terra (Sleep, 1994, plate 4); but the previous subduction under Arabia Terra could explain both its tectonic structures and the equatorial, less cratered belt. The wrinkle ridges would be conjugate sets of compressional fractures produced by the subductive push from the north, while the graben and the equatorial resurfacing would be the expression of a tensile stress field generated by a limited back-arc spreading (Figure 9). Although the final destination of Earth back-arc basins is to disappear through compression, the crosscutting of wrinkle ridges by graben in Arabia is thought to mean that the last movements in this section of the Martian lithosphere were tensile. The limited time span (~100 Ma) proposed by Sleep (1994) for his advocated subduction could explain why stresses came to a stop at an immature stage of the margin.

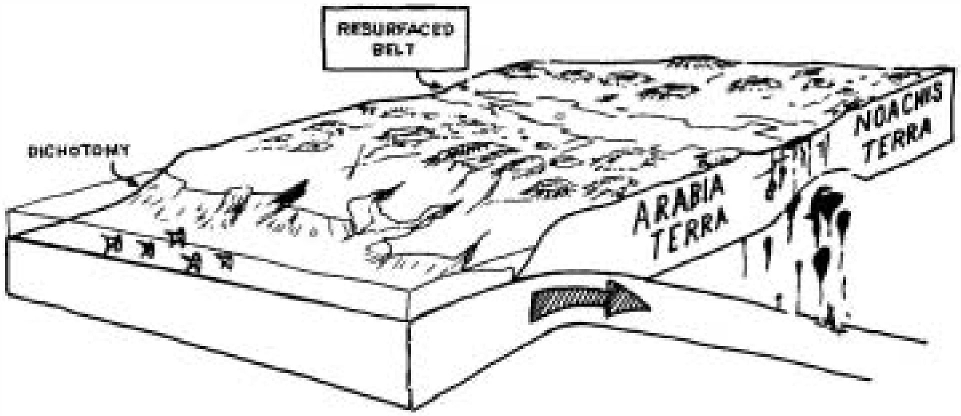

Figure 9. Cartoon showing the back-arc hypothesis for the resurfaced belt.

The main differences of this putative Martian plate tectonics as compared to Earth plate tectonics are the absence of megashears (and, in general, of strike-slip structures) and of a volcanic chain over this part of the proposed subduction zone. The first circumstance (the scarcity of strike-slip faults on Mars) has been stressed by Golombek (1985) and Forsythe (1989). According to the first author, this fact is due to the very shallow crustal levels where stresses are concentrated, thus favoring vertical maximum compressive stresses and normal faults. This topic deserves further study, since Forsythe and Zimbelman (1988) stated that their finding of a strike-slip fault set at Gordii Dorsum seems to require a certain degree of lithospheric mobility on Mars.

Regarding the volcanism, Sleep (1994) interprets the Arabia ridged plains as the product of an arc. This is likely for the northernmost plains, close to the dichotomy; but the resurfaced belt, which is ~1200 km from the boundary, must be explained by a process (such as back-arc spreading) able to generate magmas at hundreds of kilometers from a destructive margin. The back-arc active centers in the Marianas and in the Sea of Japan, for instance, are 400 and 800 km distant from the respective trenches (Karig et al., 1978; Toksöz and Hsui, 1978). In the case of Arabia, the long distance from the margin to the proposed back-arc basin would require a very shallow subduction, in agreement with the highland nature of the slab supposedly subducted at the Arabia margin (Sleep, 1994).

A prediction of our hypothesis is that the resurfaced belt would show a positive gravity anomaly, as the rigid martian lithosphere under Arabia Terra, though stretched, could not be deflected under the volcanic load. The limited precision of the present Martian gravity data hinder the geophysical confirmation of the individuality of Arabia Terra. Nevertheless, a relative gravity maximum can be found along the eastern part of the belt in the best gravimetric map available (Smith et al., 1994). The new generation of geophysical data already coming from Mars Global Surveyor will certainly add to our understanding of Martian tectonics at both the local and the global scales. For the moment, the preliminary results of laser altimetry provided by Mars Global Surveyor (Smith et al., 1998) show that the northern hemisphere of Mars is as smooth as Earth's abyssal plains, and are thus in accordance with Sleep's hypothesis. A scheme that in turn corresponds nicely to one of the classical basic ideas of comparative planetology, the 'plate tectonics window' of Condie (1989).

6. Conclusions

1. The northern sector of Arabia Terra is limited by the dichotomy and by a belt in which significant resurfacing has taken place.
2. The dense network of graben and wrinkle ridges in Arabia Terra could be explained by a N–S-directed stress field (first compressional, then tensile) caused by a limited subduction under Arabia Terra, as proposed by Sleep (1994).
3. The resurfaced belt would correspond to an incipient back-arc system, conceived as an addition to the hypothesis of Sleep (1994).
4. We therefore interpret the dichotomy as a palaeoplate border.
5. The chaotic rotational instability of Mars is not supported by Arabia Terra palaeoclimatic evidence, both published and new.

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