Chasma Boreale, Mars: A Sapping and Outflow Channel with a Tectono-thermal Origin

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A detailed geomorphological study of Chasma Boreale, a widely known feature of Mars' north polar cap, has been carried out for the first time, along with a quantitative paleohydrological model. It is concluded that the chasma was eroded by a flow whose discharge was on the order of magnitude of 10^9 m sec^{-1}. This catastrophic flow is thought to have been preceded by a powerful sapping process, caused by a tectonically focused thermal event. Several lines of evidence indicate tectonic control in the distribution and present aspect of most of the polar troughs. This tectonic forcing probably played a major role in the inception of not only Chasma Boreale but also other polar reentrants as well.

INTRODUCTION

Chasma Boreale (Fig. 1) is the largest of the polar reentrants carved in the glacial sediments (polar layered deposits, or PLD) that cover Planum Boreum, the geographical designation of Mars' northernmost latitudes. It is a broad depression 600 km in length, 200 km in width at its distal area, and up to 500 m in depth, which cuts across the outward-spiraling polar troughs.

The first concrete hypothesis regarding Chasma Boreale (Wallace and Sagan 1979) advocated a fluvial origin, envisioning an ice-choked, Arctic-type river catastrophically fed by an ice-covered lake disrupted by an impact. This model was based on the Mariner 9 Mars maps, where the apparent head of Chasma Boreale was interpreted as an impact crater. Then, the Viking images showed the crater did not exist, and other questions were raised over the feasibility of the subglacial river.

Clifford (1980, 1987) has studied in detail the mechanisms for a catastrophic water release from the permafrost, looking for analogs on both Earth and Mars. His comparison with Ravi Vallis, a box-headed channel on Mars equator (1°S, 43°) is particularly compelling, because of the angular, straight head and huge flow marks. His hypothesis of glaciovolcanic outburst water flows (*jökulhlaups* of Icelandic authors) also seems appropriate, since this mechanism is able to explain the catastrophic melting of the permafrost. Nevertheless, Clifford is also skeptical of this model in that it is difficult to accept that each of the other important Mars polar reentrants (especially Chasma Australe) was also caused by a point-like volcanic event. Clifford (1987) prefers a scenario in which a subglacial lake (possibly sheltered in an impact crater or basin and sealed by the surrounding ice) grows because of the regional geothermal heat until it reaches a volume large enough to destabilize and breach the cap.

It should nevertheless be kept in mind that Chasma Boreale is by no means a typical outflow channel: no streamlined islands or anastomosing drainage patterns are observed, and there are two tall horseshoe-shaped cliffs and no chaotic terrain in its upper course. Thus, although a fluvial origin caused by a catastrophic flow is a preferred

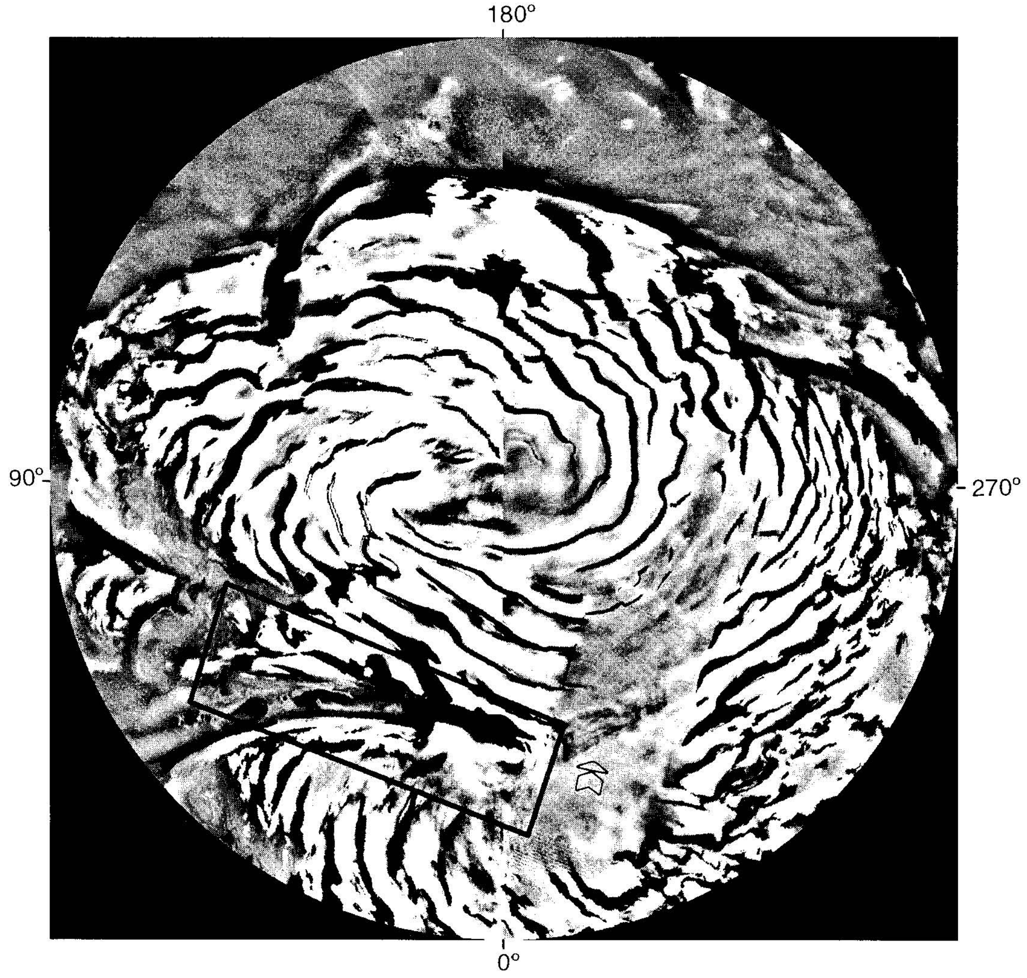

FIG. 1. Mosaic of the northern martian polar cap. Figure 2, featuring most of Chasma Boreale, is outlined. The arrow points to a series of straight troughs occurring as an uppermost extension of the chasma, and which could be related to Chasma Boreale genesis.

hypothesis to explain Chasma Boreale, little geomorphological evidence has been described. In addition, important aspects of the triggering mechanism are still unclear. Our detailed geomorphological mapping of the chasma (Fig. 2) revealed the occurrence of distinctive fluid-erosional forms that can be related to Mars and Earth analogs, thus permitting us to put forward an improved model.

CHASMA BOREALE MORPHOLOGY

The most apparent head of this chasma is located near 85°N, 0°, although a series of straight troughs 200 km long occur further east, between this point and 85°N, 325° (Fig. 1, arrow). Whether these are genetically related to the chasma is unclear from the present data. The topographic step at 85°N, 0° is an erosive scarp which constitutes the most outstanding feature of the upper part of the chasma. This part is different from the middle course with outflow marks and from the outwash plain at its distal parts.

Chasma Boreale's uppermost course comprises a short and dark polar trough striking 345°, strongly curved in its northernmost part. About 70 km further down slope (at 85°N, 0°; Fig. 3, *a*), Chasma Boreale's main scarp can be identified. It is an amphitheater about 1 km high and 50 km wide, with straight frontal and southern scarps striking at a right angle. Viewed in favorable lighting (as, for instance, on Viking Orbiter frame 57B44), a hard layer seems to cap the cliff. The presence of transverse head cuts caused by concentrated groundwater outflow is one of the features characteristic of sapping (Baker and Milton 1974). The scarp bottom area contains a transversal dune field indicating a down-channel main wind direction, the one followed by the strong winds that seasonally blow over Planum Boreum (Tsoar *et al.* 1979, Thomas and Weitz 1989).

At 85°N, 17°, about 100 km further down the main scarp, a second one (Fig. 3, *b*), 45 km in width and with a semicircular planform, can be found. The scarp

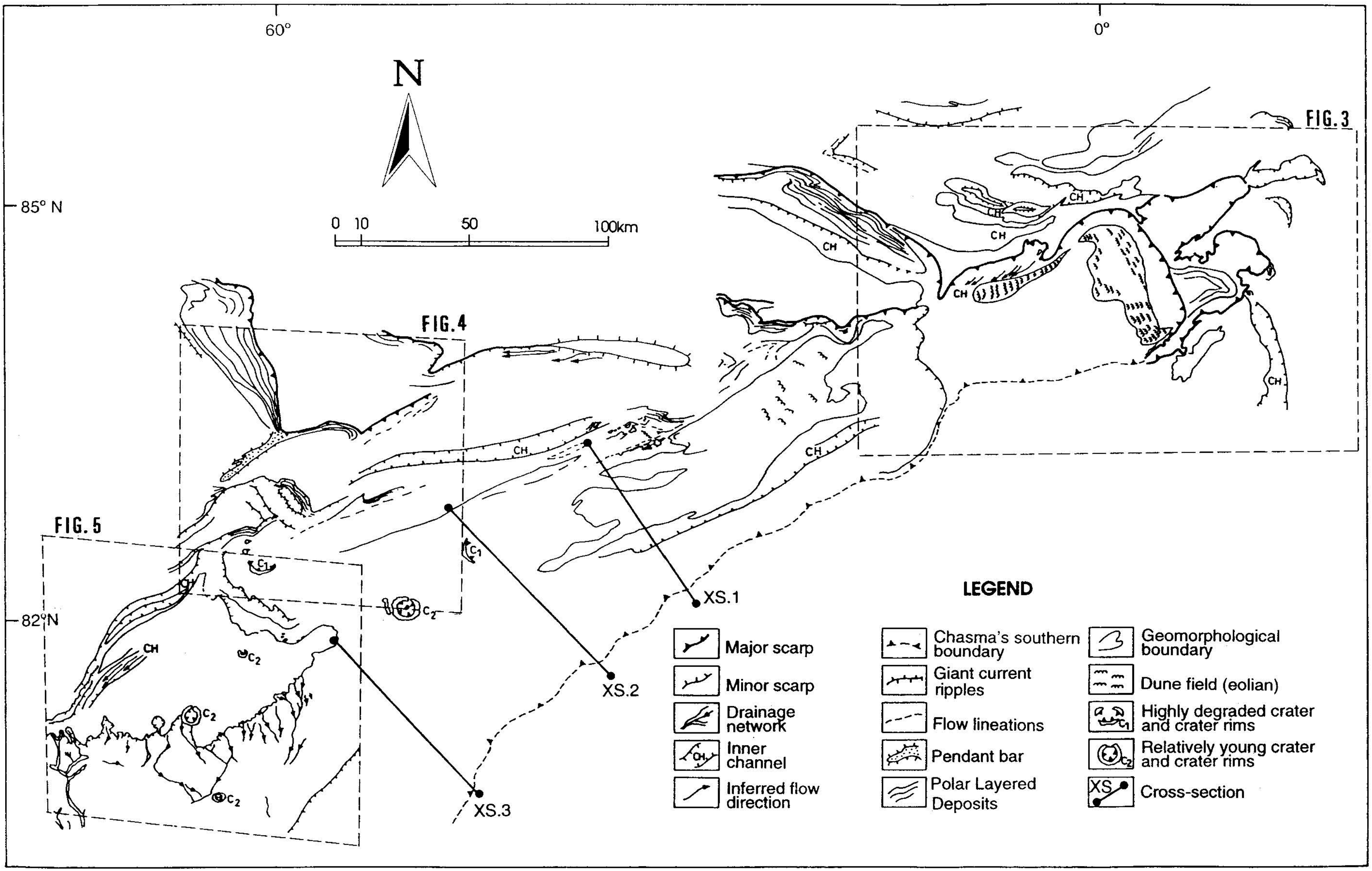

FIG. 2. Geomorphological map of Chasma Boreale. XS.1, XS.2, and XS.3 mark the locations of the cross sections used in the paleohydrological reconstruction.

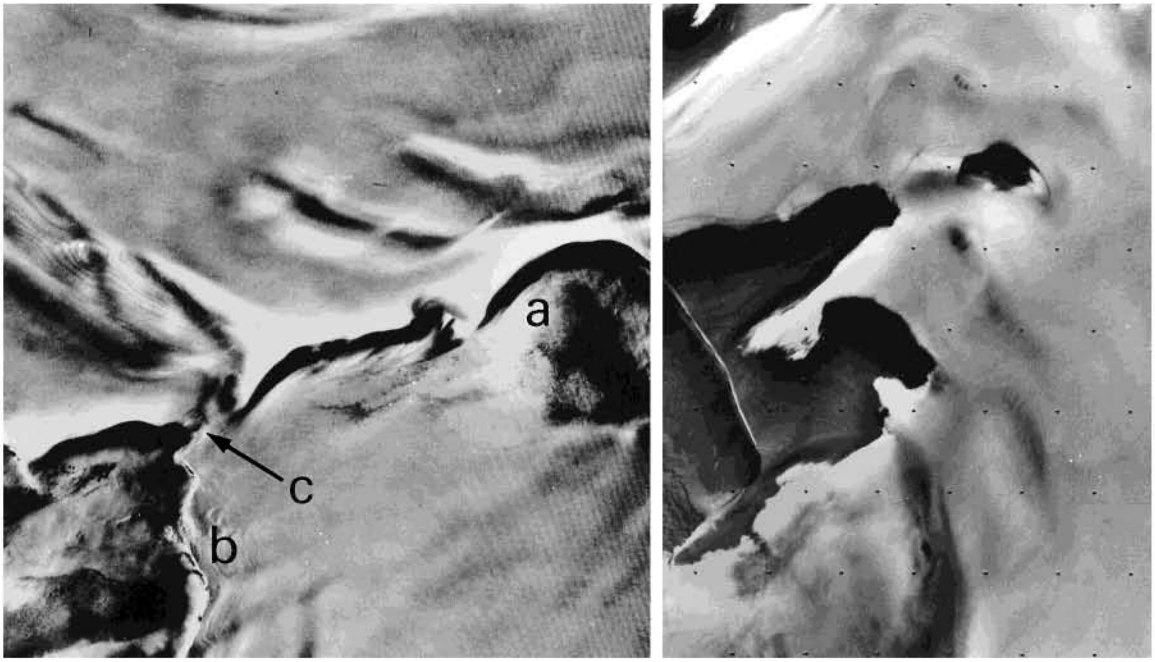

FIG. 3. Head of Chasma Boreale, showing two scarps [(*a*) a theater-like valley head at 85°N, 0°, and (*b*) a major transverse scarp in the valley bottom at 85°N, 17°] and one high-level divide crossing (*c*). Viking Orbiter frames 57B44 and 560B88.

bottom area is also covered with transverse eolian dunes apparently evolving down the channel to longitudinal ones.

The middle reaches of Chasma Boreale show erosional and depositional features with distinct shapes produced by the motion of a fluid. Regarding their origin, although these features are not as obvious water flow indicators as the typical equatorial outflow channel features, their overall assemblage and spatial relationships suggest catastrophic flooding by water as the most plausible explanation. These features are located along the chasma northern margin, where they may be associated with shallower flow conditions. The most noticeable of these features are straight or sigmoid-shaped inner channels, 25 to 100 km in length, up to 6 km in width, and 200 m deep (Fig. 4), presenting a distinct hydrodynamic shape. The martian inner channel development can be related to the generation of macroturbulent eddies superimposed on the average motion of deep, fast-moving boundary layer flows (Baker 1979). These inner channels are found along the chasma's irregular northern boundary, providing numerous points for possible flow separation, where turbulent shear stresses may generate longitudinal vortices. Furthermore, the geometry of these inner channels is consistent with this longitudinal pattern of vorticity, in which the sigmoidal shape may result from a change in the sense of helicoidal rotation.

Longitudinal grooves and other erosional flow lineations such as scour marks are developed around flow obstacles (Fig. 2). They have been described and mapped in Kasei and Maja Vallis by Baker and Kochel (1979) within similar settings. These erosional features are consistent with the local flow lineations (Figs. 4, 5). The main transversal bedforms developed on the chasma's floor include cataracts and giant current ripples. The major transverse scarps (85°N, 0°; 85°, 17°; see Fig. 3) develop by headward recession of subfluvial cataracts, which on the Earth are a common feature of catastrophic flooding (see Baker 1978 for the Late Pleistocene Missoula flooding). Unique flow features of Chasma Boreale are the trains of giant current ripples developed on the lee side of an erosional scarp (Fig. 4, *b*). This scarp represents a bed irregularity producing a regular downstream perturbation that gave rise to three trains of ripples.

Evidence for depositional forms are present in Chasma Boreale, although they are not the most common flood features. The most outstanding one is an elongate hydrodynamically shaped pendant bar up to 30 km long (Fig. 4, *c*) which developed on the lee side of a major scarp overtopped by the flooding. The extraordinarily large dimensions of this form provide excellent indications of flood depositional landforms which are rarely described in martian channels. The flow also scoured high-level divide crossings (for instance, *c* at Fig. 3) and spilled into relatively high marginal areas, forming deep troughs or inner channels. These divides establish the lower limit for the high-water elevations used in the discharge estimates described below.

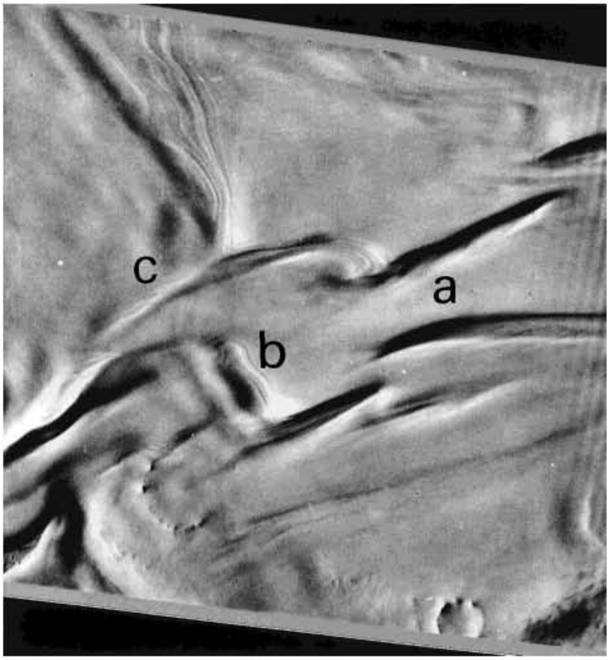

FIG. 4. Longitudinal grooves (*a*), giant current ripples (*b*), and pendant bar (*c*) on Chasma Boreale middle course. Viking Orbiter frame 560B45.

Viking images do not resolve very small features on the bottom of the troughs, except for a barchan field on the floor of one of them (Fig. 5, *a*): it seems probable that the eolian sediments pervading Planum Boreum (Cutts 1973a, b, Cutts *et al.* 1976) have mantled all but the largest features. Trains of transverse eolian dunes are also found at the foot of one of the channel walls (Fig. 5, *b*).

The broad, terminal part of the channel is characterized by the disappearance of these flow markers. Here a geological unit other than the polar laminae (namely, the plains unit) crops out under the form of hard layers, which form the channel wall. The channel floor exhibits dendritic and polygonal patterns (Fig. 5, *c*). The latter ("grooved member" of Tanaka and Scott 1987) are ascribed by McGill (1985) and by Lucchitta *et al.* (1986) to contraction and compaction of the sediments. The latter authors remark that this type of sediment is systematically associated with the outflow channel mouths. In places it is difficult to tell this polygonal pattern from braided channels of subglacial or proglacial origin; but many tracts that follow the general slope are clearly drainage features. Only one example of a possible esker (on Viking frame 560B62) was found, in accordance with the paucity of these features on soft sediments postulated for the Earth by Clark and Walder (1994).

A late erosive episode is apparent at the mouth of Chasma Boreale: the polygonal terrain is crossed by a scarp showing evidence of mass wasting. An amphitheater-shaped head is shared by this terrain and the plains unit, making clear that the chasma outwash plain was subjected to the same erosive processes as the substratum, in which residual mesas surrounded by debris aprons are the predominant morphology.

The age of Chasma Boreale carving could bear in a relevant way on the theories of Mars' palaeoclimatic evolution (Baker 1985). Cutts *et al.* (1976) have discussed the reasons for the absence of fresh impact craters on the polar layered deposits, putting forward two hypotheses: either the craters are selectively destroyed in the polar region, or this area suffered severe landscape modifications in the very recent past. We have located a small population of exhumed impact craters between 1 and 13 km across on the floor of Chasma Boreale. Their occasionally very good state of preservation (see Figs. 4, 5) argues against the first of the mechanisms proposed by Cutts *et al.* (1976) and, therefore, lends strong support to the possibility that important landscape changes have taken place very recently on Mars.

TECTONO-THERMAL OUTFLOW HYPOTHESIS

The evidence in Chasma Boreale of erosional and depositional flow features similar to the ones described for equatorial martian outflow channels by Baker and Milton (1974), Baker and Kochel (1979), and Robinson and Tanaka (1990) indicates a catastrophic flow origin. Strong

FIG. 5. Barchans (*a*), transverse dunes (*b*), and braided drainage patterns and polygonal sediments (*c*) on Chasma Boreale middle to lower course. Viking Orbiter frame 560B44.

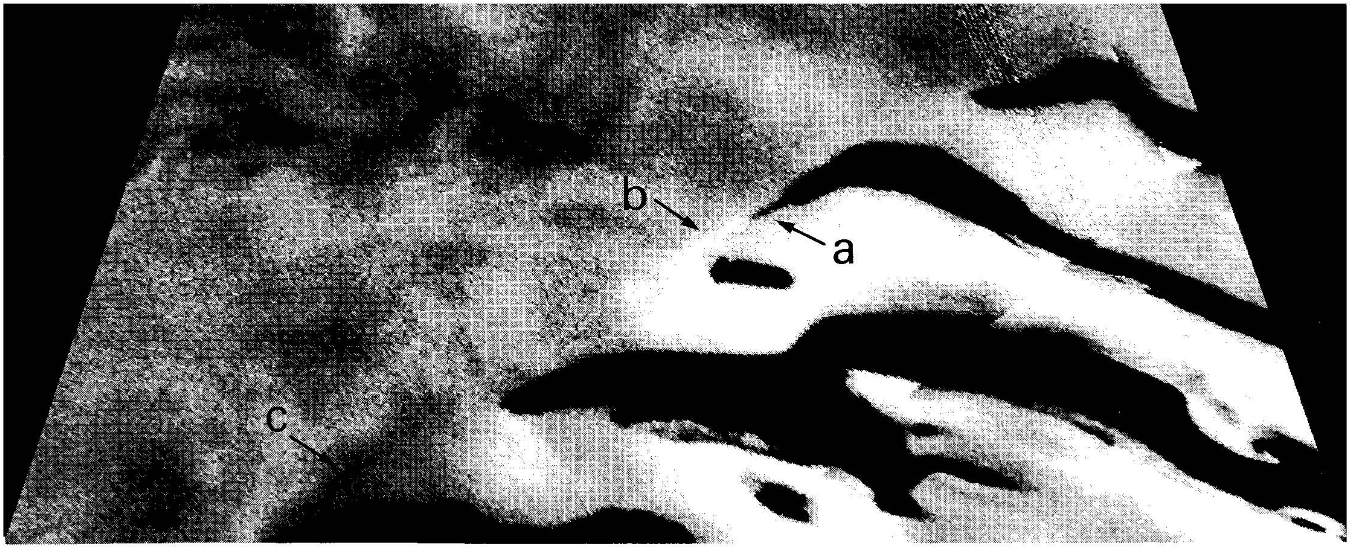

FIG. 6. Part of the Viking mosaic centered at 85°N, 320°, where Thomas and Weitz (1989) pointed out the linearity of the ends of a series of polar troughs. Note the spitted end of the trough at *a*, its linear extension at *b*, and the linear spur of the trough at *c*. All these features suggest a tectonic control.

points for this hypothesis are the longitudinal grooves, inner channels, giant current ripples, and bars, as well as the braided pattern in sediments at the chasma mouth.

Notwithstanding this, the chasma does not share some of the most characteristic features of this type of flow, such as an anastomosing drainage pattern with streamlined hills and other flow features. This means, for instance, that the Lake Missoula flooding model (Baker 1973, O'Connor and Baker 1992, Benito 1997) or other outflow examples like the Kuray Lake in Siberia (Baker *et al.* 1993) cannot be applied to Chasma Boreale without modifications. The model to be proposed must explain these peculiarities.

Ravi Vallis can be considered a paradigmatic example of an outflow channel whose origin is acceptably well understood. From its amphitheater-like valley head, clearly delimited by a fault, vast quantities of fluid were delivered in a probably thermal event. Nevertheless, there are no volcanic constructs in this area of the martian equator, so that a deep magmatic heat source has to be considered. When trying to apply this model to Chasma Boreale, we must admit that the tectonics of the martian polar latitudes is very poorly known. Thomas and Weitz (1989) stated that this had to be considered "a puzzle for future exploration." These authors, nevertheless, pointed out some apparently tectonic features (Fig. 6) that seem to influence the geometry of the dark spiral areas. In Fig. 7 we project a set of lineations on the basis of two criteria: linear scarps or troughs which form sets of parallel, frequently en echelon lineations; and angular bends or linear-trending terminations in dark spirals. The structural elements suggested by Thomas and Weitz (1989) fall into this last category.

A total of 248 lineations were measured. When projected on a rose diagram (Fig. 7, *c*), they show two general maxima peaking at 40° and 110°. The first direction is that of Chasma Boreale's middle course; the second one is followed by, for instance, the transverse ridge in Fig. 4.

The detection of these structural trends could bear significantly on the origins of Chasma Boreale. In reference to Fig. 7, we propose that at least part of the chasma was carved along a fault system and that the straight cliff at 85°N, 0° has a tectonic origin. The structural lines would play the same role as in Ravi Vallis: to bring the heat of a magmatic focus to the base of the polar cap. The localized melt would lead to a structurally conditioned, linear subglacial flow which would in turn induce a powerful sapping action. On the basis of his experimental work, Howard (1978) concludes that the morphology of sapping-modeled scarps is conditioned by the rate between depth and length of the underground flow and also by the magnitude of the critical flow needed to initiate erosion. The head width (some 50 km in our case) is proportional to the rate of sapping flow; this is a good measure of the importance of sapping in Chasma Boreale, since the heads of sapping-generated valleys in Hawaii measure 2 to 5 km (Kochel and Piper 1986).

In some areas, like that at 85°N, 0°, a structural intersection (noticeable in the strike change of the chasma at this point, see Fig. 1) would favor the inception of volcanism, with the formation of a subglacial lake. The provisions of the model put forward by Clifford (1980) would then follow, since the breaching of the lake with its catastrophic discharge would be associated with a subglacial volcanic

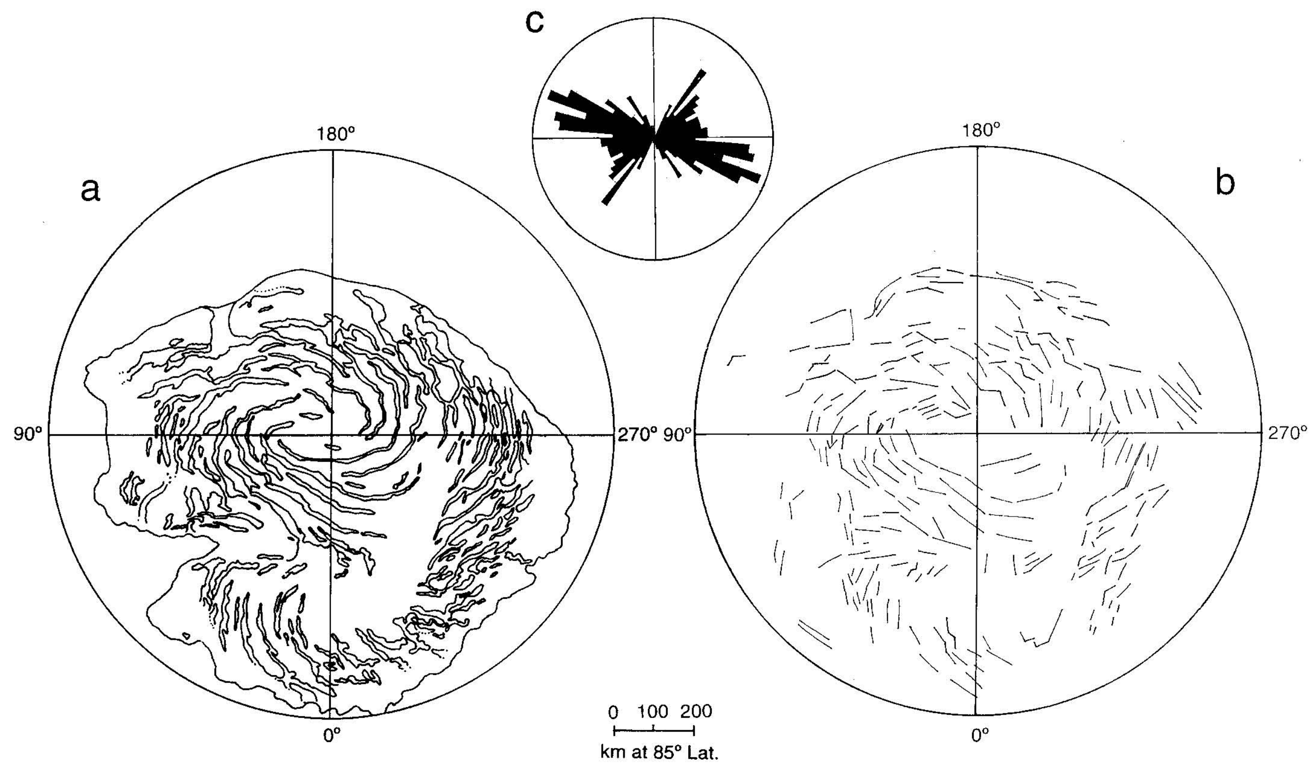

FIG. 7. Polar scarps (a), lineation map (b), and rose diagram (c).

eruption, as in Icelandic *jökulhlaups* (e.g., Nye 1976). An outcome of this model is that a geothermal flux over the mean could be expected along Chasma Boreale. On the contrary, and in view of the magnitude of the erosion implied, we have doubts about the existence under the northern martian ice caps of nonvolcanic basal lakes (like those detected under the Antarctic cap by Oswald and Robin 1973) which could explain the origin of Chasma Boreale.

It is also important to note that the discharge (or discharges) would act over a linear tract weakened by sapping; in our view, this is the best explanation of the linear, relatively contained nature of this outflow channel, in contrast to the classic martian or terrestrial examples (Table I).

PALEOHYDROLOGICAL RECONSTRUCTION

To calculate the characteristics and magnitude of the flow released through Chasma Boreale, a paleoflow reconstruction was performed on the basis of the Mars Digital Model data. The main uncertainties inherent to the model are two: the estimation of the elevation reached by the flow, and the poor definition of the topography (Fig. 8), resulting in a lack of precision of the slope and cross-section data. Given these conditions, the reconstruction has to be considered as only an approximation of the order of magnitude of the flow.

The Manning equation, modified according to Komar (1979) to take into account the smaller gravity existing on Mars, has been used in the calculation of the velocity and discharge of the flood. The flow average velocity is given by the expression

$$v = (g_m Rs/C_f)^{1/2},$$

where v = velocity of the flow (m $\sec^{-1}$), g_m = Mars' gravity (m^2 $\sec^{-1}$), R = hydraulic radius = wetted area/wetted perimeter (m), s = channel bed slope (m m^{-1}) C_f = a coefficient defined as the

$$C_f = g_e(n^2 R^{-1/3})$$

[g_e = Earth's gravity (m^2 $\sec^{-1}$), n = Manning roughness coefficient].

Three cross sections (Fig. 8) in areas with the most representative valley morphology have been used for the discharge estimation. These cross sections include only the main channel, where most of the flow was conveyed, since in the marginal areas the secondary flow and vorticity cannot be taken into account in the calculations. In each sec-

TABLE I
Sapping Characteristics for Mars and Earth Analogs

		Mars	
	Earth	Nirgal Vallis	Chasma Boreale
Genesis	Groundwater outflow undermining slopes (spring sapping)	Groundwater constant outflow fed by active hydrological cycle	Groundwater outburst: subglacial lake outburst
Geology	Slopes with resistant materials	Volcanic flows and unconsolidated cover	"Soft cohesive" polar layered deposits
Flow mechanics	Noncatastrophic	Noncatastrophic	Catastrophic
Sapping valley morphology	Elongate basin shape	Idem	Idem
	Low network drainage density	Idem	Idem
	Low degree of interfluve intersection	Idem	Idem
	Widely spaced and short tributaries	Idem	No tributaries
	Theater-like valley heads	Idem	Idem
	Local structural control	Idem	Idem
	Steep-sided valley walls meeting valley floor at sharp angles	Idem	Idem
References	Colorado Plateau (Laity and Malin 1985); Hawaii Islands (Baker 1990)	Milton 1973, Pieri 1976, Mars Channel Working Group 1983, Baker 1985	Clifford 1980, 1987; this paper

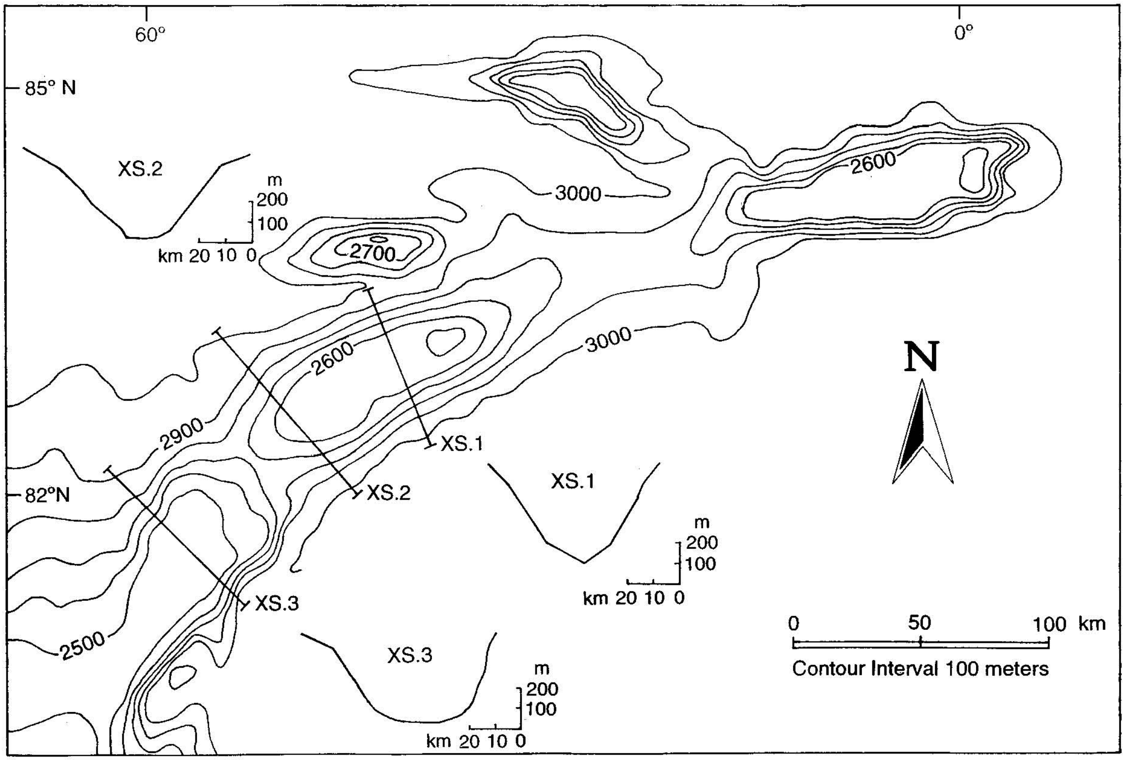

FIG. 8. Contour lines for Chasma Boreale obtained from the Digital Mars Model data, with the cross sections where discharge estimations have been carried out.

TABLE II
Hydraulic Parameters Used in the Sensitivity Test for the Cross Sections XS.1, XS.2, and XS.3

n	v (m sec^{-1})	Q (10^8 m^3 sec^{-1})
0.01	XS.1 = 26	XS.1 = 4.2
	XS.2 = 21	XS.2 = 3.1
	XS.3 = 26	XS.3 = 5.0
0.02	XS.1 = 13	XS.1 = 2.1
	XS.2 = 11	XS.2 = 1.6
	XS.3 = 13	XS.3 = 2.5
0.03	XS.1 = 9	XS.1 = 1.4
	XS.2 = 7	XS.2 = 1.0
	XS.3 = 9	XS.3 = 1.7
0.04	XS.1 = 6	XS.1 = 1.0
	XS.2 = 5	XS.2 = 0.8
	XS.3 = 7	XS.3 = 1.3
s (m m^{-1})	v (m sec^{-1})	Q (10^8 m sec^{-1})
0.0001	XS.1 = 10	XS.1 = 1.7
	XS.2 = 9	XS.2 = 1.2
	XS.3 = 11	XS.3 = 2.0
0.0005	XS.1 = 23	XS.1 = 3.7
	XS.2 = 19	XS.2 = 2.8
	XS.3 = 24	XS.3 = 4.5
0.001	XS.1 = 33	XS.1 = 5.3
	XS.2 = 27	XS.2 = 4.0
	XS.3 = 33	XS.3 = 6.4
0.005	XS.1 = 73	XS.1 = 11.2
	XS.2 = 60	XS.2 = 8.8
	XS.3 = 74	XS.3 = 14.3
d (m)	v (m sec^{-1})	Q (10^8 m^3 sec^{-1})
−50	XS.1 = 10	XS.1 = 1.3
	XS.2 = 9	XS.2 = 1.0
	XS.3 = 10	XS.3 = 1.6
−100	XS.1 = 9	XS.1 = 1.0
	XS.2 = 8	XS.2 = 0.7
	XS.3 = 10	XS.3 = 1.3

tion, the maximum and minimum heights reached by the flow were established according to the geomorphic flow marks. Expanding or contracting sections have been discarded, since these changes in morphology could denote topography inaccuracies. In addition, in these expanding or contracting reaches it is crucial to know in detail the channel bed slope, information that is presently unavailable.

Three factors are of great importance in the calculation of the velocity and discharge: the roughness coefficient (n), the channel slope (s), and the depth reached by the flow, referred to an initial estimate of water surface elevation (d). A sensitivity analysis for each of these factors was performed using the following ranges of values: 0.01 to 0.04 for n, 0.0001 to 0.005 for s, and 0 to -100 for d. The results obtained are shown in Table II.

It can be observed that the factor that most directly controls the magnitude of the discharge is the slope of the channel bed, while the maximum height reached by the flow introduces a relatively low degree of uncertainty. The roughness of the bed shows an influence intermediate between those of the other two analyzed factors. The impossibility of determining precisely the slope of the channel bed results in the broad variability of calculated velocities and discharges.

The obtained velocity figures oscillate between 5 and 74 m sec^{-1}, while the resulting discharge values oscillate between 0.8×10^8 and 14.3×10^8 m^3 sec^{-1}. Other paleoflow reconstructions for Mars (Robinson and Tanaka 1990, Komatsu and Baker, *in press*) have resulted in velocity values between 32 and 75 m sec^{-1}, and between 25 and 149 m sec^{-1} respectively. Based on these results and those obtained for paleoflood reconstructions completed on Missoula-type floods (O'Connor and Baker 1992, Baker *et al.* 1993, Benito, 1997), it seems that the lower velocity values are too low and those around 30 to 50 m sec^{-1} are more realistic. Assuming this, the most likely discharges conveyed through Chasma Boreale would be around 10^9 m^3 sec^{-1}, of a magnitude similar to those obtained by Robinson and Tanaka (1990) and by Komatsu and Baker (*in press*) for Kasei and Ares Vallis, respectively.

DISCUSSION

The fact that no volcanics crop out in the area is not considered a serious handicap for the tectono-thermal outflow hypothesis, since the considerable thickness [up to 4 to 6 km, (Dzurisin and Blasius 1975)] of the PLD, and its recent dynamics, could easily obliterate any surficial trace of the activity. Grjothfjall, a horseshoe cliff in northern Iceland, could be a good terrestrial analog of the features at 85°N, 0°, since it has been interpreted (Thorarinsson 1960) as the result of a subglacial eruption of Kverkfjöll, a volcano buried under the ices of Vatnajökull. In fact, all Chasma Boreale could be paralleled by *Jökulsá á fjöllum* (which includes the well-known Ásbyrgi Canyon) an almost 200-km-long canyon carved in the faults of the northern Iceland rift zone, and which includes not only Grjothfjall but also several large Icelandic waterfalls, such as Dettifoss and Selfoss.

We have not found any criteria to define whether there was one or more subglacial avalanches. In any case, it seems reasonable to suppose that important subglacial sapping processes were active before the chasma was finally carved out. Although the outflow would erase most traces of sapping, we still have the characteristic alcove reentrants (see for instance Fig. 3, *b*), reminiscent of the Hawaiian examples cited by Kochel and Piper (1986). The eolian mantling would complete the geomorphological partial masking of the outflow.

As for the structural control on the polar troughs, the paucity of tectonic data for the PLD makes it difficult to assess this idea. On Earth, we could be reasonably sure that perfectly straight features like some polar scarps are structurally controlled. On Mars, we are hindered by the lack of in-depth understanding of the mechanisms through which the polar scarps are formed. The suggestion by Howard (1978) of a dynamical equilibrium between ablation and deposition, which has reached some consensus, would seem to require mobile scarps, and so to run counter to the idea of structural control. Nevertheless, the hypothesis that linearity is a consequence of the erosive straightening of initially randomly shaped slopes appears to us far less convincing. Structural control (Figs. 6, 7) seems compelling in explaining not only the straight, sharply turning scarps, but also other features such as the many scarps finishing at a straight line hundreds of kilometers long. Thomas and Weitz (1989) suggested tectonic control for the 500-km scarp running from 270° to 340°, a giant structure difficult to form through ablation and which, under close examination, shows features suggesting tectonic control, as seen in Fig. 6. Either we need new hypotheses on scarp genesis, or the present straight scarps were formed through parallel erosion of former fault planes. As for the mechanical aspects, the fact that the polar temperatures can be as low as 140 K probably means that even sediments behave as hard rock when subject to stresses.

The origin of these stresses is another matter for speculation. Chasma Boreale's lower course and parts of Alba Fossae graben share a N15°W trend. Nevertheless, it is rather dubious that this coincidence could be significant, since most authors who have studied Tharsis region tectonics (see, for instance, Carr 1974, Wise *et al.* 1979, Solomon and Head 1982, Plescia and Saunders 1982, Watters and Golombek 1989, Tanaka *et al.* 1991) postulate a series of stresses originating near the center of the dome and with a more or less radial area of influence. With the data in hand, there is no basis to extend this influence up to Planum Boreum.

A perhaps more promising idea would be to relate the lineations to tectonic stresses proper of the polar area. One of the few proposals for "autochtonous" tectonics in Mars' northern lowland plains is that by Sleep (1994), who put forward an outrageous but stimulating hypothesis in which the low northern third of Mars was an old "oceanic" lithospheric plate. Though contradicting the present orthodoxy, this hypothesis could provide the frame over which to hang these first tectonic hints to reconstruct the history of Planum Boreum: a history (common by terrestrial standards) of older tectonism conditioning a young landscape. The test of this hypothesis will have to come from the new generation of image data.

CONCLUSIONS

1. Geomorphological mapping of erosional as well as depositional features indicates the fluvial origin of Chasma Boreale.
2. Sapping is indicated as the first main process in the carving of the chasma, which subsequently reached its present relief through one or more catastrophic discharges. This double mechanism explains the overall morphology of Chasma Boreale, which has only some characters in common with equatorial outflow channels.
3. Tectonic structures could have been influential in the genesis of Chasma Boreale. We contend that deep faults, probably associated with a geothermal system, determined polar basal melting (which resulted in linear sapping), followed by cataclysmic flood outflow through subglacial eruptions of the *jökulhlaup* type.
4. The present model for Chasma Boreale could be connected with recent ideas of limited lithospheric mobility on Mars. Future improved image coverage will provide data essential for confirming or rejecting this hypothesis.

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