Introduction: The existence of an ancient “Oceanus Borealis” in the Northern Lowlands (NL) of Mars, postulated on the basis on the global resemblance of the NL to the ocean bottom and on the position of alleged shorelines [1], has been constantly reexamined on several grounds: the global dichotomy of Martian crust, the presence of wide flow channels at the boundary between Noachian-Hesperian and Amazonian terrains, the smoothness of the NL, the sedimentological nature of the Vastitas Borealis formation [2]. More recent observations in favour of the ancient ocean include the analysis of dielectric soil properties in the northern lowlands, detection of phyllosilicates, the position of deltaic deposit, giant polygonal fracture patterns, the basal cliffs and aureole of Olympus Mons interpreted as subaqueous morphologies [3]. On Earth, oceanic waters are incessantly set in motion by wind shear, pressure gradients, the Coriolis force, and by variations in water temperature, salinity and solid content affecting water specific gravity. Oceanic currents are also sensitive to the topography of the oceanic floor, giving rise to both shallow and deep circulation systems of huge complexity (e.g., [4]). If an Oceanus Borealis of liquid water existed on Mars, such forces under the influence of bottom topography must have been of considerable importance in the general oceanic currents system.

The erosion furrows that on Earth accompany the flow of bottom currents may provide a guideline to infer the past action of similar currents in the ancient Oceanus Borealis. Without the complication of continental masses in the northern hemisphere of Mars, analogy with the Earth allows us to envision a global current pattern directed from west to east at high latitude and a system of circulation cells near the boundary with the highlands. Because the rotation period of Mars is only slightly greater than the one of Earth, the Coriolis acceleration has comparable magnitude. The first question becomes so: is there any morphological feature on Mars indicating the possible role of bottom currents in an ancient ocean?

Observations: Curvilinear furrows with approximate E-W orientation appear in two areas of the NL: the region surrounding the impact basin of Utopia Planitia (lat. 40°-70°, long 60°-120°), and north of Alba Patera. (lat. 40°-70°, long. 220°-270°), Fig. 1A and 1B. Furrows, about 75-100 km wide and some thousand kilometers long, are rarely isolated; rather, they appear distributed in groups of parallel units separated by ridges. These features have been interpreted as tectonic [5] or volcanic [6]. Here, they are re-interpreted as erosion marks due to water flow in Oceanus Borealis.

Figure 1. A: Set of 200-m contour lines of the Northern Plains, based on MOLA altimeter data (Mars Global Surveyor) with superimposed the regions with evident furrows along-slope (AS) and along the contour (AC). B: The same area covered by MOLA shaded relief. The white rectangles show the areas magnified in Fig. 1C-E and 1F. Dotted lines indicate furrows directed along the slope, continuous lines those along the topographic contour. C: MOLA map of the region north of Alba Patera, exhibiting parallel furrows separated by 30-50 m high levees. D: Section down slope (approximately S-N) and nearly perpendicular to furrows shows the geometry of at least four furrows separated by topographic heights (ridges), indicated with the letter “R.” The section is the thick line in Fig. 1C. E: Section parallel to one of the furrows from west to east. The “peaks” indicated with letters “P” are in reality extremely smooth features, considering the huge vertical exaggeration. F: furrows in the region surrounding the giant impact basin of Utopia Planitia (THEMIS, NASA/JPL-Caltech/Arizona State University).

Figure 1C shows the topography of furrows in the region North of Alba Patera. A North-South cross section perpendicular to furrows (black line in Fig. 1C) shows the presence of at least 4 units separated by ridges (“R”, Fig. 1D). Furrows are perched along the flanks of Alba Patera, approximately parallel to the contour lines of the volcano. Fig. 1E shows the profile along one of the furrows (dotted white line in Fig. 1C),
corresponding to an average slope angle of only 0.017°. The slope gradient along the flank of Alba Patera is approximately two orders of magnitude greater, or about 1.14°; thus, if such furrows are erosion marks, the flow was moving parallel to topographic contour rather than following the main slope gradient. In this region, furrows can be followed to a maximum altitude of -3100 m; thus the more recent lava flows of Alba Patera (LF in Fig. 1D), may have partially blanketed the furrows (if present) at higher elevations.

Interpretations: The northern flank of Alba Patera and the large depression (2300-km diameter and 1000 m deep) impact basin of Utopia Planitia would have significantly affected bottom currents. Being heavily blanketed by sediments, Utopia is very shallow for its width (Hellas Planitia of comparable width is 8 times deeper). Oceanic currents of low density excess are often approximately geostrophic, namely, the pressure gradients are balanced by the Coriolis acceleration [4]. For geostrophically driven flows, the velocities \((u,v)\) respectively eastward and northward (with corresponding coordinates \(x\) and \(y\)) satisfy the differential equation (e.g., [4])

\[
u \frac{\partial f}{\partial x} \left( \frac{f}{H} \right) + v \frac{\partial f}{\partial y} \left( \frac{f}{H} \right) = 0
\]

(1)

i.e., the flow tends to follow the contours of \(f/H\) where \(f = 2\Omega \sin \phi\) is the Coriolis parameter, \(\Omega = 7.08 \times 10^{-5}\) s\(^{-1}\) is the rotational frequency of Mars, \(\phi\) is the latitude, and \(H\) is the local oceanic depth. On Earth, this flow pattern may affect a large fraction of the water column, so that the bottom topography may have an influence on surface currents [7]. The flow direction \(\theta = \tan^{-1}(v/u)\) (i.e., the angle of the velocity field with respect to the W-E orientation) in beta-plane approximation can be calculated from Eq. (1) as

\[
\frac{v}{u} = \tan \theta = \left( \frac{f_0 + \beta y}{f_0 + \beta x} \right) \left( \frac{\partial f}{\partial x} \right) \frac{\partial H}{\partial x}
\]

(2)

As a simple model for the topography to be used in Eq. (2), a circular basin and an elliptical peak are considered with appropriate scale lengths. Figure 2 shows the result for the current velocity field vector direction. The flow largely follows the contour of both the peak and the basin, in a manner consistent with the pattern of along-contour furrows shown in Fig. 1A-B. This result elucidates the furrows orientation along the topographic contour in addition to along the slope. The radial furrows (some visible in the center of Utopia Planitia and indicated with dotted lines in Fig. 1B) were more likely eroded by denser turbidity currents or subaqueous landslides.

Conclusions: Furrows in the NL of Mars are tentatively explained as erosion marks incised by bottom contour currents in the Oceanus Borealis. While furrows directed along slope are consistent with dense flows such as turbidity currents, those along the contour lines are suggested to be the marks of contour currents. These two classes of currents are well familiar to marine geologists, and terrestrial examples are widespread [8]. Of the two, along-contour furrows are the most interesting for the assessment of Oceanus Borealis: this is because in contrast with along-slope currents that may in principle develop subaerially, along-contour currents can only be created in an ocean.