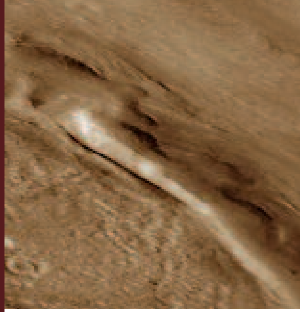

Geomorphological Evidence for Water on Mars

Victor R. Baker[1]

Martian landscapes and landforms indicate episodic activity by water and ice, extending from the planet's earliest history up to the present day. Most of the relevant fluvial, glacial, volcano–ice, periglacial, lacustrine (even "marine"), and related landforms have direct counterparts on Earth. Moreover, they exist in causally related, holistic associations of space and time that confirm their relationship to a long-term history of water-related activity. Although strong geomorphological evidence for many of these relationships has been apparent for 30 years, its scientific importance has only been recently appreciated because of direct geochemical measurements of water and ice features by surface robotic and orbital instruments.

KEYWORDS: Mars, geomorphology, landforms, climatic change, hydrology

INTRODUCTION

Despite 30 years of accumulating, increasingly abundant and unequivocal geomorphological evidence, the case for past water-related activity on Mars remained immensely controversial until very recently (Baker 2004). Ingenious models were proposed (e.g. Hoffman 2000) to ascribe non-aqueous origins to individual Martian landforms that otherwise had striking similarities to water-generated features on Earth. Nevertheless, this view is profoundly changed because of recent developments, notably the nuclear physical measurement of abundant, extant, near-surface ice (Boynton et al. 2002) and direct chemical analyses of aqueous minerals associated with sedimentary rocks (Squyres et al. 2004). Recent dampening of hydrophobic theorizing makes it appropriate to reassess the geomorphological evidence for water on Mars, and this brief overview will emphasize developments.

Geomorphology concerns the nature and origins of landforms and landscapes. Its application to extraterrestrial planetary surfaces relies upon known associations of form and process on Earth. However, the rationale for ascribing genesis to a newly discovered planetary landform is not simply a matter of comparative image analysis. Landforms and landscapes exist in complex, interrelated assemblages, in which the different elements relate to one another in time and space because of their generation by a unique sequence of formative processes. Scientifically productive alternative explanations must not merely satisfy individual, simple-minded, "look-alike" criteria. Instead, they must account holistically for the entire, genetically related assemblage, in the same way that the solution of a crime depends, not on a single clue, but on the whole interrelated web of evidence that is built up through connections of time and space by a master detective.

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CHANNELS, VALLEYS, ALLUVIAL FANS, AND SEDIMENTS

As recognized early in the era of spacecraft exploration, channels and valleys extensively dissect the surface of Mars. Channels are elongated troughs that display clear evidence for large-scale fluid flow across their floors and on parts of their walls or banks (FIG. 1A). Immense channels, with widths of tens of kilometers and lengths of up to a few thousand kilometers, display a suite of morphological attributes that are most consistent with genesis by cataclysmic flows of water and sediment (Baker 2001). On Earth such flows produced the distinctive landforms of the Channeled Scabland (FIG. 2A). An important recent discovery is that Martian flood channel activity, involving outbursts of water and associated lava flows, occurred in the Cerberus Plains region on the order of 10 million years ago (Berman and Hartmann 2002; Burr et al. 2002). The huge discharges associated with these floods and the temporally related volcanism should have introduced considerable water into active hydrological circulation on Mars.

While the huge Martian channels are generally well characterized by the older imaging systems of the 1970s, it was not until a new generation of orbital imaging capabilities in the past several years that major advances occurred in understanding the nature of valley networks (FIG. 1B). These valleys dissect the Martian highlands much more extensively than was apparent from the earlier images (Hynek and Phillips 2003). Many valleys contain relict channels comparable in their dimensions to the active river channels associated with terrestrial valleys (Irwin et

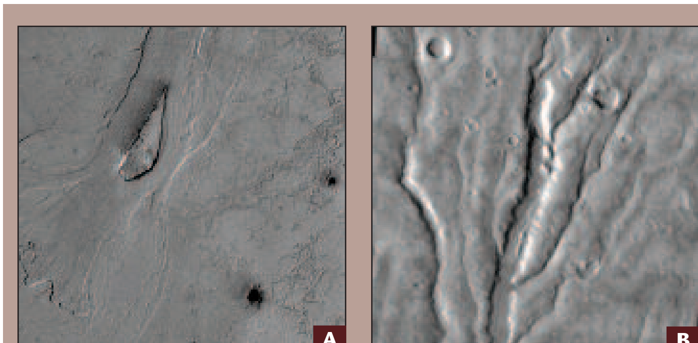

FIGURE 1

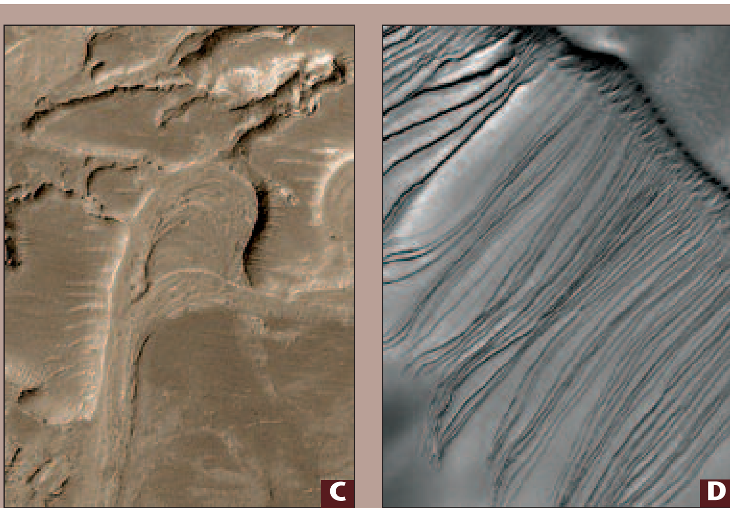

FIGURE 1 Examples of Mars landforms indicative of water and ice processes. **(A)** Cataclysmic paleo–flood channel south of Cerberus (3.8°N, 204.7°W). The 3 km wide image shows a relatively small streamlined island and a cataract. (NASA MGS Press Release No. MOC2-866) **(B)** Portion of the Warrego valley network, 24 km wide (42.3°S, 267.5°W). (NASA MGS Press Release No. MOC2-868.) **(C)** Ancient scroll topography and meander cutoff. This 2 km wide image is located at 24.3°S, 33.5°W. (NASA MGS Press Release No. MOC2-543) **(D)** Debris flow levees on a poleward-facing dune face in Russell Crater (54.7°S, 347.4°W). (MOC IMAGE M19-01170)

al. 2005). Formed about 3.9 billion years ago, Martian highland craters and impact basins were extensively eroded by surface runoff processes during episodes with Earth-like precipitation (Craddock and Howard 2002).

Large alluvial fans occur in ancient highland craters at middle-to-low southern latitudes. They are remarkably similar to low-relief terrestrial alluvial fans formed dominantly by fluvial, as opposed to debris flow, processes (Moore and Howard 2005). They probably formed during an episode of enhanced precipitation that followed the transition from the early period of heavy impact bombardment (the Noachian Epoch) to the period of lower impact rates after about 3.9 billion years ago. Relatively high denudation rates are inferred for the Noachian, and these are much greater than in later periods (Craddock and Howard 2002). The new observations are consistent with the discovery that upper layers of the ancient Martian crust of the highlands contain extensive sedimentary rocks that were emplaced during the intense denudation phases (Malin and Edgett 2000a). Now confirmed by in situ inspection (Squyres et al. 2004), sedimentary rocks were identified from orbit by their morphological expression. Imagery from the Mars Orbiter Camera (MOC) of the Mars Global Surveyor (MGS) Mission shows that the Martian highlands do not consist of an initial lunar-like surface, underlain by an impact-generated megaregolith, as presumed in previous models (e.g. Carr 1996). Instead, cratering, fluvial erosion, and deposition of layered materials probably all occurred contemporaneously, leading to a complex interbedding of lava flows, igneous intrusions, sediments, buried crater forms, and erosional unconformities (Malin and Edgett 2000a).

ANCIENT OCEANS, SEAS, LAKES, AND DELTAS

Morphological evidence for past large bodies of water covering the northern plains of Mars, apparent by the late 1980s, includes the morphological characteristics of sedimentary deposits and, more dramatically, a pattern of surrounding shorelines (Clifford and Parker 2001). Evidence for the latter was systematically criticized in a global sense (Carr and Head 2003), but was supported for local areas by very detailed mapping (e.g. Webb 2004). Nevertheless, the general concept of past inundations on the northern plains, constituting an "Oceanus Borealis," at least for geologically short episodes, has been found to be generally consistent with considerable geomophological evidence. The distinctive water-laid sedimentary deposits that cover parts of the Northern Plains, known as the Vastitas Borealis Formation, afford the most convincing evidence (Carr and Head 2003), including (1) margins that roughly mark the surface to which a body of water would approximate, (2) a distinctive population of impact craters indicating associated ice and sediments (Boyce et al. 2005), and (3) a phenomenally flat and smooth surface expression, similar to that of abyssal plains in Earth's ocean basins.

The water body associated with emplacement of the Vastitas Borealis Formation was approximately contemporaneous with the floods responsible for the largest outflow channels, and it may have covered as much as 3 million km^2 to average depths of hundreds of meters. The largest estimates involve as much as 20 to 60 million km^3 of water, equivalent to 200 to 400 meters spread evenly over the whole planet and comparable to the inferred collective flows from the outflow channels (Carr and Head 2003; Boyce et al. 2005), as proposed by Baker et al. (1991). Other periods of outflow channel activity and associated inundations of the northern plains (Clifford and Parker 2001; Fairen et al. 2003) are far less certain as to extent, relative timings, and durations of the various inundation episodes.

Though the debate over the Martian "ocean" has received much attention, even more compelling evidence supports the existence of numerous lakes and seas, which were temporarily extant on the surface of Mars at various times in the planet's history (Cabrol and Grin 2002). The more ancient lakes occupied highland craters during the heavy bombardment epoch, spilling over to feed valleys such as Ma'adim Vallis (Irwin et al. 2004). The floodwater spilled from lakes that held up to several hundred thousand cubic kilometers of water, covering an area of about 1 million cubic kilometers, and flows achieved peak discharges of millions of cubic meters per second (Irwin et al. 2004). Abundant crater paleolakes seem to have developed just after the heavy bombardment, and especially large lakes occupied the floors of the impact basins, Hellas and Argyre.

Fluvial deltas are commonly associated with the paleolakes. One complex of ancient meandering alluvial channels, comprising a fan-delta partly filling the crater Eberswald or NE Holden (Malin and Edgett 2003; Moore et al. 2003), displays Earth-like morphologies that can only be explained by persistent fluvial activity on time scales ranging from centuries (Jerolmack et al. 2004) to hundreds of millennia (Bhattacharya et al. 2005). Paleo–meander bend topography (FIG. 1C) shows that these were laterally accreting, alluvial rivers of a similar type to the modern Mississippi.

THE CRYOLITHOSPHERE OF MARS

What happened to the huge water inventory necessary for generating channelized megafloods and relatively short-lived lakes and seas? While a variety of atmospheric-loss processes undoubtedly occurred, the geomorphological evidence suggests that water, even the "Oceanus Borealis," was not on the surface for prolonged periods. Instead it resided nearly all the time, except for brief, sometimes spectacular episodes, within or beneath semipermanent, ice-rich permafrost. The long-term existence of this ice-rich layer, constituting a cryolithosphere about 1–2 km thick in equatorial areas and 5–6 km thick at the poles, is documented by a variety of geomorphological features (Kuzmin 2005).

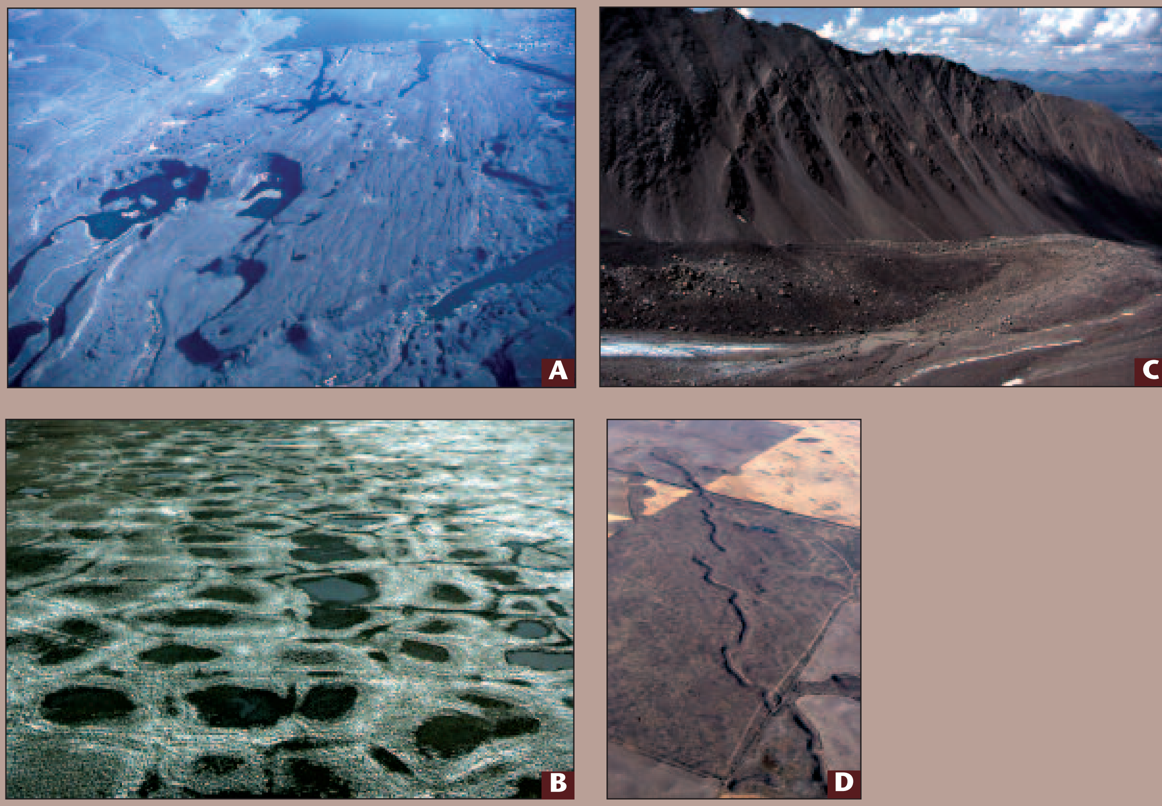

FIGURE 2 Examples of Earth water- and ice-related landforms with distinctive morphologies that have equivalents on Mars. **(A)** Longitudinal grooves and inner-channel cataract complex eroded into basalt by the catastrophic Pleistocene megafloods of the Channeled Scabland in east-central Washington (USA). **(B)** Ice-wedge polygons formed in permafrost terrain near Barrow, Alaska, USA. **(C)** Small rock glacier and adjacent periglacial debris fans in the Altai Mountains of south-central Siberia. **(D)** Esker on the Waterville Plateau in eastern Washington, formed by gravel deposition by meltwater that flowed though tunnels beneath the late Pleistocene Okanogan Lobe of the Cordilleran Ice Sheet. This esker is about 30 m wide and 3 km long.

Most of these have been well known since the 1970s, including various types of flow-lobed ejecta blankets (rampart craters), debris flows, lobate debris aprons, and polygonal terrains. A variety of landforms related to volcano–ice interactions (e.g. Chapman et al. 2000) document the occasional short periods of volcanically induced water outbursts from this reservoir of ice and underlying ground water. Following these episodes, surface water seems to have very rapidly returned to the cryolithosphere. Thus, despite considerable theorizing (reviewed by Carr 1996), a clear indication of the size of Mars' mostly hidden global water inventory cannot be gleaned from the isotopic composition of the tiny fraction of that inventory which was subject to long-term exospheric escape processes.

RECENT GULLIES, GLACIERS, AND RELATED ACTIVITY

Recent discoveries from Mars Orbiter Camera (MOC) images show that Mars displays a diverse suite of exceptionally young, globally distributed landforms that are water-related. If observed on Earth, these landforms would generally be well understood to have aqueous origins, involving dynamical hydrological cycling on relatively short time scales (hundreds to thousands of years) in a warmer, wetter, and denser atmosphere than occurs on Mars today. Perhaps the most striking of the recent discoveries made from the high-resolution MOC images is that of numerous small gullies (Malin and Edgett 2000b), developed on hillslopes associated with crater rims and channel or valley walls. Morphological similarity of these hillslope gullies to terrestrial, high-latitude, periglacial gullies suggests an origin by aqueous debris flows, involving the melting of near-surface ground ice. The gullies are uncratered, and their associated debris-flow fan deposits are superimposed on both eolian bedforms (dunes or wind ripples) and polygonally patterned ground, all of which cover extensive areas that are also uncratered (Malin and Edgett 2000b). The patterned ground is itself a very strong indicator of near-surface, ice-related processes in the active (seasonally thawed) layer above the Martian permafrost zone (Siebert and Kargel 2001).

At the regional scale, gullies occur in high-latitude bands on Mars. They are associated with a variety of other landforms that indicate direct emplacement and local degradation of mantles of ice and dust, possibly even dirty snow, all derived from the atmosphere (Head et al. 2003). The evidence consists of small-scale polygonal or patterned terrains, similar to the ice-wedge phenomena of Earth's high-latitude permafrost regions (FIG. 2B); the mobilization of rocky debris on slopes, similar to the rock glaciers of Earth's periglacial regions (FIG. 2C); and a sort of regional smoothing of small-scale topography by deposits, a few to several meters thick, that are internally layered and locally eroded (Mustard et al. 2001). The emplacement of ice-rich deposits at low- to mid-latitudes seems to be consistent with geologically recent episodes of higher tilt (obliquity) in the axis of Mars' planetary spin. This would result in warming of the polar caps, thereby increasing the sublimation of ice and migration of water vapor to the then-cooler lower latitudes.

Another class of very distinctive debris flows occurs on the debris-mantled slopes of large sand dunes (FIG. 1D) (Mangold et al. 2003). Water–sediment mixtures afford the most likely mechanism for producing these landforms. More controversial are the abundant dark slope streaks developed in currently active dust mantles on hillslopes; a case can be made that these result from local, occasional water activity (Miyamoto et al. 2004).

Glaciated landscapes are some of the most important landform features to be documented with the newer high-resolution data. Earlier arguments for extensive glaciation on Mars were severely criticized, in part because glaciation has immense hydrological and climatological implications. The growth and persistence of large glaciers require a dynamic hydrological system that moves large quantities of water from surface-water reservoirs, such as lakes and seas, through the atmosphere to sites of precipitation. Resistance to the idea of ancient glaciers on Mars is especially curious, given that there was a general scientific consensus that Mars displays an immense variety of periglacial landforms, most of which require the activity of ground ice. The periglacial landforms include debris flows, polygonally patterned ground, thermokarst, frost mounds, pingos, and rock glaciers. On Earth most of these landforms develop under climatic conditions that are both warmer and wetter than the conditions for the cold-based glacial landforms now known to abound on Mars (Baker 2001).

The new evidence of glaciation is distinguished by its abundance, the complex detail of its assemblages, and the commonly very young geological ages (Kargel 2004). The glacial landforms of Mars include erosional grooves, stream-lined/sculpted hills, drumlins, horns, cirques, and tunnel valleys; depositional eskers (Fig. 2D), moraines, and kames; and ice-marginal outwash plains, kettles, and glaciolacustrine plains. These landforms occur in spatial associations, proximal-to-distal in regard to past ice margins, that exactly parallel terrestrial glacial geomorphological settings. Long-recognized areas of past glaciation on Mars include lobate debris aprons near uplands surrounding Argyre and Hellas (Kargel 2004), lineated valley fills in the fretted troughs of the highlands/lowlands boundary north of Arabia Terra, and polar regions, where the ice caps were much more extensive during portions of post-Noachian time. Huge glaciers marked the western flanks of the Tharsis volcanoes. Debris aprons at the bases of massifs in eastern Hellas show clear morphological evidence of sublimation, ice-rich substrates, and glacial-like viscous flow (Fig. 3). Geologically recent ice-rich rock glaciers (or debris-covered glaciers) occur at the base of the Olympus Mons scarp, where they are superimposed on older, much larger, relict, debris-covered piedmont glacial lobes (Head et al. 2005).

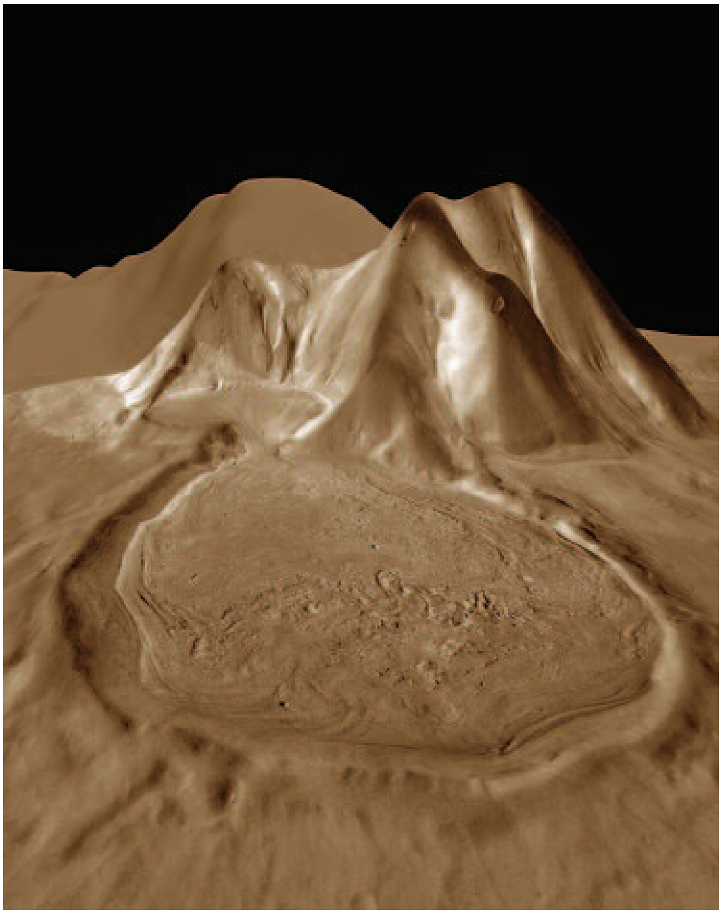

Figure 3 Mars Express High Resolution Stereo Camera perspective view (30X vertical exaggeration) of debris, from a 4-km-high mountain massif, that has flowed into two adjacent craters. The debris is organized into crater-filling flow patterns of parallel ridges that spread out to a width of 16 km in the foreground. This landform assemblage, located east of Hellas, is analogous to terrestrial debris-covered piedmont glaciers. Numerous pits and depressions show wastage of the glacial ice, which may have been active only several tens of millions of years ago (Head et al. 2005).

DISCUSSION AND CONCLUSIONS

Theorizing about past water on Mars oscillates between a hydrophilic view of a wet surface environment and a hydrophobic view of a dry surface environment. Geomorphological evidence from the 1970s and 1980s pointed to a Mars that was episodically active in a hydrological sense during post-Noachian time. Hypotheses that explained all these features as interrelated were extensively criticized and pronounced inferior to the long-prevailing view that Mars had been continuously dead and dry since the Noachian. Though the latter view had considerable theoretical support, it failed to explain the mounting new data that Mars has experienced episodic hydrological activity throughout its geological history (Baker 2001)—most remarkably, even up to the last several million years. While much of the relevant new data, like those of the 1970s, is geomorphological, the change in scientific thinking is occasioned by geochemical and mineralogical measurements, both remote and in situ.

Geomorphology will continue to contribute to the understanding of Mars' watery past, but this contribution will be less in the realm of theoretical models and more in the realm of the unique realities that are distinctly Martian. The relevance is perhaps best expressed in Stephen Jay Gould's "principle of planetary individuality," described as follows (Gould 1991, pp 506–508):

- The surfaces of planets and moons cannot be predicted from a few general rules.
- To understand planetary surfaces, we must learn the particular history of each body.
- As an individual object… Their major features are set by unique events—mostly.
- Catastrophic—that shape their surfaces… Planets are like individual organisms.
- Not water molecules; they have irreducible personalities built by history.

ACKNOWLEDGMENTS

This necessarily brief overview cites only a small sampling from hundreds of relevant geomorphological publications that document past aqueous activity on Mars. The author both thanks and apologizes to authors of those studies not included, especially to the many who recognized, as early as the 1970s and 1980s, the compelling geomorphological evidence for Mars' aqueous past.

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