Hydrogeologic processes of large-scale tectonomagmatic complexes in Mongolia–southern Siberia and on Mars

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ABSTRACT

Large-scale tectonomagmatic complexes are common on Earth and Mars. Many of these complexes are created or at least influenced by mantle processes, including a wide array of plume types ranging from superplumes to mantle plumes. Among the most prominent complexes, the Mongolian plateau on Earth and the Tharsis bulge on Mars share remarkable similarities in terms of large domal uplifted areas, great rift canyon systems, and widespread volcanism on their surfaces. Water has also played an important role in the development of the two complexes. In general, atmospheric and surface water play a bigger role in the development of the present-day Mongolian plateau than for the Tharsis bulge, as evidenced by highly developed drainages and thick accumulation of sediments in the basins of the Baikal rift system. On the Tharsis bulge, however, water appears to have remained as ground ice except during periods of elevated magmatic activity. Glacial and periglacial processes are well documented for the Mongolian plateau and are also reported for parts of the Tharsis bulge. Ice-magma interactions, which are represented by the formation of subice volcanoes in parts of the Mongolian plateau region, have been reported for the Valles Marineris region of Mars. The complexes are also characterized by cataclysmic floods, but their triggering mechanism may differ: mainly ice-dam failures for the Mongolian plateau and outburst of groundwater for the Tharsis bulge, probably by magma-ice interactions, although ice-dam failures within the Valles Marineris region cannot be ruled out as a possible contributor. Comparative studies of the Mongolian plateau and Tharsis bulge provide excellent opportunities for understanding surface manifestations of plume-driven processes on terrestrial planets and how they interact with hydro-cryospheres.

Keywords: Mongolia, Mars, Tharsis, ice, floods, plumes.

INTRODUCTION

Prominent internal activity of terrestrial planets is often manifested by large-scale tectonic frameworks and associated widespread volcanism and dike emplacement on and near the surfaces. We call such manifestations large-scale tectonomagmatic complexes. These complexes may be formed or affected by plumes of diverse dimensions and origins ranging from superplumes (e.g., Maruyama, 1994) to mantle plumes (e.g., Mège and Ernst, 2001). Plumes are an integral part of the internal dynamics of terrestrial planets, having profound influences on surface and subsurface geology and hydrology over long time scales; e.g., they can significantly alter large-scale topography, drainages, landscapes, sedimentation, and even climate (Baker et al., 1993b; Maruyama, 1994; Dohm et al., 2002). Breaking up of continents can also be attributed to plume activity (e.g., Li et al., 2003).

We discuss two large-scale tectonomagmatic complexes on Earth and Mars, the Mongolian plateau and the Tharsis bulge, respectively (Figs. 1A, 1B), both of which occur in cold climate and have remarkably similar tectonic and magmatic elements, although differences also exist (Fig. 2). Both complexes have been hypothesized to be plume related. Because Earth and Mars are dynamic planetary bodies with hydro-cryospheres, the interaction of plume-driven activity with water is a significant planetary phenomenon that needs to be thoughtfully explored. Therefore, we highlight discoveries that show the significant interaction between water (particularly in ice form) and plume tecto-

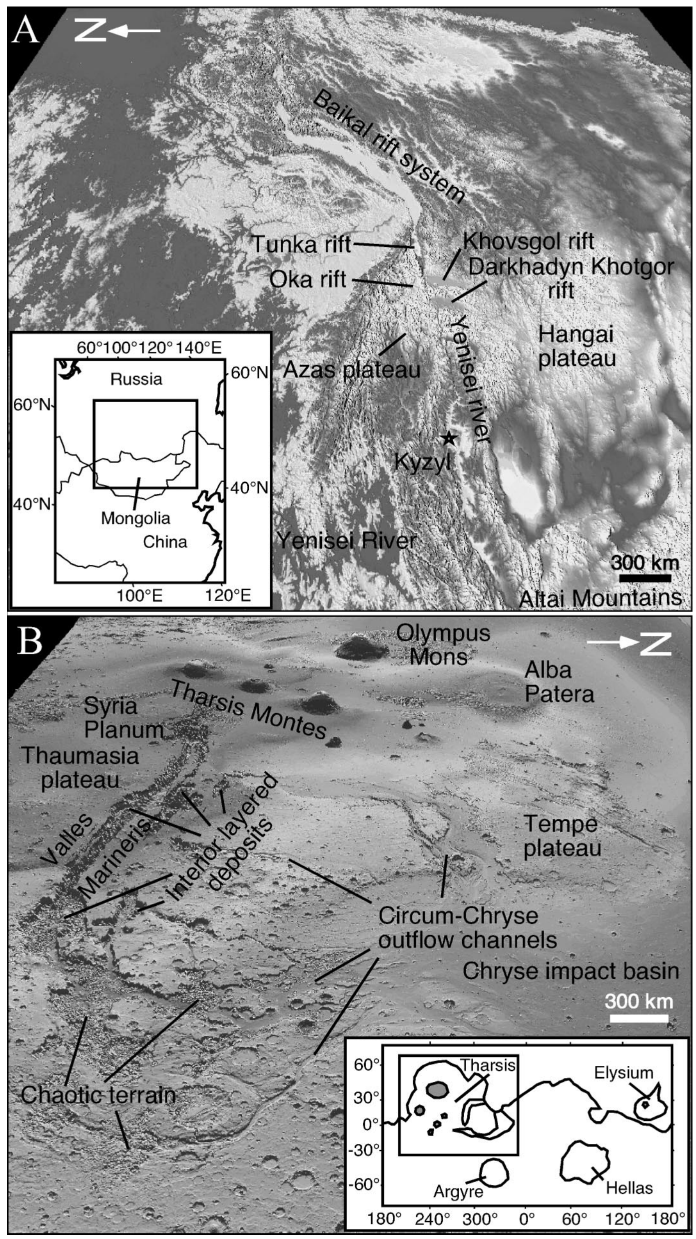

Figure 1. Three-dimensional views of (A) Mongolian plateau and (B) Tharsis bulge (its main part is shown) displaying major landforms related to their development. Insets show locations of two three-dimensional views.

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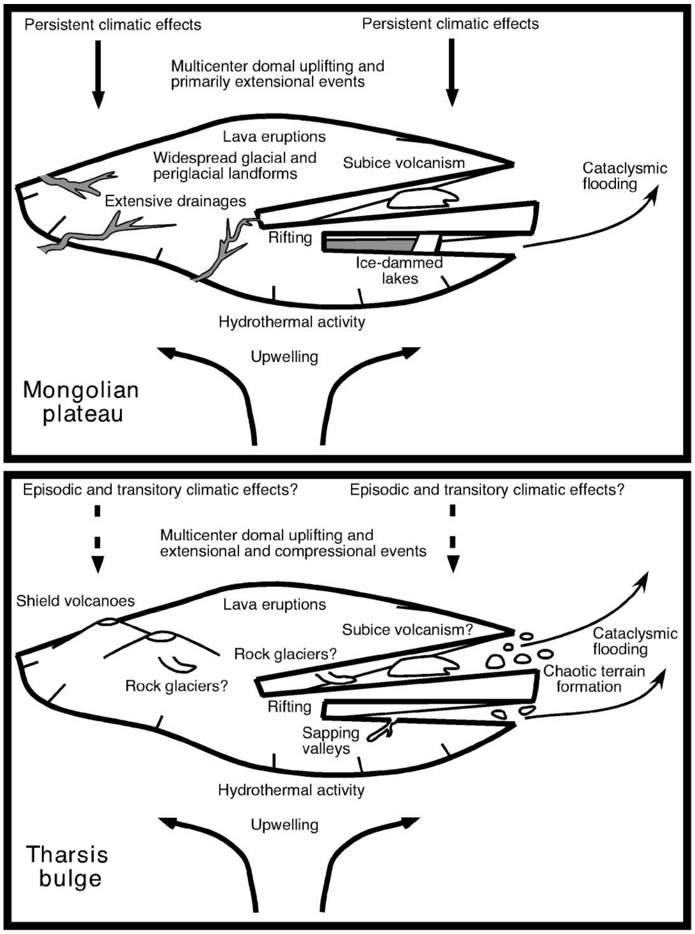

Figure 2. Schematic diagrams of processes involved with Mongolian plateau and Tharsis bulge.

nism and magmatism, and the resulting manifestation of such combined activity (Fig. 2).

Comparison of these two unique features on Earth and Mars could provide a potentially deep understanding of how certain geomorphic processes are caused by plume-driven activity in water-rich terrestrial planets.

TECTONIC FRAMEWORK AND ASSOCIATED VOLCANISM

The Mongolian plateau (2500 × 1000 km), which occupies a large part of Mongolia and southern Siberia, is a vast upland region characterized by a complex geologic history. The basement geology of this region reflects continental formational processes involving interactions among cratons and arcs, mainly during the Paleozoic (Şengör and Natal'in, 1996). Evidence for postcontinental formation activity is widespread. Lake Baikal occupies the Cenozoic Baikal rift (~700 km long, <100 km wide) (Fig. 1A), and has a maximum water depth of ~1600 m. The Baikal rift is one of the deepest active rifts on Earth, reaching depths of 8–9 km with a thick accumulation of sediments. The rift system records the tectonomagmatic history of the region, which includes the formation of many subparallel grabens (collectively the entire system is >1500 km long and 200–300 km wide) and the episodic emplacement of lavas as young as the Holocene. Cenozoic volcanic rocks of primarily alkaline-rich basaltic composition are distributed widely, but mostly as isolated patches that are both axial and off axial of the rifts (Litasov et al., 2001b). Large domal uplifted areas are common within the Mongolian plateau, the most prominent being the Hangai plateau (Fig. 1A). The South Baikal hotspot (Yarmolyuk and Kovalenko, 1990), for example, may have caused one of the domal uplifting events; the highest altitude is >3000 m above sea level at the junction of the Khovsgol basin, the Tunka valley, and the Oka-Azas troughs (Fig. 1A). The Baikal rift system extends to the area proposed to be the South Baikal hotspot, and is considered to be underlain by lithosphere that is regionally <50 km in thickness (Zorin et al., 1990). Based on these elements, Windley and Allen (1993) proposed that the Mongolian plateau, including the Baikal rift system, resulted from a late Cenozoic mantle plume. Petit et al. (2002) argued against the high-heat-flux mantle plume hypothesis, citing observations such as the relatively low regional heat flow with respect to the time duration of volcanic emissions and results from xenolith analyses. It is also true that the collision of India and Eurasia has been contributing to the mountain building in central Asia (Tapponnier and Molnar, 1979). Nevertheless, a gravity- and topography-based model employed for the Khovsgol-Hangai region (Petit et al., 2002) is still in agreement with low-activity mantle upwelling occurring beneath Baikal and Mongolia.

The Tharsis bulge (8000 × 7000 km in area) has been recently interpreted to be a superplume (Baker et al., 2002; Dohm et al., 2002) consisting of numerous components that represent the surface manifestations of purported plume-driven activity. Major components include regional and local centers of domal uplift, tectonism, and volcanic, intrusive, and hydrothermal activity, igneous plateaus, large shield volcanoes, lava flow and shield fields, and fault, graben, rift, and wrinkle ridge systems (Fig. 1B) (e.g., Scott and Tanaka, 1986; Anderson et al., 2001; Dohm et al., 2001a, 2001b; Williams et al., 2003). Detailed mapping records at least five major pulses during the evolution of the Tharsis bulge (Dohm et al., 2001a, 2001b, 2002). Such magmatic activity may result from a stagnant-lid regime, where the internal heat of the planet builds over time to catastrophically erupt magmas and volatiles at the Martian surface (Baker et al., 1991). This pulsating activity appears to be decreasing, and the result is the formation of an ever-thickening cryosphere (Baker, 2001).

Valles Marineris (Fig. 1B) is a gigantic system of canyons that is ~4000 km long, as much as 600 km wide, and nearly 10 km deep in places. These canyons have been proposed to be a rift system (e.g., Blasius et al., 1977) probably caused by one or multiple mantle plumes, although its development certainly involved other processes, including erosion and collapse (Lucchitta et al., 1992). At this time, it is difficult to determine the size of the intrusive body or bodies that may have contributed to the surface expression of the Valles Marineris region. Fault and rift systems, which trend both parallel and radial to the vast Valles Marineris canyons, are of varying extent and ages (Scott and Tanaka, 1986; Dohm et al., 2001a). The systems of structures are interpreted to be the site of a lithospheric zone of weakness, as well as vertical uplift related to plume manifestation dating to at least the end of the heavy bombardment (Dohm et al., 2001a, 2001b).

WATER-RELATED PROCESSES

On Earth

Precipitation in the form of rain or snow is common on Earth, contributing to the extensive development of radial drainage systems and high erosion rates on updomed regions of Earth (Cox, 1989), such as the Mongolian plateau. In addition, paleoclimatic conditions such as observed for the Quaternary ice age resulted in tremendous surface modification, especially highlighted at the high latitudes of northern Eurasia. During the Quaternary period, glaciers in central Asia and Siberia covered the Pamir, Tian Shan, Altai, and Trans-Baikal mountain ranges, but the exact extent of the glaciers remains controversial. Ice caps of various sizes developed over high uplifted plateaus of southern Siberia (Lehmkuhl, 1998; Grosswald, 1999), and the drainage system of the region was reorganized because of changes in precipitation, temperature, and humidity, but also because the ice caps blocked water flows. For example, drainage reorganizations at Manzurka, located within the Lake Baikal region, have been extensively studied (e.g., Grosswald and Kuhle, 1994; Osadchiy, 1995). Paleolakes (Fig. 2) were formed in various basins because of changes in environmental conditions (e.g., Komatsu et al., 2001), but also because of damming by glaciers (Grosswald and Rudoy, 1996). In addition, structural dams and damming by landslides and lava flows in this active tectonomagmatic complex cannot be ruled out.

Ample evidence has been found along the Chuja River for the Pleistocene cataclysmic outbursts of the glacier-dammed lakes in Kuray and Chuja basins located in the Altai mountain range, which is contiguous to the Mongolian plateau (Baker et al., 1993a; Rudoy and Baker, 1993). The evidence includes giant current ripples, flood-scoured gorges, and giant bars (e.g., Rudoy, 2002). The maximum flood discharge is estimated to be 18×10^6 m^3/s, which is the greatest freshwater flood discharge documented to date on Earth (Baker et al., 1993a). Prominent cataclysmic flood landforms are also known along the upper reaches of the Yenisei River in the Sayan Mountains, mostly in the Tuvan Republic (Grosswald and Rudoy, 1996). The landforms include giant current ripples near the capital Kyzyl (Fig. 1A), gravel-rich bars, large sand ridges, and paleohollows. A glacier-dammed lake in the Darkhadyn Khotgor basin of the Baikal rift system (Fig. 1A), upstream of Little Yenisei River, is considered to be one of the main sources for the Yenisei River flooding (Fig. 2) (Grosswald, 1999). Ages of the events are most likely to be late Pleistocene, because of the pristine appearance of the landforms and the radiocarbon-dated basin sediments. Permafrost is widely developed in Siberia, and a wide range of periglacial landforms is observed, e.g., in the rift basins. Cryogenic processes revealed by frost heaves, cracks, icing, thermokarst, solifluction, and stone polygons are common in the permafrost zone (Sharkhuu, 2002). Today, geomorphic processes linked to ground ice in the Mongolian plateau are caused by climatic fluctuations over multiple time scales. However, both catastrophic and gradual melting of ground ice and resulting hydrothermal activity may have occurred when magmatic activity was high.

The rift-forming magmatic activity in the cold and wet climatic regime of Siberia resulted in subice volcanism (Fig. 2). Subice eruptions of lavas melt the overlying ice and often form flat-topped edifices, called tuyas, within the meltwater englacial lakes. A typical tuya is characterized by pillow lavas overlain by a thick hyaloclastite unit and a subhorizontal lava layer unit. Tuyas are widespread on the Azas plateau within a rift basin of the Tuva Republic of the Russian Federation (Fig. 1A). The volcanic rocks are alkaline basalts and basanites (Litasov et al., 2001a). The subice volcanism of the Azas plateau records climatic episodes significantly different from today's. The tuya edifices on the Azas plateau are Pleistocene, and their formation coincides with extensive glaciation in the region.

On Mars

Precipitation on Mars has been a controversial subject owing to uncertainty in interpreting landform origins. Early Mars (early and middle Noachian, a period of heavy bombardment) is generally considered to have been subject to somewhat Earth-like conditions involving an appreciable amount of early precipitation followed by a continuous decline in precipitation and erosion throughout the rest of history (Carr, 1996). Limited valley development, which is observed in the Valles Marineris region, may be explained by groundwater sapping. New data from the Mars Global Surveyor (MGS) are providing new insights on the role of glaciation during the Amazonian, the youngest geologic period on Mars (Baker, 2001). For example, landforms interpreted as rock glacier deposits on the Tharsis bulge were observed by using high-resolution imagery acquired by the Mars Orbiter Camera (MOC) onboard the MGS. These landforms include slope deposits in Valles Marineris (Rossi et al., 2000) and parts of a fan-shaped, possible glacier deposit complex on the western flanks of Arsia Mons, one of the Tharsis Montes volcanoes (Head and Marchant, 2003). The possibility of snow precipitation at low latitudes during high obliquity was pointed out by Jakosky and Carr (1985), but temporal climatic shifts due to endogenic causes may also explain these features (Baker et al., 1991).

Cataclysmic floods have occurred repeatedly, as evidenced by the presence of outflow channels, some of which are connected to the canyons. McCauley (1978) suggested that lake bodies may have occupied the canyons of Valles Marineris. Although we cannot rule out these putative canyon-filling lakes as possible contributing sources for the incising of the circum-Chryse outflow-channel system (Fig. 1B), these channels distinctly originated from collapsed areas called chaotic terrain (Figs. 1B and 2), implying that catastrophic flooding likely resulted from the melting of ground ice by magmatic mechanisms. For example, ice bodies and ground ice in the canyons may have been melted by eruptions, thus producing jökulhlaup-type floods (Chapman and Tanaka, 2002). Hydrothermal activity may have also been prevalent during periods of elevated magmatic activity.

Internal layered deposits in Valles Marineris are characterized by their extensive thin layering and their unique relation with the canyon system (Fig. 1B). Some internal layered deposits in Valles Marineris have a striking resemblance to the tuyas in terms of overall geomorphology, i.e., semiflat cap units, steep gullied sidewalls, and parts of edifices extend like wings in various directions. Dike and volcanic neck–like landforms observed in the Gangis internal layered deposit, for example, may be consistent with feeder dikes and necks associated with tuya formation (Komatsu et al., 2004). Hence, the subice volcanism hypothesis (Chapman and Tanaka, 2001; Komatsu et al., 2004) may explain the formation of at least some of the internal layered deposits. Whether this hypothesis is valid for all the internal layered deposits or for only some is yet to be investigated.

DISCUSSION AND CONCLUSIONS

The role of water in forming landforms on the Mongolian plateau is important (Fig. 2), but it is unclear whether magmatism associated with the formation of the Mongolian plateau influenced the geomorphic processes observed on the plateau by inducing local climate change. The larger southern Pacific superplume event represented by the Ontong Java plateau is considered to have caused the Cretaceous warming event (Larson, 1991), and the capacity for a plume to alter the climate may be primarily a function of its size and type. Superplume activity on Mars would trigger enhanced atmospheric conditions and hydrologic dynamics, especially considering that Mars lacks a buffering biosphere and that it is less than half the size of Earth, allowing a greater relative impact on the climatic system. For example, pulse-like magmatic activity recorded for the Tharsis bulge, specifically observed in central Valles Marineris—which includes uplift, dike emplacement, fissure-fed volcanism, and hydrothermal activity (McKenzie and Nimmo, 1999; Dohm et al., 2001a, 2001b; Chapman and Tanaka, 2002)—contributed to the episodic cataclysmic floods and related climatic perturbations (Fairén et al., 2003). Nonetheless, in comparison to the Mongolian plateau, the landforms produced by precipitation on the Tharsis bulge are limited in their extent, indicating the transitory nature of such climatic perturbations on Mars.

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