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978-0-521-86852-5 - Megaflooding on Earth and Mars
Edited by Devon M. Burr, Paul A. Carling and Victor R. Baker
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1 Overview of megaflooding: Earth and Mars

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Summary

After centuries of geological controversy it is now well established that the last major deglaciation of planet Earth involved huge fluxes of water from the wasting continental ice sheets, and that much of this water was delivered as floods of immense magnitude and relatively short duration. These late Quaternary megafloods, and the megafloods of earlier glaciations, had short-term peak flows, comparable in discharge to the more prolonged fluxes of ocean currents. (The discharges for both ocean currents and megafloods generally exceed one million cubic metres per second, hence the prefix 'mega'.) Some outburst floods likely induced very rapid, short-term effects on Quaternary climates. The late Quaternary megafloods also greatly altered drainage evolution and the planetary patterns of water and sediment movement to the oceans. The recent discoveries of Mars missions have now documented the importance of megafloods to the geological evolution of that planet. As on Earth, the Martian megafloods seem to have influenced climate change.

1.1 Introduction

Up until the middle nineteenth century considerable progress was being made in scientific studies of the role of catastrophic flooding in the geological evolution of river valleys. While some of these studies invoked a kind of biblical catastrophism, much of the work merely employed hypotheses of immense floods because these inferences seemed to provide the best explanations for such features as scoured bedrock and accumulations of huge, water-transported boulders. This whole line of scientific inquiry was seriously curtailed because of the popularity of certain of Charles Lyell's (1830–3) logically flawed notions of uniformitarianism. Lyell's methodology for geology resulted in an epistemological stigma for hypotheses invoking types and magnitudes of flood processes not directly observed today. As discussed below, many geologists either ignored or failed to understand the flaws in Lyell's overly prescriptive forms of uniformitarianism, which came to be imbedded into the practice of geology, thereby greatly hindering progress in the understanding of cataclysmic flooding as a geological process (see also, Baker, 1998).

Two developments of the twentieth century produced a renaissance in cataclysmic flood studies. The first was the prolonged scientific controversy over the origin of the Channeled Scabland in the northwestern United States (Baker, 1978, 1981). Extending from the 1920s to the 1970s, the great 'scablands debate' eventually led to a general acceptance of the cataclysmic flood origin for the region that had been championed by J Harlen Bretz, a professor at The University of Chicago. The second important development was the discovery in the early 1970s of ancient cataclysmic flood channels on the planet Mars (e.g. Baker and Milton, 1974; Baker, 1982). The Martian outflow channels were produced by the largest known flood discharges, and their effects have been preserved for billions of years (Baker, 2001).

Relatively recently it has come to be realised that spectacular cataclysmic flooding was a global phenomenon that accompanied the termination of the last major glaciation on Earth, involving huge fluxes of water from land to sea (Baker, 1994). Baker (1997) employed the term 'megaflooding' without definition to describe the association of cataclysmic outburst flooding with the great late Pleistocene ice sheets of North America and Eurasia. The appropriateness of this term was reinforced by the fact that floods of interest generally had peak discharges in excess of one million cubic metres per second (hence the prefix 'mega'). Moreover, this same unit of water flux, designated one 'sverdrup' (named for the pioneering Norwegian oceanographer Harald Sverdrup), is the same measure that is applied to ocean currents, which are the other major short-term water movements on the surface of the Earth (Baker, 2001). When such huge discharges are combined with appropriate energy gradients to produce very high flow velocities, bed shear stresses and unit power expenditures, the result is the phenomenon of high-energy megafloods (Baker, 2002a), which might also deserve the name 'superfloods' (Baker, 2002b). It is such flows that produce distinctive suites of consequent phenomena, many of which are described in other papers in this volume.

1.2 Historical and philosophical overview

According to the *Oxford English Dictionary*, the first reported use of the word 'geology' as pertaining to a branch of science was in the title of the 1690 book *Geologia: or, a Discourse Concerning the Earth Before the Deluge*, written by Erasmus Warren. Warren's *Geologia* concerned the literal truth of the Book of Genesis. However, like biblical literalists before and since, Warren had to resolve a

Megaflooding on Earth and Mars, ed. Devon M. Burr, Paul A. Carling and Victor R. Baker.
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paradox: the mixing in Genesis of two very different accounts of the Noachian Debacle. In one account, The Flood derives from 'foundations of the great deep' (Genesis 7:11). In the other, The Flood derives from 'the windows of heaven', such that it rained continuously for 40 days and 40 nights (Genesis 7:12). Warren privileged the first account, postulating that water burst from great caverns. The irrelevance of the whole question actually had been recognised during the early history of the Christian church by Saint Augustine, who noted that God would not make the mistake of having his revealed creation in conflict with scriptural interpretation. To claim superiority for the latter over what is actually revealed in nature would make the Christian God appear inferior in comparison with the deities of other religions. It is therefore quite ironic that this long Christian tradition of valuing what is revealed in God's creation (nature) is currently being denigrated by the historically recent (Numbers, 1993) development of a so-called 'creationism' based in a biblical literalism that makes the highly dubious claim of being fundamental to its theological underpinnings.

Although the first geology was arguably 'flood geology', it soon became apparent that geologists would not be worthy of the appellation 'scientists' (coined in 1840 by the famous Cambridge polymath William Whewell) if their activity were to consist solely of bearing witness to authoritative pronouncements, including those presumed to come from a deity. It is unfortunate that today 'flood geology' commonly refers to a branch of 'creation science', sharing with that enterprise a misleading use of the word 'science'. Science is no more and no less than an unrestricted inquiry into nature. To have its answers ordained in advance is a restriction on free inquiry and the result is sham reasoning (Haack, 1996), not science. Besides being flawed as science, 'creation science' is also based on dubious theology because of its rejection of the reading by human inquiry of divine creation (nature) in favour of the authority of an imperfect 2000-year-old written account thereof.

By the early nineteenth century, geology had evolved to a science concerned with observations of nature on a path to whatever could be discovered about causal patterns in regard to those observations. The inquiries of geologists had to be free to lead anywhere the observations and their implications required, unconstrained by prior notions of what was true, or even of what might be thought to be proper in the pursuit of that truth. Unfortunately, there also emerged confusion over the last point, and vestiges of that confusion linger even to the present day. This confusion involves the notion of 'uniformitarianism' (another word coined by William Whewell). When it is used as a kind of stipulative prohibition against the valid inference of cataclysmic processes, uniformitarianism is invalid as a concept in science, i.e., it blocks the path of inquiry (Baker, 1998). Indeed, there is nothing wrong, scientifically speaking, with invoking cataclysmic flooding as a natural explanation, if the facts, rather than some preconceived belief, lead the inquiry in that direction.

Prior to Charles Lyell's somewhat misguided advocacy of uniformitarianism in the middle 1800s (Baker, 1998), it was common for genetic hypothesising in natural philosophy to invoke cataclysmic flooding as a mechanism to explain such features as erratic boulders, widespread mantles of boulder clay (so-called 'diluvium'), and wind and water gaps through the ridges of fold mountain ranges (Huggett, 1989). For example, Edward Hitchcock (1835) explained the sediments and landforms of the Connecticut River valley as products of the Noachian debacle. Cataclysmic flooding was generally not invoked for reasons of scriptural literalism. Rather, it was genuinely perceived to provide a reasonable explanation for the phenomena of interest. An example is James D. Dana's (1882) study of the high glacial terraces of the Connecticut River. In addition to Hitchcock's debacle hypothesis, these had been interpreted alternatively to be products of marine submergence or the result of deposition by proglacial outwash streams forming valley fills that were later incised by postglacial river with less sediment load (Upham, 1877). Dana argued that the terraces resulted from a large-scale glacial flood, and he used their heights to infer its high-water surface, averaging about 50 m above the present river profile. From his data one can calculate a maximum paleodischarge for this 'flood' of $2.4 \times 10^5\ m^3\ s^{-1}$ (Patton, 1987).

1.3 The Great Scablands Debate

The 1920s/1930s debates over the origin of the Channeled Scabland landscape in eastern Washington, northwestern United States, were critical to the recognition of the geological importance of megaflooding. It was in this region that University of Chicago Professor J Harlen Bretz formulated the hypothesis of cataclysmic flooding (Baker, 1978, 1981). Bretz (personal communication, 1977; Figure 1.1) recalled that he first conceived of the cataclysmic flood hypothesis when in 1909 he saw a topographic map depicting the immense Potholes Cataract, which is now known to have conveyed cataclysmic flood water as part of the Channeled Scabland. However, Bretz forgot about this problem until the summer of 1922 when he led a field party of advanced University of Chicago students into the region. The travels through the Channeled Scabland reminded Bretz of his earlier hypothesis and he decided to devote that field season to an examination of that landscape.

In a paper published in the *Journal of Geology*, Bretz (1923) formally described his hypothesis that an immense late Pleistocene flood had derived from the margins of the

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Figure 1.1. Professor J Harlen Bretz (left) at his home with Victor R. Baker (right). Photographed in 1977 by Rhoda Riley.

nearby Cordilleran Ice Sheet. Named the 'Spokane Flood', this cataclysm neatly accounted for numerous interrelated aspects of the Channeled Scabland landscape and nearby regions. In his various papers Bretz noted features that marked the high levels reached by the floodwaters. These included scarps cut into the loess-mantled uplands adjacent to the scabland channels, high-level gravel-bar deposits of the floods, and divide crossings where one scabland channel spilled over into another (Bretz, 1923, 1928).

During the 1920s and 1930s the geological community strongly resisted Bretz's cataclysmic flood hypothesis. The most dramatic confrontation occurred at the 'The Great Scablands Debate' of the 1927 meeting of the Geological Society of Washington. At this meeting Bretz provided an overview of his hypothesis and a detailed listing of the numerous, otherwise anomalous phenomena that were explained by it. His talk was then followed by well-prepared criticisms by selected members of the audience. Almost continuously until 1940 there was nearly unanimous antipathy toward the cataclysmic flooding hypothesis, despite Bretz's eloquent defence thereof. Sceptical attitudes only began to change because of a technical session at the 1940 meeting in Seattle of the American Association for the Advancement of Science (AAAS).

Although the early papers in the AAAS session merely reiterated the various previously published alternatives for the origin of the Channeled Scabland, the eighth paper surprised an audience that expected no one to directly support Bretz's Spokane Flood hypothesis. The speaker was Joseph Thomas Pardee, whose paper was entitled 'Ripple Marks (?) in Glacial Lake Missoula'. Pardee described Camas Prairie, an inter-montane basin in northwestern Montana, on the floor of which were giant 'ripple' marks (probably fluvial dunes) composed of coarse gravel, piled up to 15 m high and spaced up to 150 m apart (Figure 1.2). The ripples had formed in a great ice-dammed lake, glacial Lake Missoula, which Pardee (1910) had earlier documented to have covered an immense area in western Montana. This late Pleistocene lake had held about 2000 cubic kilometres of water, and it was impounded to a maximum depth of about 600 m behind a lobe of the Cordilleran Ice Sheet occupying what is now the modern basin of Lake Pend Oreille in northern Idaho. In his presentation, and in a subsequent extended paper (Pardee, 1942), Pardee presented his new evidence that the ice dam for glacial Lake Missoula had failed suddenly, with a resulting rapid drainage of the lake. Evidence for the latter included the ripple marks, plus severely eroded constrictions in lake basins and giant gravel bars of current-transported debris. Some of the latter accumulated in high eddy deposits, marginal to the lake basins, showing that the immensely deep lake waters were rapidly draining westward toward the heads of the various scabland channels that had been so well described by Bretz.

Though Pardee did not directly claim the connection of glacial Lake Missoula to the Channeled Scabland, his evidence provided needed coherence to Bretz's hypothesis of cataclysmic flooding. Despite this, resistance to Bretz's flood hypothesis remained strong, not subsiding until the accumulated field evidence became overwhelming (e.g. Bretz *et al.*, 1956). When it was eventually demonstrated that the relevant physical processes are completely consistent with that evidence (Baker, 1973), there was no way to continue to invoke a muddled view of uniformitarianism against Bretz's hypothesis.

1.4 Terrestrial megafloods

Continental ice sheets that form during epochs of glaciation exert immense influences on water drainage across the land. Their huge loads depress the underlying land surface, and lakes form in the moats that surround the ice sheets. They can block the lower courses of major rivers, impounding flow, and even diverting it into adjacent drainage basins. Meltwater from glacial margins may introduce huge discharges into land-surface depressions that hold much smaller lakes during non-glacial periods. The lakes may climatically alter water balances, promoting further glaciation by a kind of positive feedback. There are modern examples for all these situations but the relatively small size and different thermal regimes of modern versus ice-age glaciers pose problems of extrapolation to the past conditions of major continental glaciation that favoured the development of glacial megalakes.

1.4.1 Cordilleran Ice Sheet: ice-dammed lakes

Very deep lakes can form when a glacier advances down a mountain valley to block a river. The famous example is glacial Lake Missoula, noted above, which formed

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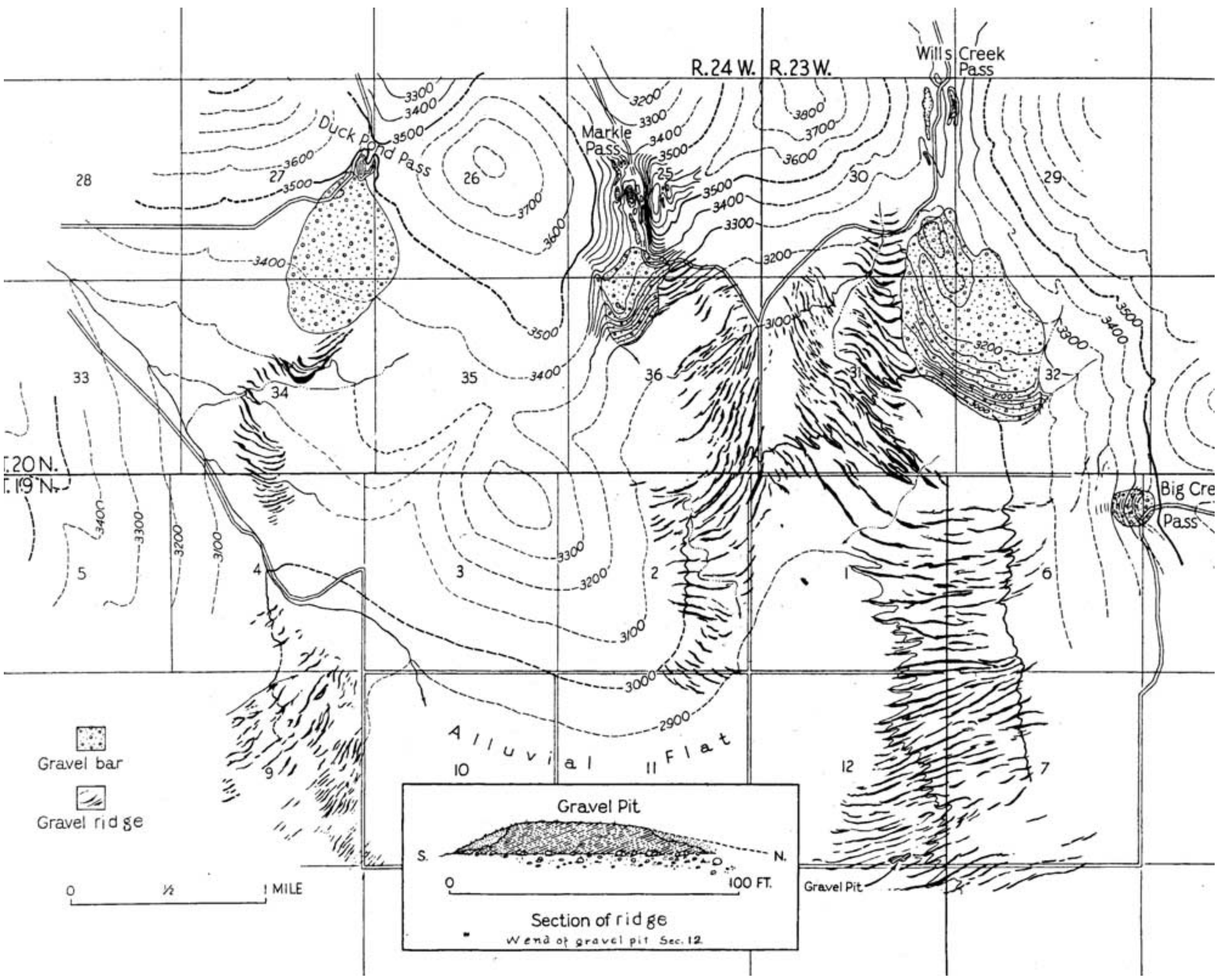

Figure 1.2. Map of giant current 'ripple marks' in the northern part of Camus Prairie Basin of glacial Lake Missoula (Pardee, 1942).

south of the Cordilleran Ice Sheet, in the northwestern United States. The Purcell Lobe of the ice sheet extended south from British Columbia to the basin of modern Pend Oreille Lake in northern Idaho. It thereby impounded the Clark Fork River drainage to the east, forming glacial Lake Missoula in western Montana. At maximum extent this ice-dammed lake covered 7500 km^2, holding a water volume of about 2500 km^3 with a depth of 600 m at the dam. Repeated failures through subglacial tunnels are inferred to have occurred between about 17 500 and 14 500 calendar years ago (Waitt, 1985; Atwater, 1986). Cataclysmic failure of the ice dam impounding this lake resulted in discharges into the Columbia River system of up to about 20 sverdrups (O'Connor and Baker, 1992). As recognised by Baker and Bunker (1985), the multiple outburst events were of greatly differing magnitudes. About 15 exceeded 3 sverdrups, and at least one of these exceeded about 10 sverdrups in discharge (Benito and O'Connor, 2003). The largest failure or failures probably involved a different source mechanism than the subglacial tunnelling envisioned by Waitt (1985) because that mechanism yields discharges of only 1 to 2 sverdrups (Clarke *et al*., 1984). Upon reaching the Pacific Ocean the Missoula floodwaters continued flowing down the continental slope as hyperpycnal flows and associated turbidity currents (Normark and Reid, 2003). The sediment-charged floodwaters followed the Cascadia submarine channel into and through the Blanco Fracture Zone and out onto the abyssal plain of the Pacific. As much as 5000 km^3 of sediment may have been carried and distributed as turbidites over a distance of 2000 km west of the Columbia River mouth.

1.4.2 Laurentide Ice Sheet: ice-marginal lakes

The largest well-documented glacial megalake formed in north-central North America in association with the largest glacier of the last ice age, the Laurentide Ice

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Sheet. This ice sheet is known to have been highly unstable throughout much of its history. Not only did freshwater discharges from the glacier result in ice-marginal lakes; outbursts of meltwater into the Atlantic Ocean may have generated climate changes by influencing the thermohaline circulation of the North Atlantic Ocean (Teller *et al.*, 2002). As the Laurentide Ice Sheet of central and eastern Canada retreated from its late Quaternary maximum extent, it was bounded to the south and west by immense meltwater lakes, which developed in the troughs that surrounded the ice. As the lake levels rose, water was released as great megafloods, which carved numerous spillways into the drainages of the Mississippi, St Lawrence and Mackenzie Rivers (Kehew and Teller, 1994). The greatest megafloods developed from the last of the ice-marginal lakes, a union between Lake Agassiz in south-central Canada and Lake Ojibway in northern Ontario. The resulting megalake held about 160 000 km^3 of water, which was released subglacially about 8200 years ago under the ice sheet and into Labrador Sea via the Hudson Strait (Clarke *et al.*, 2004).

1.4.3 Eurasia ice sheets: river diversions

In Europe, as in North America, there was a long period of controversy before late-glacial megaflooding was broadly recognised as an important geological process. One reason was that much of the megaflooding from the western part of the Fennoscandian Ice Sheet seems to have been conveyed through the English Channel, morphological evidence of which has only recently become compelling (Gupta *et al.*, 2007). In the 1970s the Russian palaeoglaciologist Mikhail G. Grosswald recognised that the Quaternary ice-sheet margins of northern Eurasia, like those of northern North America, held huge proglacial lakes, and great spillways developed for the diversion of drainage. Not only was meltwater diverted to the south-flowing Dnieper and Volga Rivers but also the great north-flowing Siberian rivers, the Irtysh, Ob and Yenisei, were impounded by ice sheets that covered the modern Barents and Kara Seas. Grosswald's original work was highly criticised, but more recent work confirms these impoundments and ice sheets, though there remains considerable controversy over their extent, timing and genesis (Mangerud *et al.*, 2004). Grosswald (1980) interpreted this blockage to be Late Weichselian in age (about 15 000–20 000 years ago). However, more recent work considers the events to have been Early Weichselian (Arkhipov *et al.*, 1995), about 90 000 years ago, when ice-sheet growth was enhanced by the climatic influence of the ice-dammed lakes (Krinner *et al.*, 2004).

The largest lake, formed on the west Siberian plain, was estimated by Mangerud *et al.* (2004) to cover 600 000 km^2 at a surface elevation of 60 m. However, both Arkhipov *et al.* (1995) and Grosswald (1980) postulate a much larger palaeolake, about 1 200 000 km^2 in area, with a volume of about 75 000 km^3 at a surface elevation of 128 m. This west Siberian megalake was the Asian equivalent of Agassiz. It drained southward, through the Turgai divide of north-central Kazakhstan, to the basin of the modern Aral Sea. This megalake had an elevation of 70 or 80 m, higher than the 1960 elevation of 53 m, and an area of 100 000 km^2 compared with 60 000 km^2 in 1960. This palaeolake then drained southwestward through the Uzboi channel into the basin of the modern Caspian Sea. Also fed by glacial meltwater from northern Europe via the Volga, the Caspian expanded to a Late Quaternary size over twice its modern extent. Known as the Khvalyn palaeolake, it inundated an area of 950 000 km^2, holding a volume of 135 000 km^3 at an elevation of 50 m (the modern Caspian level is −28 m). The Khvalyn palaeolake spilled westward through the Manych spillway into the Don valley, then to the Sea of Azov, and through the Kerch Strait to the Euxine Abyssal Plain, which is the floor of the modern Black Sea.

In full-glacial time the Black Sea basin was disconnected from the Aegean and partially filled by freshwater (the New Euxine phase). The glacial meltwater filled the basin to an elevation of −60 m. This basin functioned in two modes during the Quaternary. Its cold-climate mode was a freshwater lake (that may have filled and drained through northwestern Turkey to the Aegean). Its warm-climate phase involved rising global sea level, inducing salt-water invasions through the Turkish straits to form the saline Black Sea, the last of which occurred about 8000 years ago, an inundation claimed by Ryan *et al.* (2003) to have inspired the biblical story of Noah (see further discussion below).

1.4.4 Central Asian mountain areas: ice-dammed lakes

In the mountain areas of central northern Asia, there were several great ice-dammed expansions of modern lakes, such as Issyk-Kul, Kyrgyzstan, the second largest modern mountain lake in the world (6000 km^2 area; 4000 km^3 volume). It was an even larger ice-dammed lake during the last glaciation, rising to 300 m above the present lake level (Grosswald *et al.*, 1994). Spectacular erosion at the full-glacial lake outlet, Boam Canyon, indicates that this palaeolake failed by cataclysmic outburst flooding. In the Altai Mountains, great megafloods emanated from the late Pleistocene ice-dammed Chuja-Kuray palaeolake, covering 12 000 km^2 and holding between 600 and 1000 km^3 of water, perhaps 600 m deep at the ice dam (Baker *et al.*, 1993; Carling *et al.*, 2002, 2008). Downstream of this ice-dammed lake, the Chuja and Katun River valleys are characterised by immense gravel bars, emplaced by the flooding into various valley-side embayments. The bars are

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up to 5 km long and 120 m in height. The bar surfaces and associated run-up layers of flood-transported gravel indicate maximum flow depths of about 320 m. Flow modelling of the associated palaeoflood discharges retrodicts a peak flow of about 11 sverdrups and mean flow velocities of about 30 m/s (Herget, 2005).

Another region with extensive evidence of Late Quaternary megafloods is Tuva. The Tuvan palaeofloods derived from an ice-dammed lake in the Darkhat depression of north-central Mongolia (Grosswald and Rudoy, 1996). The palaeolake held about 250 km^3 of water with a depth of 200 m at its ice dam. The palaeoflooding entered the upper Yenisei River and it was remarkable for the emplacement of spectacular trains of giant current ripples (gravel dunes) near the Tuva capital city of Kyzyl. Following the Yenisei River valley, the Tuvan floods emerged from canyons of the West Sayan Mountains and entered the Abakan Basin, where they deposited a great fan complex.

1.5 Martian megafloods

Earth and Mars are the only two planets known to have geological histories involving vigorous surface cycling of water between reservoirs of ice, liquid and vapour. Although the current state of the Martian surface is exceedingly cold and dry, there are extensive reservoirs of polar ice and ground ice (Boynton *et al.*, 2002), plus probable immense quantities of groundwater beneath an ice-rich permafrost zone (Clifford, 1993; Clifford and Parker, 2001). As recognised 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. Immense channels, with widths of tens of kilometres and lengths of up to a few thousand kilometres, display a suite of morphological attributes that are most consistent with genesis by cataclysmic flows of water and sediment (Baker and Milton, 1974; Baker, 1982). On Earth such flows produced the distinctive landforms of the Channeled Scabland (Baker, 1978). In contrast to terrestrial megafloods, however, the Martian outflow channels involved much larger cataclysmic flood flows (Baker, 2001), and many floods emanated from subsurface sources, mostly during periods of Martian history during the billion years or so after termination of the heavy bombardment phase at about 3.9 Ga. The huge peak discharges implied by the size and morphology of the outflow channels (Baker *et al.*, 1992; Baker, 2001) are explained by several models. A currently popular view holds that a warm, wet climate phase during the heavy bombardment was followed by a progressively thickening ice-rich permafrost zone during subsequent, cold and dry Martian history. The outflow channels result from releases of subsurface water that was confined by this cryosphere (Carr 1979, 2000). However, the geological record shows that volcano–ice–water interactions are commonly associated with outburst flood channels. Thus, episodic heat flow and volcanism (Baker *et al.*, 1991) affords a reasonable alternative to the linear model of progressive pressurisation of confined water by cryosphere thickening.

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. The process could have been a trigger for atmospheric water migration leading to ice emplacement (Baker, 2003) in latitudinal zonation for which orbital variations likely acted as the pacemaker (Head *et al.*, 2003).

1.6 Global consequences

1.6.1 Earth

The oceans of the Earth constitute a vast, interconnected body of water that covers about 70% of the surface of the planet. This immense water reservoir is integral to long-term climate change. Ocean currents distribute heat between the equator and the poles. For example, the Gulf Stream flows at discharges of up to 100 sverdrups, involving relatively slow-moving water 1 km in depth and 50 to 75 km wide. As northward-flowing Atlantic Ocean seawater evaporates and becomes more saline, it increases in density, eventually sinking in the northern Atlantic. This process forms a portion of the great global thermohaline circulation pattern, which acts as a conveyor belt for heat in the oceans. However, this global-scale circulation pattern was disrupted during the last glaciation when megafloods introduced relatively low-density, freshwater lids over large areas of ocean surface. The resulting disruption of sea-surface temperatures and density structure drastically altered the meridional transport of heat on a global scale (Clark *et al.*, 2001). The global climate of the Earth was altered on time scales of decades to centuries (Broecker *et al.*, 1989; Barber *et al.*, 1999).

The connections between Pleistocene ice sheets and the oceans are still very poorly understood. An important link is inferred from relatively brief (100- and 500-year) intervals in which thick marine layers of ice-rafted material were widely distributed across the North Atlantic. Called ‘Heinrich events’, these layers are thought to record episodes of massive iceberg discharge from unstable ice sheets. The youngest Heinrich events date to 17 000 (H1), 24 000 (H2) and 31 000 (H3) years ago. Closely related is the Younger Dryas (YD) event, a global cooling at 12 800 years ago, which is also associated with North Atlantic

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ice-rafted rock fragments. There is evidence from corals at Barbados that sea level rose spectacularly, about 20 m during H1 and about 15 m just after YD. Such rises would require short-term freshwater fluxes to the oceans respectively of about 14 000 and 9000 km^3/yr. (Fairbanks, 1989). These events are thought to relate to ice-sheet collapse, reorganisation of ocean–atmosphere circulation, and release of subglacial and proglacial meltwater, most likely during episodes of cataclysmic megaflooding.

Terrestrial megafloods influence the global climate system through their interactions with the ocean. A megaflood can enter the ocean either as a buoyant spreading freshwater plume over higher density (salty) seawater (Kourafalou *et al.*, 1996), or as a descending flow of sediment-laden, high-density fluid, known as a hyperpycnal flow (Mulder *et al.*, 2003). The turbidity current deposits of hyperpycnal flows may extend across hundreds, even thousands of kilometres of abyssal plain seafloor, as in the case of the Missoula Floods of the Cordilleran Ice Sheet (Normark and Reid, 2003). Nevertheless, these flows gradually lose momentum as they drop their sediment loads, thereby releasing low-density freshwater from the bottom of deep ocean basins. The buoyant freshwater then moves upward in massive convective plumes (Hesse *et al.*, 2004). These plumes disrupt the thermal structure of the ocean, with consequences for the currents that distribute heat and moderate climates.

1.6.2 Mars 'oceans'

Evidence for persistent standing bodies of water on Mars is abundant (e.g. Scott *et al.*, 1995; Cabrol and Grin, 2001; Irwin *et al.*, 2002). Despite the lack of direct geomorphological evidence that the majority of the surface of Mars was ever covered by standing water, the term 'ocean' has been applied to temporary ancient inundations of the northern plains, which did not persist through the whole history of the planet. Although initially inferred from sedimentary landforms on the northern plains (e.g. Lucchitta *et al.*, 1986), inundation of the northern plains has been controversially tied to identifications of 'shorelines' made by Parker *et al.* (1989, 1993).

Sediment-charged Martian floods from outflow channels (Baker, 1982) would have entered the ponded water body on the northern plains as powerful turbidity currents. This is the reason for the lack of obvious delta-like depositional areas at the mouths of the outflow channels. High-velocity floods, combined with the effect of the reduced Martian gravity (lowering the settling velocities for entrained sediment) promotes unusually coarse-grained washload (Komar, 1980), permitting the turbidity currents to sweep over the entire northern plains. The latter are mantled by a vast deposit, the Vastitas Borealis formation, that covers almost 3×10^7 km^2, or approximately one-sixth of the area of the planet. This sediment is contemporaneous with the post-Noachian outflow channels and it was likely emplaced as the sediment-laden outflow channel discharges became hyperpycnal flows upon entering ponded water on the plains (Ivanov and Head, 2001). In another scenario, Clifford and Parker (2001) envision a Noachian 'ocean', contemporaneous with the highlands valley networks and fed by a great fluvial system extending from the south polar cap, through Argyre and the Chryse Trough, to the northern plains.

The immense floods that initially fed the hypothetical Oceanus Borealis on Mars could have been the triggers for hydroclimatic change through the release of radiatively active gases, including carbon dioxide and water vapour (Gulick *et al.*, 1997). During the short-duration thermal episodes of cataclysmic outflow, a temporary cool-wet climate would prevail. Water that evaporated off Oceanus Borealis would transfer to uplands, including the Tharsis volcanoes and portions of the southern highlands, where precipitation as snow promoted the growth of glaciers and rain contributed to valley development and lakes. However, this cool-wet climate was inherently unstable. Water from the evaporating surface-water bodies was lost to storage in the highland glaciers, and as infiltration into the porous lithologies of the Martian surface.

1.7 Modern controversies

1.7.1 Black Sea

Although Late Quaternary freshwater inundation of the Black Sea is well recognised, it is usually correlated to enhanced proglacial meltwater flow via the many rivers draining southward from the northern Eurasian ice sheets, as noted above. A recent controversy has arisen, however, over the marine influx to the Black Sea that occurred during rising Holocene sea level, which spilled Mediterranean water through the Hellespont and Bosporus, reaching the Black Sea about 9500 years ago. One view (Bryan *et al.*, 2003) holds that the global ocean rose to the level of a relatively shallow sill of the Bosporus outlet and catastrophically spilled into the Black Sea basin, which then was then partly filled with freshwater to a level about 85 m below that of today. The resulting cataclysmic inundation presumably displaced a large human population in a calamity that is equated to the Noachian flood myth. An alternative view is that much of the Bosporus is underlain by freshwater facies of late Pleistocene age, derived from the Black Sea. The minimal erosion of these sediments is not consistent with cataclysmic flooding leading to the overlying Holocene marine facies of Mediterranean origin.

Based on marine science data from the Black Sea, Ryan and colleagues (Ryan *et al.*, 1997) proposed that the Black Sea basin had been catastrophically flooded

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during the early Holocene, now thought to have been about 8400 years ago (Ryan, 2007). Ryan and Pitman (1998) subsequently elaborated that, prior to this flood, the Black Sea basin held an isolated freshwater lake, which was separated from the world ocean (then at a much reduced sea level) by the mountains of Turkey. Moreover, a large number of people inhabited the shores of this lake.

Rising world sea level eventually resulted in the breaching of the mountain divides that separated the freshwater lake of the Black Sea from the world ocean. As the water burst through the modern Bosporus Strait, the water rose 15 cm per day in the Black Sea, filling its basin in about 2 years. The human population that experienced this cataclysm was forced to disperse, carrying with it a memory of the great flooding, and conveying that story to the many other cultures that were encountered. Given that one of those cultures provided the Mesopotamian influence on the author(s) of Genesis, it was appropriate to label the model for this event, the 'Noah's Flood Hypothesis'.

The current status of this hypothesis, modified from the original by Ryan *et al.* (2003), is defended by Ryan (2007). Hiscott *et al.* (2007) present an alternative model, the 'Outflow Hypothesis', involving a gradual transition in salinity of the late Quaternary Black Sea. These latter authors do not accept the early Holocene evaporative drawdown of the freshwater lake in the Black Sea basin that preceded the 8.4 kyr BP cataclysmic saltwater inundation of the 'Noah's Flood Hypothesis'. However, they do accept one of the modifications made in the original Ryan *et al.* model, specifically that late-glacial, meltwater-induced inflow to the Black Sea basin induced it to spill freshwater through the Bosporus to the Sea of Marmara. This late Pleistocene freshwater flooding was on an immense scale, such that Chepalyga (2007) claims that 'The Flood' was not the 8.4 kyr BP saltwater inundation of the Black Sea basin (derived from the world ocean via the Bosporus, Sea of Marmara, etc.). Instead, there was an earlier, much larger catastrophe in which a cascade of spillings occurred from the Aral to the Caspian basins, and ultimately to the Black Sea via the Manych Spillway. Additional water was supplied by 'superfloods' in the river valleys of European Russia, the Don, Dneiper and Volga.

Was the Black Sea inundation the source of a flood myth, specifically one that inspired western Asiatic peoples to the beliefs that inspired the account of Noah in Genesis? The anthropological implications of the 'Noah's Flood Hypothesis' were greeted with considerable scepticism by many archaeologists. Nevertheless, physical aspects of the Ryan *et al*. model of early Holocene saltwater flooding of the Black Sea basin receive some support from Coleman and Ballard (2007), Algan *et al.* (2007) and Lericolais *et al.* (2007). These studies document spectacular evidence for submerged palaeoshorelines, including drowned beaches, sand dunes and wave-cut terraces. Some radiocarbon dates (Ryan, 2007) support the proposed early Holocene age for these presumed shorelines of the freshwater lake that existed prior to the cataclysmic inflow of marine water. Other studies find no evidence in preserved fauna or sediments that there was a cataclysmic flood (e.g. Yanko-Hombach, 2007).

1.7.2 Subglacial megafloods

The recent documentation of subglacial flood flows as a modern process for Antarctic subglacial lakes (Wingham *et al.*, 2006; Fricker *et al.*, 2007) leads to the tantalising suggestion that the large late-glacial continental ice sheets may also have experienced subglacial flooding. Indeed, the topic of subglacial flooding has been the subject of a major controversy in glacial geomorphology over the last 25 years or so. The controversy has arisen from John Shaw's (1983, 2002) quite original emphasis on flooding as the mechanism for the generation of subglacial landforms. A broad variety of enigmatic landforms, involving water erosion and deposition, developed beneath the Laurentide Ice Sheet. These landforms include drumlins, Rogen moraines, large-scale bedrock erosional flutings and streamlining, and tunnel channels (valleys). Though most commonly explained by subglacial ice and debris-layer deformational processes, the genesis of these features cannot be observed in modern glaciers that are much smaller than their late Quaternary counterparts. Shaw (1996) explains the assemblage of landforms as part of an erosional/depositional sequence beneath continental ice sheets that precedes regional ice stagnation and esker formation with a phase of immense subglacial sheet floods, which, in turn, follows ice-sheet advances that terminate with surging, stagnation and melt-out. Shaw (1996) proposes that peak discharges of tens of sverdrups are implied by the late Quaternary subglacial landscapes of the southern Laurentide Ice Sheet. Release volumes are also huge; Blanchon and Shaw (1995) propose that a 14 m sea-level rise at 15 ka resulted from this megaflooding.

Shoemaker (1995) provides some theoretical support for Shaw's model, though at smaller flow magnitude levels. Arguments against the genetic hypotheses for the landforms are given by Benn and Evans (1998, 2006). Walder (1994) criticises the hydraulics, and Clarke *et al.* (2005) object that the theory requires unreasonably huge volumes of meltwater to be subglacially or supraglacially stored and then suddenly released. Shaw and Munro-Stasiuk (1996) respond to these and other criticisms.

Subglacial cataclysmic flooding has been proposed recently for the Mid-Miocene ice sheet that overrode the Transantarctic Mountains (Denton and Sugden, 2005; Lewis *et al.*, 2006). Spectacular scabland erosion occurs on plateau and mountain areas up to 2100 m in elevation,

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over an 80 km mountain front. The inferred high-energy flooding could have been supplied from subglacial lakes, such as modern Lake Vostok (Siegert, 2005). Such lakes would have formed beneath the thickest, warm-based portion of the ice sheet, located inland (west) of the mountains (Denton and Sugden, 2005). Thinner ice overlying the mountains was probably cold-based, thereby generating a seal that could be broken when the pressure of water in the lakes, confined by thick overlying ice, reached threshold values. The water from the lakes would move along the ice–rock interface, along the pressure gradient up and across the mountain rim. The high-velocity flooding would be further enhanced to catastrophic proportions as conduits were opened by frictional heat in the subglacial flows (Denton and Sugden, 2005).

Perhaps the most spectacular hypothesised subglacial flooding is envisioned by Grosswald's (1999) proposal that much of central Russia was inundated in the late Quaternary by immense outbursts from the ice-sheet margins to the north. Using satellite imagery to map large-scale streamlined topography and flow-like lineations, Grosswald (1999) infers colossal flows of water from beneath an ice cap that covered the entire Arctic Ocean. His hypothesised floods entered what is now central Siberia from the north and turned westward to follow the Turgai and other spillways noted above, eventually reaching the Caspian and Black Sea basins.

1.8 Discussion

Too much can be made in science of the current philosophical fad of testing (falsifying) hypotheses. As long recognised in geological investigations, hypotheses about past phenomena cannot function as propositions to be experimentally manipulated in a controlled laboratory setting. Because geologists study a past that is inaccessible to experimentation, they follow 'working hypotheses', testing for their consistency and coherence with the whole body of collected evidence. Applying methods described by T. C. Chamberlin, G. K. Gilbert and W. M. Davis (see Baker, 1996), geologists have long used their working hypotheses to advance a path of inquiry toward the truth of the past, while avoiding the blockage of that inquiry by privileging any particular take on that past. It is certainly within this tradition that the various studies in this volume have operated. For both its advocates and detractors, the 'Noah's Flood Hypothesis' of Ryan and colleagues, Shaw's subglacial floods, and Grosswald's ice sheets have provided stimuli to further inquiry, made more productive by having a target to consider for the investigation. That these targets involved considerable inspiration to the popular imagination just makes the inquiry more intense and compelling. For what more could one ask in a scientific controversy?

With much of North America and Eurasia experiencing huge diversions of drainage by glacial meltwater flooding during the period of major ice-sheet decay, it is not surprising that many human cultures developed narrative traditions involving 'worldwide flooding'. Certainly, 'the world' for a local human society of 12 000 years ago involved a much smaller geographical extent than that word would convey to the global human society of today. Thus, there is no mystery that the most impressive event in the lives of many late ice-age cultures would have been 'worldwide flooding', and the collective memory of this experience would be conveyed via oral traditions to later generations, inspiring awe up to the present day.

Acknowledgements

My early studies of megafloods were stimulated and encouraged by William Bradley, Hal Malde, David Snow and, especially, J Harlen Bretz.

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