The Restructuring of Analogical Reasoning in Planetary Science

Richard J. Soare

Department of Geography
McGill University
Montreal, Canada
August 2004

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
of the degree of Master of Science

Your file Votre référence
ISBN: 0-494-12543-8
Our file Notre référence
ISBN: 0-494-12543-8

Abstract

Despite its ubiquity in planetary science, analogue-based reasoning largely has remained unbounded by guidelines of use. Establishing analogical guidelines and putting them to the test is the main aim of the thesis. Towards this end, I discuss the philosophical foundations of analogical reasoning in planetary geomorphology and posit rules of use that facilitate the evaluation of analogical hypotheses. Subsequently, I present four hypotheses concerning aeolian, fluvial and periglacial processes on Mars. Each of these hypotheses is evaluated in terms of the analogical rules presented. The fourth hypothesis is original to this thesis and suggests that a periglacial landscape comprising pingos and small-scale polygonal ground exists in an impact crater located in northwest Utopia Planitia.

Résumé

Malgré son omnipresence dans les sciences planétaires, le raisonnement analogique demeure largement non restreint par des normes d'usage. L'établissement de ces normes est l'objectif principal de la présente thése. En cette fin, la thése découvre les fondations intellectuelles du raisonnement analogique dans le domaine scientifique et geomorphologique. Basées sur cette élaboration, des regles permettant l'évaluation de la viabilité analogique sont présentées et la signifiance de quatre analogues Martiens est estimée. La quatrième hypothése est originale et propose la presence d'un paysage periglacial dans un cratère situé dans le coin nord-ouest de Utopia Planitia.

Acknowledgements

In preparing this thesis I benefited greatly from discussions with Jean-Michel Wan Bun Tseung, Devon Burr and Claude Peloquin. The thesis could not have been completed without the ongoing support and friendship of my supervisor Nigel Roulet as well as Tim and Catherine Moore. Deep gratitude must be expressed to Debbie, my wife. Her understanding, patience and advice were cornerstones of my work. Thanks to Wayne Pollard for introducing me to the exciting domain of periglacial geomorphology. Permits issued by the Aurora Research Institute, the Inuvialuit Land Administration, Parks Canada (Western Arctic Division), the Hunters and Trappers Committee of Tuktoyaktuk and the Hamlet of Tuktoyaktuk enabled me to conduct research in the Tuktoyaktuk peninsula of the Northwest Territories in Canada. This research was facilitated by Michelle Crossfield (Aurora Research Institute), Brian Johnson (Parks Canada, Western Arctic Division) and Jim McTaggart (Inuvialuit Land Administration). Funding for field work at the McGill Axel Heiberg Research Station in Nunavut was provided by the Northern Scientific Training Programme and by the McGill Centre of Global Climate Change Research. Logistical support was given by the Polar Continental Shelf Project.

Table of Contents

Chapter 1: Introduction

Unlike so much of terrestrial geomorphology, the study of Martian landscapes is practised *in absentia,* at a distance: field data are obtained remotely and field work is undertaken robotically. Dissatisfied with the constraints of study from afar, some planetary scientists are looking at the geomorphology of Mars through the lens of terrestrial analogues. For example, the deserts of the American southwest are seen as sources of insight on some Martian aeolian processes. Areas that are very cold and dry - the Arctic and the polar deserts of the Antarctic - have drawn attention as periglacial and glacial analogues, respectively. Often, the Channeled Scablands of Washington state and the cataclysmic discharge that led to their formation are seen as analogues for outflow channel genesis and landscape development in the highlands of equatorial Mars. But despite its ubiquity within Martian geomorphology, analogue-based reasoning largely has remained unbounded by guidelines of use or tests of viability (Soare *et al.* 2001; Soare *et al.* 2002). Establishing and then testing a proposed set of analogical guidelines are the principal goals of the thesis.

In chapter two, "The Role of Terrestrial Analogues in Exploring Martian Landscape Development," I set the conceptual foundation for this endeavour. First, I elaborate the aims, methods and day-to-day work of science. Second, I discuss the ongoing tension between reasoning that is constrained and reasoning that is unconstrained by orthodox paradigms and mainstream modes of thought. I argue that a middle course between too much and too little freedom is required in order to conduct scientific inquiries properly.

The detailed study of Martian landscapes dates back no further than the low resolution images of the Martian surface delivered by the Mariner missions of the mid-nineteen sixties and early nineteen seventies. Despite improvements in the resolution and scale of Mars imagery, speculation concerning the evolution of Martian landscapes has continued to be hampered by a lack of comprehensive primary data. The use of terrestrial landscapes as geomorphological analogues is an attempt to overcome this limitation.

Groundbreaking as this analogical approach may seem, the history of its use has been marked by two principal shortcomings. First, analogical opinions, hypotheses and arguments have been propagated in an intellectual environment lacking a critical framework of analysis. Second, there has been a failure to recognise that the relevance of a terrestrial analogue to a non-terrestrial landscape is directly proportional to one's understanding of that non-terrestrial landscape. If one's understanding of an non-terrestrial environment is poor, then the potential relevance of a terrestrial analogue will be difficult to ascertain or indeterminate.

I argue that relieving this indeterminacy requires an ongoing commitment to data collection and interpretation. When it is possible, different data streams should be integrated. Also, simplicity and plausibility ought to be cornerstones of hypothesis generation. By elaborating these guidelines in chapter two, I hope to facilitate the ability of planetary scientists to posit insightful and sound analogical hypotheses.

In chapter three, "The Dust Devil and Cataclysmic Discharge Hypotheses," I present two analogically driven hypotheses. The first hypothesis discuses aeolian processes and asks whether dust devils are one of the transport mechanisms contributing to the massive presence of dust in the Martian atmosphere. The second hypothesis discusses fluvial processes and evaluates whether some of the ancient channels near the Martian equator could be the work of large-scale fluvial discharges. Using the analogical guidelines presented in chapter two, I compare the two hypotheses critically.

In chapter four, "Pingos and Periglacial Processes on Mars," I evaluate the analogical standing of Martian pingo hypotheses. The first hypothesis is based on the possible presence of large pingo-like mounds in a near-equatorial impact crater named Gusev. The second hypothesis is based on the identification of small pingo-like mounds, small-scale polygonal patterned ground and a possible drainage system on the floor of a sub-polar impact crater to the north of the equator in northwest Utopia Planitia. The similarity between the Utopia crater floor landscape and the drained-lake landscape of the Tuktoyaktuk peninsula in northern Canada will be highlighted.

In chapter five, the conclusion, I summarise the four hypotheses presented in chapters three and four and compare their analogical soundness. In so doing I provide planetary scientists with four case studies and a template of evaluation that can be used to test the viability of other analogical hypotheses.

Chapter 2: The Role and Value of Using Terrestrial Analogues to Understand Martian Landscape Development

2.1 Analogical Reasoning in Planetary Science

Planetary scientists who are dissatisfied with the constraints of studying Martian geomorphology from afar have begun to look at landscapes on the red planet through the lens of terrestrial analogues. They argue that the processes forming the surface features of Mars and Earth are common to both terrestrial planets. Moreover, as terrestrial analogues are closer to hand, easier to study and understood better than are Martian landscapes, these analogues offer a unique opportunity for bridging the physical and conceptual space between Earth and Mars. For example, the dry, hot deserts of the American southwest have been identified as a useful test for evaluating ideas and hypotheses concerning dust upliftment and transport on Mars (Houser *et al.* 2003; Greeley *et al.* 2002). Areas that are very cold and dry - the Arctic (Andersen *et al.* 2002; Arcone *et al.* 2002; Lee and Rice 2003; Lee and Mackay 2003; Pollard *et al.* 1999; Soare and Pollard 2002; Soare and Peloquin 2003) and the polar deserts of the Antarctic (Andersen *et al.* 1991, Arcone *et al.* 2002; Haberle *et al.* 2001; McKay 1986; Priscu *et al.* 1998; Simmons *et al.* 1993, Thomas and Dieckmann 2002; Wharton *et al.* 1989; Wharton *et al.* 1990) have been sought out for possible insight on Martian cold-climate processes. When the origin and subsequent bedform development of the larger outflow channels on Mars are discussed, the Channeled Scablands of Washington state are cited frequently (Baker 1978, 2001; Baker *et al.* 1992; Baker and Milton 1974; Burr *et al.* 2002; Carr 1979, Carr *et al.* 1995; Masursky *et al.* 1977; Murray *et al* 1971a; Murray *et al.* 1971b; Simmons *et al.* 1993; Wharton 1990). Attractive as terrestrial analogues may be on practical grounds, for analogically derived hypotheses to be deemed conceptually valuable their plausibility and merit must be demonstrable on scientific grounds (Soare *et al.* 2001, 2002).

The aim of physical science is to explain and understand the behaviour of phenomena in the natural world. Towards this end, the scientific method encompasses four key parts: 1. observation of data; 2. hypothesis generation by deduction; 3. consolidation of general theories and laws by induction; and 4. testability of hypotheses by experiment (Chamberlin 1890, 1897; Gilbert 1896; Russell 1962; Kuhn 1970; Schumm 1998). While each of the four parts is integral to the proper conduct of scientific inquiry, potential testability is at the fulcrum. Absent of the potential opportunity for testing hypotheses or theories, the ability to differentiate meaningful from meaningless pursuits, to distinguish valid from invalid arguments and to establish the truth or falsehood of contentious premises, lapse. In turn, the conditions under which hypotheses are tested must be transparent, replicable and available for the peer review of the scientific community. Ultimately, the intersubjective judgement of this community is the determinant of scientific validity and plausibility (Kuhn 1970; Rorty 1979; Russell 1962; Wittgenstein 1971).

When hypotheses are anomalous or on the cutting edge of understanding, the general community of scientists may greet them with resistance, doubt and the anxiety born of the community's desire to safeguard its way of thinking. Admittedly, this initial response may be informed as much by pride and ideological prejudice as by the dictates of reason and sound judgement (Kuhn 1971). However, with the passage of time the influence of pride and prejudice fall before that of reason and judgement. Eventually, the collective understanding of the scientific community coalesces intersubjectively around ideas and hypotheses that meet the requirements of the scientific method.

By contrast, when the validation of hypotheses is left entirely in the hands of individual scientists, they may lapse into

> ...an unconscious selection and magnifying of phenomena that fall into harmony with the[ir] theory and support it, and an unconscious neglect of those that fail of coincidence. The mind lingers with pleasure upon the facts that fall happily into the embrace of the theory, and feels a natural coldness toward those that seem refractory (Chamberlin 1890).

This is not to depreciate the potential value of partiality and bias in the evolution of scientific understanding. Sometimes, partiality and bias may be just the spark required to ignite debate that has stagnated or become inert (Feyerabend 1980). In the long run, however, recourse to peer review is what enables the work of science not to be led astray. For example, in 1989 Martin Fleischmann and Stanley Pons presented a set of unlikely findings that startled the scientific community: that fusion could be induced at very low temperatures, in a test tube and deficient of a massive neutron flux (Collins and Pinch 1998). These claims engendered bewilderment and scepticism amongst fellow scientists. In part, this response was understandable. Fusion reactions are induced when the natural repulsion between particles is overcome; in turn, this creates a massive flux of neutrons. It is thought that extremely high temperatures are the sole physical means of overcoming particle repulsion (personal communication, Dr. Ernest Lo, University of Quebec at Montreal, February 2004). For Flesichmann and Pons to argue otherwise, as they did, was to turn orthodox thinking on its head.

In the day to day work of science, the occurrence of anomalous hypotheses and findings neither are unexpected nor undesirable. Anomalies are a litmus test. If the dominant hypotheses and findings of science survive the questions raised by anomalies, then the viability of these hypotheses and findings grows. If anomalies incite a revision of orthodox thinking then, once again, the sweep of scientific understanding broadens. The theory of cold fusion presented science with the opportunity to appraise and to re-evaluate the solidity of its conceptual footings. This is not to suggest that the scientific community welcomes contrary findings and theories warmly in all instances. For contrarian ideas may be deeply unsettling and disturb the perceived equilibrium of thinking in that community.

In the late 18th century Antoine Lavoisier identified oxygen as an element that was essential to many basic chemical reactions. The scientific community reacted to the hypothesis with bewilderment and scepticism equal to that which greeted the findings of Pons and Fleischmann (Kuhn 1970). At the time, belief in phlogisten was indefatigable and fundamental to the understanding of chemical changes in matter. Phlogisten was described as an undetectable substance that was consumed when a material burns (Silberberg 1996). Highly combustible materials such as charcoal were thought to contain large amounts of phlogisten; the phlogisten is used up as charcoal burns, leaving a residue of ash that is deficient of phlogisten (Silberberg 1996). In principle, the loss of phlogisten through the reactive process suggests that the total mass of the products should be less than the total mass of the reactants. Critics of the theory such as Lavoisier pointed out that when careful measurements were taken using the experimental method, no net loss of mass could be detected in the reactants (Silberberg 1996). This practical finding clearly was inconsistent with the theory of phlogisten. Other unsettling questions arose as well: why is air needed for combustion?; and why does charcoal burn only for a short time in a closed vessel? (Silberberg 1996). Lavoisier answered that combustion occurs only in the presence of oxygen and that a combustible substance such as charcoal stops burning in a closed vessel once it has combined with all of the available oxygen (Silberberg 1996).

Despite its initial scepticism, the scientific community scrutinised the evidence presented by Lavoisier and found that the arguments in favour of oxygen outweighed those supportive of phlogisten (Kuhn 1979; Silberberg 1996). Belief in phlogisten dissipated; a new paradigm centred around oxygen arose. The work of Fleischmann and Pons did not bear up as well to the judgement of their peers. Putting aside their doubts about the theory of cold fusion, peer reviewers found that the experimental data presented in support of the cold fusion hypothesis were inconsistent; equally, they surmised that the measurements derivative of the data were imprecise, inconclusive and not replicable (Collins and Pinch 1998). Initially, the negative response to the hypothesis by the scientific community may have been fueled by a desire to protect the *status quo*. In the end, the hypothesis was rejected because the results were untenable.

When data are sparse and the opportunities for field work are limited, the ability to test geomorphological hypotheses may not be ample. This is particularly the case when it comes to evaluating analogically driven hypotheses of Martian landscape development. First, the study of Martian geomorphology suffers from a shortfall of primary data. For example, the collection of ground-based surface data has been limited by the immobility of the twin Viking landers and the relatively modest range of the Pathfinder, Spirit and Opportunity rovers. At the same time, despite the work of the Mars Odyssey and the Mars Global Surveyor in mapping Mars remotely from orbit, much of the Martian surface has not been imaged at a high resolution. Just as primary data are of fundamental importance to the building of stable hypotheses, the plausibility of hypotheses is proportional to the completeness of the data-base upon which the hypotheses rest. Data sets deficient of information make it more difficult for scientists to arrive at consensual evaluations of hypotheses, particularly those on the edge of current understanding. Second, while a number of large-scale landscapes point suggestively to the erosive work of water, ice or mixed debris, active flows of these elements seemingly are absent from present-day landscapes. Their absence ought not to be surprising. The surface pressure of the Martian atmosphere is very low, as is the average surface temperature. Liquid water, on its own or as a fraction of a water-ice flow, is stable only in amounts that are small and where conditions are exceptional (Haberle *et al.* 2001; Hecht 2002).

Limited by data sets that are incomplete and by landscapes whose suggestive morphology does not fit contemporary boundary conditions, analogists must choose one of two paths: 1. continue searching for a critical mass of understanding that reconciles the suggestive appearance of Martian landscapes with contemporary boundary conditions; or, 2. discard the suggestiveness of the landscapes and search for hypotheses that are consistent with contemporary boundary conditions.

In order to dissuade analogists from abandoning analogically driven inquiries that may yet be validated, the development of an analytic framework that helps distinguish plausible from implausible, or meaningful from meaningless hypotheses would be highly beneficial. Fundamental to this framework are three key questions that are essential to establishing rules of procedure: 1. have alternative hypotheses been considered?; 2. does the leading hypothesis incorporate recent (a) primary or secondary data drawn from (b) disparate albeit converging sources - i.e. morphological, meteorological and geological?; and, 3.

to what extent does the leading hypothesis conform to or deviate from expectations carved from terrestrial analogues?

A weak analogical hypothesis is deficient of alternatives, based on data that are sparse and singular in their source and does not conform easily to speculation derived from terrestrial analogues. Moreover, a weak analogical hypothesis could be identified by the amount of *ad hoc* reconfiguration and adaptation required to make it fit analogically-driven expectations. A strong analogical hypothesis stands significantly above its alternatives, is based on data that are reasonably comprehensive and drawn from a multiplicity of sources, and does not require substantial reconfiguration to fit the geomorphological facts of a Martian landscape.

With the set of three critical questions to hand, three disparate Martian geomorphological hypotheses will be evaluated in chapter 3: 1. the dust devil hypothesis; 2. the fluvial outflow channel and cataclysmic genesis hypothesis; and, 3. the impact crater- based pingo hypothesis.

2.2 Multiple Hypotheses

In the main, scientists are trained to see that which they see by the community and the intersubjective circle of understanding of which they are a part (Schumm 1998). However, the mark of a truly outstanding scientist may lie in the ability to move beyond the constraints of formal training by allowing, on occasion, intuition to run its course. In so doing, the mind opens itself up to a multiplicity of possible explanations and hypotheses (Chamberlin 1890, 1896; Gilbert 1896; Rhoads and Thorn 1996; Russell 1962; Schumm 1998). "[T]he power of simultaneous vision from different standpoints," of seeking multiple working hypotheses as the guideposts of inquiry, enhances the credibility of speculation, sharpens discrimination and broadens the foundations of scientific understanding (Chamberlin 1890). This type of competence is especially valuable when leading hypotheses appear to be untestable and when the data sets upon which they are built seem shallow or even inconsistent. In these instances, being open-minded means formulating an array of plausible alternate hypotheses (Chamberlin 1890, 1897; Gilbert 1896; Schumm 1998) and keeping them in view until one of two things happen.

First, as an inquiry becomes increasingly comprehensive one may find that hypotheses generated early on may no longer seem as reasonable or as plausible as they once were. Indeed, the light of new evidence or data may falsify hypotheses previously thought to have been quite strong. Second, the evidence or data supportive of one hypothesis may come to outweigh the evidence or data supportive of its alternatives. As the focus of an inquiry becomes increasingly clear, a scientist may be able to identify data streams from disparate domains converging in support of one hypothesis. A strong and highly plausible hypothesis incorporates data from multiple streams. For example, arguments suggesting that small-sized mounds on Mars are pingos are more plausible when they are based upon climatological, hydrological, periglacial and morphometric data than when they are based upon only one source.

Another criterion of comparative strength is simplicity: does an analogically driven hypothesis need to be substantially reformulated and reconfigured in order to fit new data acquired in the field?; or, is it capable of sustaining a reasonable explanation of landscape presence and genesis in the absence of substantial reformulation and reconfiguration? In some instances, paradigm changes are induced by the adoption of hypotheses that diverge sharply from antecedent understanding. An example is the Channelled Scabland hypothesis posited by J.H. Bretz in the nineteen twenties. During the 19th century, a pillar of geological and geomorphological theory was catastrophism: the belief that landform development or evolution was a function of cataclysmic, unpredictable events. Early on in the 20th century belief in catastrophism came to be displaced by the theory of uniformitarianism: that landform development was evolutionary and predictable. Bretz's hypothesis seemed to turn the theoretical clock back to its earlier setting. He argued that the Channelled Scablands of eastern Washington state were the erosional artefacts of an anomalous and cataclysmic discharge of water in the late Pleistocene (Baker 1978). His calculations, based on the extensive collection of data in the field, pointed to flow of a magnitude that was not similar to any other landscape, contemporary or past.

Informed more by its collective faith in uniformitarianism than by a desire to evaluate critically the evidence in favour of the cataclysmic hypothesis, the scientific community reacted to Bretz's ideas with derision and condemnation (Baker 1978). However, as the assemblage of field-based data and calculations grew in support of Bretz's hypothesis, the antipathy to it amongst his fellow geologists dissipated. Eventually, the hypothesis was accepted. To this day, the cataclysmic hypothesis posited by Bretz remains the leading explanation of Scabland genesis.

In the absence of challenging or anomalous hypotheses, the day-to-day work of science is uneventful and proceeds incrementally, perhaps even ploddingly, by small steps. But regardless of whether science follows steps small or large, and whether the field of inquiry lies on the cutting edge of understanding or not, science is meaningful only when it is adaptable, revisable and rigourous at one and the same time. In that which follows, the degree to which the analogue-driven study of possible dust devils, outflow channels and pingos on Mars encompasses these attributes will be put to the test.

Chapter 3: The Dust Devil and Cataclysmic Discharge Hypotheses

3.1.1 Dust Devils on Mars?

As early as 1956, telescopic observations of Mars at perihelion - summer solstice in the Martian southern hemisphere - identified dust storms that were global in reach. When Mariner 9 arrived at the red planet in 1971, Mars was shrouded in dust once again. Planetary scientists were and are puzzled by the

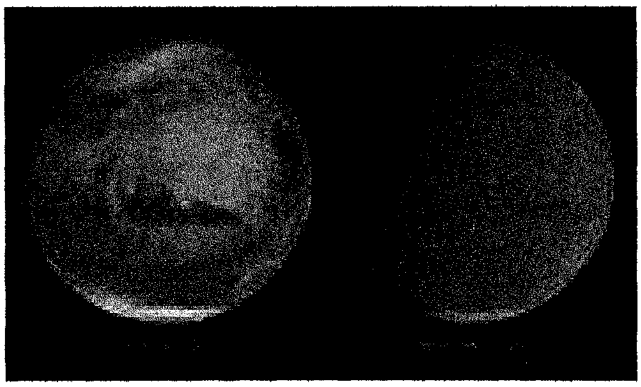

fig. 1: ST Sci-PRC2001-31
A global dust storm captured by the Hubble Wide Field Planetary Camera 2 (Bell, J., M. Wolff & Hubble Heritage Team)

magnitude of these dust storms (fig.1). The average surface pressure of the Martian atmosphere was thought to be quite low, ~ 5 -15 mb (Sagan *et al.* 1971). Mathematical models indicated that surficial wind velocity as high as ~ 80 m s^{-1} would be required to initiate the movement of dust grains that are 200 μ in radius (Sagan *et al.* 1971). But remote observation of near-surface aeolian activity on Mars had failed to detect winds of this velocity.

Hypotheses capable of reconciling the existence of global dust storms with the absence of lifting mechanisms competent to incite these storms were sought. Three possible explanations were posited. First, the combined force of regional winds superimposed upon global wind circulation might provide uplift sufficient to engender planet-wide dust storms (Sagan *et al.* 1971; Leovy *et al.* 1973). Second, regional winds on their own might attain the velocity required to uplift massive amounts of dust, but they do so only over short periods of time. As the remote observation of the Martian surface and atmosphere is intermittent and of a relatively low resolution, these winds could have escaped detection (Ryan 1964). Third, the large-scale loading of atmospheric dust might arise if highly localised, rotational and cyclonic winds, similar to terrestrial dust devils, were present on Mars (Neubauer 1966; Ryan 1964; Sagan and Pollack 1969; Sagan *et al.* 1971).

On Earth, dust devils are small, warm-core vortices that dislodge and uplift surface debris by means of vertical convective currents (Sinclair 1969). These currents are the product of low ambient wind speed, diurnally induced surface heat flux and a superadiabatic atmospheric boundary layer. The latter is common on clear hot days, when a layer close to the ground becomes superheated. Dust devils tend to occur in deserts, where hot days, large temperature fluxes and low ambient wind are not unusual. (Sinclair 1969; Carroll and Ryan 1970; Ringrose and Zarnecki 2002; Sagan *et al.* 1971) (fig. 2).

fig. 2: dust devil (~ 50 m in height),
southern end of Death Valley near Saratoga Springs, April 1977
http://geoimages.berkeley.edu/GeoImages/Johnson/WXPages/DustDevil.html

On occasion, dust devils have been identified in the sub-Arctic during the summer (Rennó *et al.* 2000), when the surface heat flux and aridity mimic the conditions required by dust devil formation in desert regions. Terrestrial dust devils range in height from ~ 75 m - 100 m, sometimes reaching 1 km; their diameters run from a few to hundreds of metres (Cooke *et al.* 1992).

3.1.2 Confirming the Martian Dust Devil Hypothesis

During 1976 - 1977 the arrival of two major dust storms in the northern hemisphere of Mars were recorded by the Viking Landers at Chryse and Utopia Planitia. In the aftermath of the storms, highly localised disturbances of air pressure, temperature and wind velocity were recorded; in a terrestrial environment, these data would be synonymous with the presence of dust devils (Ryan and Lucich 1983). Visual confirmation of the dust devil hypothesis was provided by the Viking Orbiters as they flew over Amazonis and Arcadia Planitia, areas of high topographic uniformity similar to Chryse and Utopia Planitia. Transient funnel shaped clouds elongated in shape and vertically oriented were photographed (Thomas and Gierasch 1985). Nearly two-thirds of the ninety-nine clouds imaged ranged in size from 1.0 - 2.5 km in height [± 200 m]; the maximum height of a cloud was 6.8 km (Thomas and Gierasch 1985). Except for their larger size, these funnel shaped clouds were identical in appearance to terrestrial dust devils. Underpinned by the ground-based meteorological data provided by the Viking Landers, the orbital images of dust-devil like funnels confirmed the

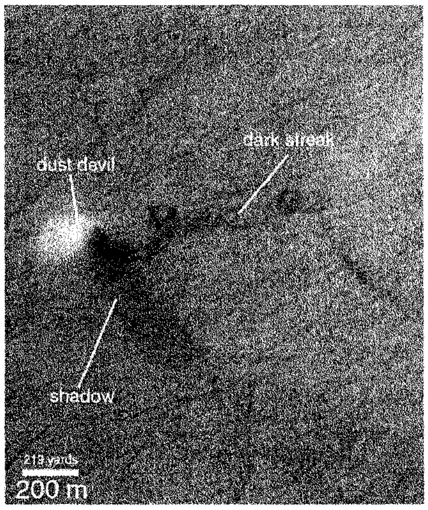

fig. 3: MOC 2-220-C, Promethei Terra. Image is ~1.5 km across (NASA/JPL/MSS).

presence of dust devils on Mars and ruled out alternate explanations of localised dust displacement. Recently, images generated by the Mars Global Surveyor have revealed that dust devils, identified unambiguously by their peculiar shape and by the sinuous ground streaks that arise in the wake of their passage, are omnipresent in both hemispheres of Mars (Cantor *et al.* 2002; Edgett and Malin 2000) (fig. 3).

As their understanding of surface boundary conditions improved, planetary scientists recalculated stress thresholds and suggested that velocities need not be as high as had been thought to initiate the movement of surficial dust particles, perhaps by saltation. (Greeley *et al.* 1992). Wind tunnel data pointed to required speeds falling within the range of ~ 25 - 75 m s^{-1} (Greeley *et al.* 1976). Other studies indicated that at 1.6 m in height, the height of the Viking Lander wind sensors, a velocity of ~ 20 - 30 m s^{-1} might be sufficient to engender the uplift of dust (Ryan and Lucich 1983; Zurek *et al.* 1992). Interestingly, the wind velocity associated with the passage of the dust devils at the Lander sites fell within the boundaries of these lower estimates (Ryan and Lucich 1983).

The extent to which Martian dust devils contribute to the global loading of atmospheric dust continues to be debated. Recently, a vortex generator has been set up in a laboratory to replicate terrestrial wind stress thresholds for dust entrainment and to evaluate the atmospheric dust loading competence of dust devils on Earth (Balme *et al.* 2002). In order to ascertain wind stress thresholds and dust loading competence on Mars, tests are planned under conditions of reduced atmosphere pressure and varied topography. Observationally, the hypothesis linking the evolution of global dust storms to the localised activity of dust devils is unsubstantiated (Cantor *et al.* 2002). Indeed, much of the work being done to explain global dust storm genesis focuses on processes unrelated to dust devils. The principal hypotheses relate the large-scale loading of atmospheric dust to the confluence of regional winds and global circulation (Kahn *et al.* 1992), especially at perihelion (Ryan 1964; Leovy 1999; Peterfreund and Kieffer 1979), to thermally induced atmospheric tides (Bridger and Murphy 1998) and to polar cap-edge thermal contrasts (Toigo *et al.* 2002).

3.1.3 The Analogical Value of the Dust Devil Analogue

The evolution of the dust devil analogue exemplifies the transition from data-less speculation and hypothesis construction to data-based explanation in the development of a scientific theory. In the 1960's and early 1970's the genesis of global dust storms on Mars was poorly understood. Invoking principles of aeolian uplift on Earth, planetary scientists suggested that dust devils were a plausible mechanism for initiating dust uplift under conditions of low-atmospheric pressure and low-velocity surface winds. In time, complementary streams of data gained from the Viking Landers and Orbiters converged in support of the dust devil hypothesis. By contrast, the hypothesised connection between dust devils and global dust storms has not survived the critical scrutiny of planetary scientists. In as much as the data were unambiguous in identifying the possible presence of dust devils on Mars, the analogical value of the dust devil hypothesis is of the first and highest order.

Outflow Channels on Mars & the Cataclysmic Discharge Hypothesis

3.2.1 Discharges Small and Large

Until quite recently, the low atmospheric pressure of Mars, $\leq \sim 10$ mb, and a mean surface temperature of ~ 223 K, had led planetary scientists to assume that the persistent presence of liquid water on the Martian surface was unlikely. Minute traces of water vapour are present in the Martian atmosphere, equivalent to a total volume of ~ 1 - 2 km^3 (Carr 1996). This compares to a total equivalent volume of ~ 13,000 km^3 of water vapour in the Earth's atmosphere (Ames Mars Atmosphere Modelling Group, NASA 2003). Water is present surficially at the polar caps (Mitrofanov *et al.* 2002) but only as ice. The neutron spectrometric data delivered by the Mars Global Surveyor suggests that near-surface hydrogen, possibly in the form of water-ice, may be widespread in sub-polar latitudes (Boynton *et al.* 2002; Feldman *et al.* 2002; Mitrofanov *et al.* 2002). As the spectrometer can generate returns no deeper than one metre beneath the Martian surface, validating the hypothesis of wide-spread sub-surface water awaits further research.

The identification of features that look like seepage-fed runoff gullies has led planetary scientists to reconsider the possibility of liquid water, albeit in small amounts, being present in the very recent past on the Martian surface (Hartmann *et al.* 2003; Knauth and Burt 2002; Malin and Edgett 2000; Mellon and Phillips

2001) **(fig. 4)**. Incised into crater walls (Carr 2000; Malin and Edgett 2000), these gullies are relatively small, often ~ 1 km in length, and often comprise many of the features associated with terrestrial fluvial analogues: rills, channels and debris aprons (Malin and Edgett 2000). Impact craters are largely absent in the area of these gullies; channel incisions are sharp; debris aprons often flow over dunes and aeolian bedforms (Malin and Edgett 2000). These data point to the gullies being relatively young (Costard *et al.* 2002; Malin and Edgett 2000).

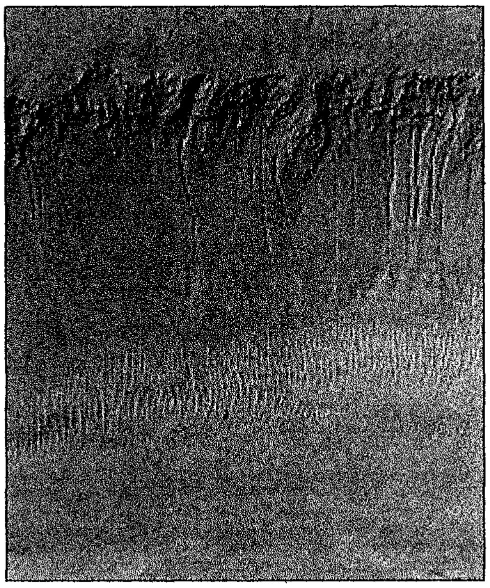

fig. 4: MOC image 2-240 (res. 3.44 m/pixel), Nirgal Vallis: possible fluvial gullies (~ 1 km in length) on the wall of a valley in the southern hemisphere (29.71^0 S, 38.99^0 W). Image is 2.3 km across (NASA/JPL/MSS).

Explanations of gully genesis have been numerous and disparate: aquifer driven seepage of water (Malin and Edgett 2000) or brines (Knauth and Burt 2002); a combination of intermittently favourable obliquity and near surface ground ice (Costard *et al.* 2002); the transportation of polar snow to the mid-latitudes at high obliquity followed by snow-melt and mass wasting at low obliquity (Christensen 2003); winter accumulations of surface frost in high latitude depressions and gullies that are subsequently melted by normal-incidence insolation in the summer (Hecht 2002); and, highly localised regions, perhaps comprising ~ 29% of the total surface area of Mars, at which the atmospheric pressure and surface temperature briefly could sustain water or brines in liquid form (Haberle *et al.* 2001). A few planetary scientists dissent from these water-based scenarios and suggest that the gully-like landforms, channels and aprons could be artefacts of dry granular flows (Treiman 2003) or flows of liquid carbon dioxide (Hoffman 2000).

Recently, data suggestive of liquid water having been present on a larger scale, have been uncovered at Meridiani Planum (7^0 N to 5.6^0 S - 351.1^0 E to 5.5^0 E). These data include hematite-rich layered deposits as well as very high concentrations of salt and iron sulphide hydrate in some of the rocks sampled by the Opportunity Rover (Newsom *et al.* 2003; Lubick 2004a, b). These evaporites have been identified in areas of the plain whose topography and morphology is consistent with the work of running water (Newsom *et al.* 2003; Lubick 2004a, b). Cross-stratification and ripples in a small outcrop of rock may be indicative of running water too (Lubick 2004b). Speculation concerning the age of the rocks sampled and of the local geology, as well as on the temporal and spatial scale of the hypothesised presence of liquid water at Meridiani Planum, awaits further investigation.

Very old large-scale landscapes that may be indicative of the work of running water, are also thought to have been identified (Baker 1978, 1979b, 1985, 2001; Carr 1979, 1996; 2000; Chapman and Kargel 1999; Dohm *et al.* 2001; Florenski *et al.* 1975; Nelson and Greeley 1999; Theilig and Greeley 1979). Hypotheses relating the origin of these features to massive fluvial discharges date back to the photographic images returned by Mariner 9 in 1971 and to the twin Viking missions of the mid-nineteen seventies. These images depicted crater rims breached and re-sculpted in linear fashion, dendritic tributaries that appeared to be organised hierarchically, v-shaped valleys and deep canyons, sinuous channels and braided bars, as well as geomorphological footprints reminiscent of massive runoff and outflow channels on Earth (Carr 1979; Florenski 1975; Malin 1976; McCauley *et al.* 1972; Masursky *et al.* 1977; Milton 1973; Squyres 1984; Thielig and Greeley 1979).

The principal outflow channels on Mars are located equatorially. They are heavily cratered and eroded. Channel formation may date back to the mid- to late Hesperian period, following the period of heavy bombardment (Carr 1996, 2000). In general, outflow channels are identified by five geomorphological characteristics 1. features and bedforms such as anastomoses, expanding and contracting reaches, streamlined uplands, pendant forms on the down current sides of flow obstacles, longitudinal grooves, and scour marks around obstacles; 2. very low sinuousity and high width to depth ratios - suggestive of large scale discharge; 3. full-born origin arising from flat-floored or blocky canyons (chasmae); 4. channel diameters as broad at the head as at the mouth and, 5. a deficiency of tributaries upstream and, contrary to most drainage basins on Earth, branching downstream (Baker 1979b, 1985b, 2001; Carr 1979, 1996, 2000; Robinson and Tanaka 1990; Sharp and Malin 1975; Squyres 1984; Theilig and Greeley 1979)

3.2.2 Equatorial Outflow Channels: a cataclysmic genesis?

The outflow channels are amongst the most spatially prominent and intellectually captivating of the hypothesised fluvial landforms on Mars. Their voluminous size - often thousands of kilometres in length, hundreds of kilometres in width and hundreds of metres in depth- and their possibly cataclysmic origin, evoke comparisons with the Channeled Scablands of eastern Washington State (Baker 1974, 1979a, 2001; Coleman 2002; Komatsu and Baker 1997; Milton 1973; Sharp and Malin 1975; Squyres 1984; Theilig and Greeley 1979).

The Channeled Scablands - scablands being defined as vast plains of bedrock incised by deep channels - are thought to be the artefacts of immense, periodic floods that occurred at the decline of the last ice age. These floods were the end-product of the Cordilleran ice sheet that edged its way into Idaho, blocked the Clark Fork River and created a glacial lake of ponded water behind the blockage - Lake Missoula; at the apex, Lake Missoula might have been 320 km in diameter and filled with 2048 km^3 of water. The episodic breaching of the dam, perhaps 700 m in height, would have engendered a massive discharge of ice- and dirt-filled water: - ~1 - 2 x 10^7 m^3 s^1 (Baker 1978; Carr 1996; Robinson and Tanaka 1990) that could have lasted 10 - 15 days. By comparison, the average discharge of the Mississippi River is ~ 2 - 3 x 10^4 m^3 s^{-1} (Carr 1996). The floodwater swept through the drainage basin of the Columbia River, across northern Idaho, eastern Washington, central Washington and then Oregon, racing into the Pacific Ocean at the mouth of the Columbia River. At the breach point water may have been discharged at a rate ten times greater than the combined discharge of every river on Earth (USGS 2002).

The legitimacy of ascribing a fluvial or mixed-debris origin to the large Martian channels is contingent on three questions being answered. First, could water have been available in a quantity sufficient to initiate and sustain the massive discharges thought to have carved the channels? Second, is the morphology of the channel features and bedforms consistent with a fluvial genesis alone or could other flow regimes have contributed to their development? Third, to what extent are fluvial channel formation hypotheses consistent with present boundary conditions?

3.2.3 Kasei and Ares Valles

The largest of the circum-Chryse outflow channel systems is Kasei Valles.

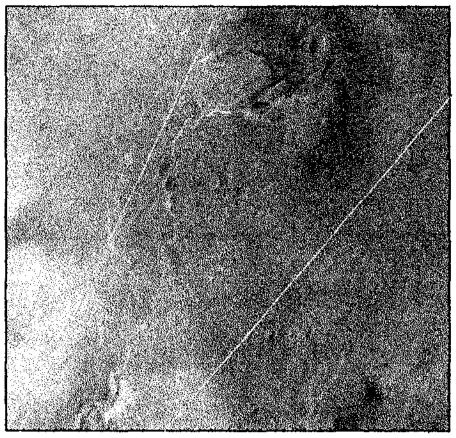

fig. 5: Mars Chart 10 (NASA/JPL/MSS)
Kasei Valles, the main channel runs to the northeast and then bifurcates before debouching into Chryse Planitia (not seen)

The channel is ~ 3200 km in length, is ~ 300 km at its broadest width and reaches a depth of ~ 3 km in some places (Robinson and Tanaka 1990) **(fig. 5).** Geographically, the origin of Kasei Valles coincides with Echus Chasma, a lacustrine-like depression directly to the north of Valles Marineris. Valles Marineris is the largest valley system on Mars **(fig. 6).**

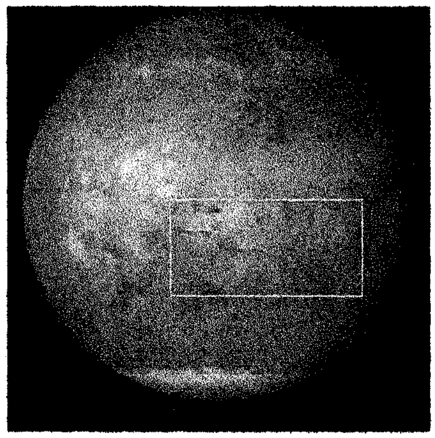

fig. 6: MOC2-402-25 (NASA/JPL/MSS)
Valles Marineris, ~ 4000 km in length,
~ 6.4 km avg. depth

To the east of Kasei Valles lie Simud, Tiu and Ares Valles. Compared to Kasei Valles these three channels seem to flow from highly localised regions of collapsed and jostled ground (Baker 2001; Carr 1996; Malin 1976; Sharp and Malin 1975; Squyres 1984; Tanaka 1997). Defined as "chaotic terrain," these

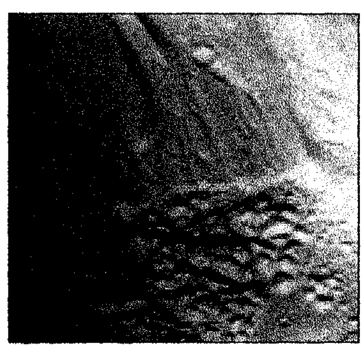

fig. 7: Viking image 742A12
Channel arising from rubble-filled chaotic terrain (Carr 1996). Image is ~ 62 km across.

regions of collapse and jostle typically lie ~ 1 - 2 km below the surrounding terrain are characterised by a steep circular or horseshoe like scarp bordering an area of tilted slump blocks, depressions and irregular hummocks (Masursky *et al.* 1977; McCauley *et al.* 1972; Carr 1979; Squyres 1984; Tanaka 1997; Theilig and Greeley 1979) **(fig. 7)**.

Using Manning's equation [($v = (1.49 / n) R^{2/3} S^{1/2}$)) ($v$ = the mean velocity in metres per second, n = coefficient of roughness, R hydraulic radius, S = slope)] modified to account for the lower acceleration of gravity on Mars, to derive discharge, planetary scientists have argued that Kasei Vallis and Ares Vallis could have produced peak bankfull discharges of ~ 1.4×10^9 m^3 s^{-1} (Carr 1996; Robinson and Tanaka 1990) and ~ 0.57×10^9 m^3 s^{-1} respectively (Komatsu and Baker 1997). These rates are similar in magnitude to western oceanic boundary currents such as the Gulf Stream, the Kuroshio and the Agulhas (Baker 2001) and are two scales of magnitude higher than estimate of the Lake Missoula discharge.

3.2.4 Outflow Origins

Morphologically, Kasei Vallis appears to flow from Echus Chasma, a flat floored, highly layered depression that may have been an open or ice-covered lake (Carr 1996; Coleman 2002; Robinson and Tanaka 1990; Williams *et al.* 2000). The volume of Echus Chasma is ~ 5×10^5 km^3 (Robinson and Tanaka 1990). If one-half of its volume had been available for flooding, a discharge of ~ 1.4×10^9 m^3 s^{-1} could have been sustained for two days (Robinson and Tanaka 1990). Questions concerning the source of the lake water have been addressed by a number of alternative hypotheses.

The first hypothesis connects the possible presence of water in Echus Chasma to Valles Marineris. Numerous faults and tension cracks within Valles Marineris could have collected and then drained large amounts of aquiferic water into Echus Chasma (Robinson and Tanaka 1990). The second hypothesis links Hebes Chasma, a completely enclosed canyon adjacent to Echus Chasma, as a possible source of lake water for Echus Chasma (Carr 1996). An island composed of layered sediments lies within Hebes Chasma, suggesting the presence of a lake in the past (Carr 1996). Whether the lake would have been open or ice-covered is unclear. This notwithstanding, were the lake to have drained by sub-surface flow into Echus Chasma, Echus Chasma could have been provided with a local source of water sufficient to generate the channel forming discharges of Kasei Vallis (Carr 1996). On the other hand, the channel forming discharge of Echus Chasma may have been fed by a sub-surface aquifer that was global in reach. The third of the three channel source hypotheses, is fundamental to four different scenarios. Each of them is set against an environmental backdrop whose boundary conditions of air temperature and pressure are similar to those that prevail today.

According to the first scenario, a global aquifer exists and dates back to the late Noachian period (Carr 1996, 2000). As Mars cooled following the period of heavy bombardment, a cryosphere evolved and placed the aquiferic water under increasing hydrostatic pressure (Carr 2000). This could have induced periodic break-outs of water on a massive scale. The second scenario suggests that global temperatures cooled, the global aquifer continued to be fed by the sub-surface flow of water from the poles; this led to a rise in the global water table and generated high artesian pressures (Carr 2000). In both cases, breakouts would have occurred equatorially, where the elevation is relatively low and where the frozen ground would be at its thinnest (Carr 2000). The third scenario points to the possibility of trapped aquiferic water, which may or may not be global in reach, being liberated by the impact of a large body on the Martian surface. The impact could generate a pressure pulse that fractures the frozen regolith, producing a pipeline of flow directly to the surface (Baker 1985; Carr 1996; Tanaka 1997). In the place of an impact-induced pressure pulse, a fourth scenario suggests that a geologically or volcanically induced quake could fracture the frozen regolith and liberate the aquiferic water trapped at depth (Tanaka 1997).

The apparent absence of large impact craters or volcanic features near the head of Kasei Valles leaves the pressure pulse and volcanic scenarios deficient of empirical support. Whether or not geological activity could have contributed to the release of aquifer water and a breakout from Echus Chasma cannot be evaluated on the basis of the available data.

With regard to the first two scenarios, large-scale breakouts induced by artesian pressure ought to have left jumbled, chaotic terrain in their wake, not a flat, lacustrine-like Chasma. Questions concerning why the floor of Echus Chasma is not chaotic, as one would have expected it to be in the aftermath of a massive surface break-out, remain open. Perhaps repeated episodes of break-out induced ponding, of a very small magnitude, led to the transformation of chaotic terrain into a lacustrine basin. By contrast, the chaotic terrain at the head of the three eastern circum-Chryse channels could be indicative of ground subsidence in the aftermath of a large-scale aquiferic breakout (Carr 1996, 2000; Nelson and Greeley 1999; Tanaka 1997).

A recent study of possible flood features at Athabaska Valles, located equatorially and southeast of Elysium Mons, proposed that the ~ 300 km Athabaska channel was formed by a massive discharge arising from the Cerberus Fossae; the discharge may have lasted no more than seven days (Burr *et al.* 2002). This proposal is consistent with earlier hypotheses suggesting that when aquifer breakouts are sufficiently intense, the formation of large-scale fluvial or mixed debris channels could take place very quickly (Carr 1996). The origin of the Athabaska flood features is not tied to periods of high obliquity, when equatorial temperatures and air pressure may have been higher. Thus, the Athabaska flood hypothesis suggests that when aquifer breakouts are sufficiently intense - $\sim 2 \times 10^6$ m^3 s^{-1} - the formation of large-scale fluvial or mixed debris channels could take place under the influence of Martian boundary conditions that are similar to the ones that prevail today.

The Athabaska flood hypothesis, focused as it is on a fossae-based breakout whose reach extends no further than a few hundred kilometres, offers no relevant insight on two matters: 1. why the massive breakout that is thought to have occurred at Echus Chasma left no chaotic ground in its wake; and, 2. whether the fluvial or mixed debris discharge that are thought to have formed Kasei Valles, a channel that is ten times the length of Athabaska Valles, could have remained fluid through its entire reach under conditions of very low temperature and pressure.

3.2.5 Alternative Hypotheses

Some of the landforms associated with the outflow channels - streamlined uplands and islands, inner channels or terraces, perched rocks that may be erratics, longitudinal grooves and scour marks - are not inconsistent with other types of flow (Chapman and Kargel, 1999; Tanaka 1997; Lucchitta 1982, 1996). Channel formation as a product of glacial flow is a hypothesis that dates back to the earliest images of Mars delivered by the Mariner probes. But were the outflow channels to have been formed by the flow of ice, the presence of accumulation zones in the region of the channel heads would be expected. On Earth, the flow of glacial ice is associated with large, cold-climate regions of generally flat topography such as the Antarctic or with smaller, high elevation alpine landscapes. In the western Antarctic and Greenland, for example, glacial flow originates in huge accumulation zones. In alpine regions, cirques often are at the head of valley glaciers.

Large-scale accumulation zones of either type are not readily identifiable at the head of the circum-Chryse outflow channels (Carr 1996; Squyres 1984). On the other hand, ice accumulation could have been initiated downstream from the point of initial discharge. This hypothesis obviates the need to identify large accumulation zones in the area of the channels heads and is easier to reconcile with current boundary conditions than are fluvial or mixed debris channel formation hypotheses (Lucchitta 1982). The extent to which water, water-ice, ice or even mixed debris contributed to channel formation continues to be debated and awaits the results of further investigation. But as many of the channel features and bedforms point strongly in the direction of a fluvial origin, the ice formation hypothesis is looked upon less favourably by planetary scientists than are fluvial or mixed-debris hypotheses.

Explanations of outflow channel genesis based on volcanism also have been posited. Evidence of volcanic activity concurrent with channel formation or of lava fields proximate to the circum-Chryse channel heads are unapparent

(Carr 1996; Milton 1973; Sharp and Malin 1975; Squyres 1984). Furthermore, lava erodes by thermal incision and tends to form simple channels that are scour free, unlike the complex and scoured channels revealed by Viking generated imagery (Carr 1996). On the side of wind action, there is some evidence of erosional modification of the Kasei Valles channels but on a modest scale and only subsequent to the genesis of the channels (Chapman and Kargel 1999; Squyres 1984). In addition, wind patterns are independent of topographic gradients, whereas the Martian channels flow invariably from areas of higher relief to areas of lower relief.

Lately, liquid carbon dioxide has been cited as the agent responsible for the genesis of some outflow channels (Hoffman 2000). The strength of the hypothesis lies in its consilience with contemporary boundary conditions; the principal weakness is the fact that gas supported debris flows cause little erosion beyond the debris zone typically flow in lobate form and follow rather than carve surficial channels (Coleman 2002).

3.2.6 Comparing the Dust Devil and Outflow Channel Hypotheses

Mars is a world whose geomorphological processes often seem mysterious and incomprehensible. For example, fluvial break-out of a scale sufficient to generate the massive equatorial channels on Mars is without equal on Earth. Against the backdrop of mainstream terrestrial geomorphology, surficial discharges of ~ $1.4 \times 10^9\ m^3\ s^{-1}$ and channels that are as large at the head as at the mouth, seem equally implausible. In order to make sense of Martian outflow channel morphology, some planetary scientists have pursued their inquiries by studying terrestrial cataclysmic events. In this regard, the Channeled Scablands have become integral to explanations of Martian outflow channel genesis.

At the same time, the viability of this terrestrial analogue and of derivative hypotheses of outflow channel formation is undermined by a number of unanswered questions: 1. was there an aquifer, global or regional, sufficient in size to have fed the massive channel forming discharges of the equatorial channels?; 2. under conditions of low temperature and pressure could fluvial or mixed debris discharges have remained fluid through the enormous reach of channels such as Kasei Valles?, and 3. is the lacustrine-like depression from which Kasei Valles appears to flow consistent with outbreak hypotheses?

Based on elevation data tracks gnerated by the MOLA and the MOC, new topographic profiles of Kasei Valles have been organised (Williams *et al.* 2000). The revised profiles depict an array of narrow inner channels within Kasei Valles. These inner channels may be indicative of multiple flow episodes of a smaller magnitude than that which has been associated with channel formation heretofore (Williams *et al.* 2000). If further data consolidates this multiple episode hypothesis, the need to invoke a channel formation theory based upon cataclysmic events may not be required. For the moment, questions concerning the source and availability of water remain problematic. Equally unresolved are questions pertaining to whether the formation of far-reaching channels by the flow of water or of mixed debris is plausible when the air temperature and pressure are very low.

By contrast, the dust devil hypothesis was validated by data sets that converged unambiguously and by evidence that was incontrovertible. Alternative hypotheses were ruled out quite easily. Moreover, the plausibility of the dust devil hypothesis did not require the elaboration of a highly speculative theory that engenders geomorphological consequences whose magnitude is without parallel on Earth. For these reasons, the dust devil hypothesis ranks above the cataclysmic discharge hypothesis on a scale of analogical meaningfulness and value.

Chapter 4: The Drained-Lake Pingo Hypotheses

4.1 Pingos on Mars?

The origin of terrestrial or Martian landforms suggesting aqueous flow - such as gullies, channels and valleys - could be explained by many different flow regimes. By contrast, hydrostatic pingos are perennial ice-cored mounds whose origin and evolution are uniquely dependent upon the availability of surface water and of deep, continuous, ice-cemented permafrost (French 2000; Mackay 1979, 1998; Müller 1962). Small mounds that look like terrestrial hydrostatic pingos have been identified in three areas of Mars where water is thought to have been present: 1. the vast northern plains (Kargel and Costard 1993; Parker and Banerdt 1999; Seibert and Kargel 2001) encompassing Acadilia (Lucchitta 1981), Chryse (Theilig and Greeley 1979), Elysium (De Hon 1997; Rice 2002) and Utopia Planitiae (Tanaka *et al.* 2000; Seibert and Kargel 2001; Thomson and Head 1999); 2. Vastitas Borealis, the sub-polar region lying directly above the seasonal frost line to the north of these plains (Greeley and Guest 1987); and, 3. Gusev crater, a near-equatorial impact crater that may have been a paleo-lake hundreds of millions of years ago in the late Amazonian period (Cabrol *et al.* 1997, 2000; Cabrol and Grin 2002; Grin and Cabrol 1998).

Despite the value of pingos as geomorphological markers of water, most references to them in the planetary science literature are brief and nested within broader discussions of cold-climate landscapes on Mars (De Hon 1997; Greeley and Guest 1987; Seibert and Kargel 2001; Lucchitta 1981, 1996; Parker and Banardt 1999; Rice 2002; Theilig and Greeley 1979). Exceptionally, the identification of pingo-like mounds within the Gusev crater is accompanied by detailed morphometric comparisons with terrestrial pingos and by an elaborate fluvio-periglacial formation hypothesis (Cabrol *et al.* 1997; 2000; Grin and Cabrol 1997). However, the hypothesis is formed on the basis of coarse Viking Orbiter images.

I have identified a sub-polar (64.8° N / 292.7° W), crater-based landscape (MOC image EO300299, res. 5.5 m/pixel) in northwest Utopia Planitia comprising eight main features: 1. an assemblage of pingo-like mounds in two main groups (A and B) **(fig. 8**); 2. a slightly elevated terrace upon which the mounds of group

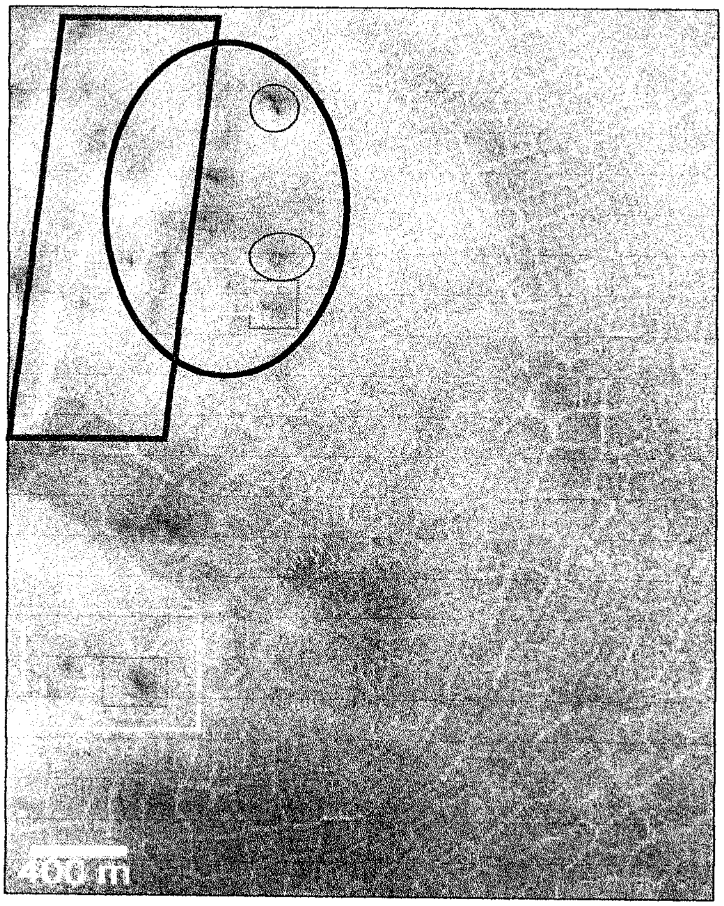

fig. 8: MOC image EO300299 (res. 5.05 m/pixel). The sun illuminates the landscape from the southwest. Image is 3.2 km across

Legend

large oval - mound group A
large box - mound group B
parallelogram - dendritic tributaries and main trunk
small box - mounds crossed by crack
small oval - summit depression or crater

A sit (**fig. 10**); 3. a curvilinear feature to the east of the terrace that loses elevation southwardly in the direction of one or possibly two very small and old impact craters **(figs. 9 and 10)**; 4. a small basin in which the mounds of Group B reside (**fig. 8**); 5. small-scale, polygonal patterned ground - (~ 40 - 300 m in diameter) (**fig. 8**); 6. a set of dendritic tributaries, connected to a main trunk **(figs.**

8, 9 and 10); 7. summit depressions **(fig. 8)**; and, 8. mound cracks **(fig. 8)**. This assemblage is consistent with the possible past presence of water and of

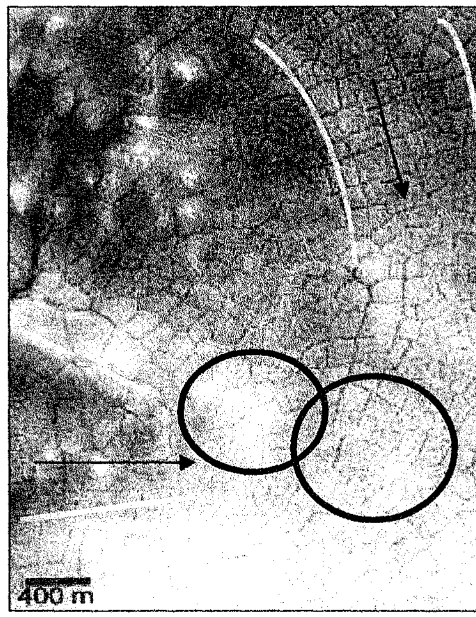

fig. 9: MOC image EO300299: reversed grey scale

Legend

---- outline of drainage basin

small impact craters

periglacial processes on Mars (Soare and Peloquin 2003). Equally, the landscape is reminiscent of the coastal drained-lake landscape of the Tuktoyaktuk peninsula in northern Canada (**fig.11**) (Soare and Peloquin 2003).

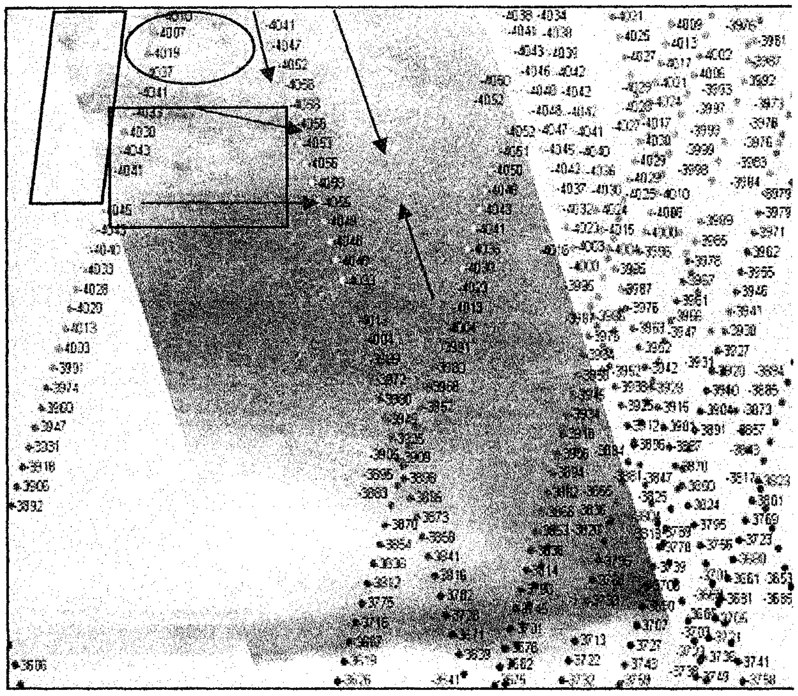

fig. 10: MOLA altimetric data in metres from a zero equatorial datum superposed with MOC image EO300299 (personal communication, D.M. Burr)

Legend

elevation loss, in the direction of a small, old impact crater(s)

possible local confluence of dendrites and basin immediately to the west of the image

plateaus

basin

This chapter comprises five sections. First, I discuss the genesis and growth of pingos on Earth, with attention being focused on the formation of hydrostatic pingos by lake drainage in the Tuktoyaktuk peninsula. Second, I describe the formation of thermal contraction cracks and of polygonal patterned ground in periglacial environments. Third, I present the Gusev-crater pingo hypothesis and evaluate its analogical foundations. Fourth, I describe the Utopia crater landscape features and suggest that the crater-floor mounds are hydrostatic pingos. The description is based on an inspection of MOC image EO300299 (**figs. 8 and 9**), individual data tracks generated by the MOLA (**fig. 10**) and aerial photograph A27917-35 of the Tuktoyaktuk peninsula (**fig. 11**).

Fifth, I compare the analogical arguments of the Gusev-crater hypothesis to those of the Utopia-crater hypothesis.

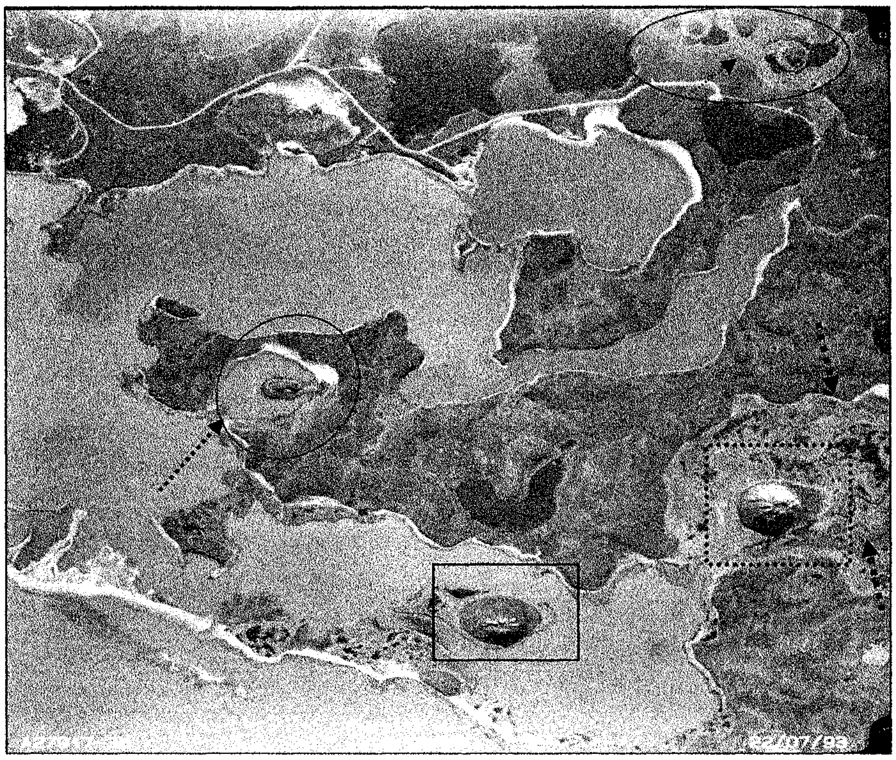

fig. 11: Coastal pingos to the southwest of Tuktoyaktuk. Image is 3..4 km across. (Aerial photograph A27917-35, National Air Photo Library, Ottawa)

Legend **Scale 1:15,000**

Split pingo (~ 300 m, long axis; ~ 35 m height)

Ibyuk pingo (~ 300 m, long axis; ~ 49 m height) is the second highest pingo in the world. On average, most pingos are much smaller

Other pingos; the pingo slightly to the left of centre is a particularly good example of genesis and formation induced by drainage, possibly due to the erosion of ice wedges by wave action

Ice-wedge polygons

4.1.2 Pingo Genesis and Growth on Earth

There are two main types of terrestrial pingos: hydrostatic (closed-system) or hydraulic (open-system) (**fig. 12**). Hydrostatic pingos arise when soil moisture migrates into an increasingly small near-surface pocket of non-frozen soil as a result of permafrost aggradation; the formation of hydraulic pingos is driven by the movement of groundwater under high pressure (French 1993; Mackay 1979; Müller 1962; Washburn 1973). The greatest spatial concentration of hydrostatic pingos in the world is in the Tuktoyaktuk Peninsula of northern Canada (Mackay 1998). There may be as many as 1380 pingos in the area (Müller 1962). The Tuktoyaktuk pingos are underlain by a large fraction of deltaic sand [0.1 - 0.05 mm] and a much smaller fraction of silt [< 0.05 mm] (Mackay 1979; Müller 1962). The coarseness of the soil facilitates the migration of intra- or sub-permafrost water to the area of pingo genesis. Ninety-eight percent of these pingos reside in lake basins that are adjacent to the Beaufort Sea and have lost their water through drainage (Mackay 1962, 1979, 1998). The drainage of these lakes has been triggered by one of three factors: 1. coastal recession (MacKay 1979, 1998; Washburn 1973); 2. ice wedge erosion at lake outlets as a result of coastal wave action (Mackay 1979, 1998) or, 3. the headward erosion of rivers or lakes, perhaps at a time of lower sea-level (Mackay 1998).

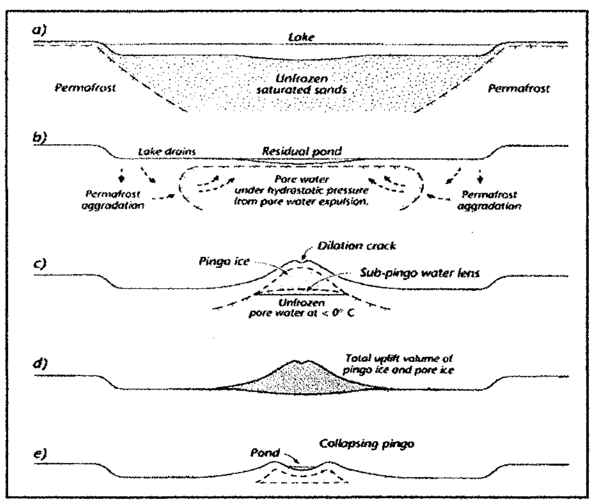

fig.. 12: Model of hydrostatic pingo origin and growth (Mackay 1998)

The evolution of a drained lake pingo comprises two phases: growth (**fig. 12**) and decay (**fig. 13a and 13b**). Often, the growth of a hydrostatic pingo is initiated when a lake is drained and the unfrozen water-saturated sediment beneath the lake floor is exposed directly to freezing temperatures for the first time (MacKay 1966). The downward aggradation of permafrost ensues. Pore water is expelled from the saturated soil as the freezing front advances and the water becomes trapped in an increasingly small space. The pressure of this trapped pore water rises substantially (Mackay 1966, 1979; Müller 1962). As the freezing process continues, a core of ice begins to form above the trapped pore water. Under intense hydrostatic pressure the ice begins to deform the overburden lying above it, creating a small mound. If the pore water pressure is sufficiently intense, a transient lens of water may also form beneath the core (Mackay 1979, 1998). Constrained by a growing ice core and ongoing permafrost aggradation, the lens dissipates and eventually disappears (MacKay 1979).

Compared to distal areas of higher elevation in the basin, the deepest part of the former lake basin is the last region to undergo permafrost aggradation (Mackay 1962, 1999). This is because pockets of vestigial water collect in residual ponds on the lake floor. These residual ponds buffer the underlying sediments from freezing until the pond water evaporates or is drained away. Permafrost is at its minimum thickness in the area directly beneath the residual ponds. Thin permafrost is more susceptible to deformation by the flow of groundwater under pressure and by an incipient core of ice than is thick permafrost (MacKay 1962, 1979). The growth of hydrostatic pingos tends to occur in these areas of thin permafrost (Mackay 1962, 1987, 1998, 1999).

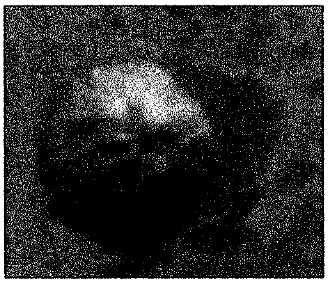

fig. 13a: Enlargement: summit cracks and crater, Ibyuk Pingo, Tuktoyaktuk peninsula. Image is ~ 450 m across (Aerial photograph A27917-35 (1993), National Air Photo Library, Ottawa).

When a pingo grows, summit cracks appear **(fig. 13a)**. Summit cracks are produced by the dilation of the pingo overburden (Mackay 1987; 1998). As the cracks widen, the overburden that lies at the bottom of the cracks becomes increasingly thin (Mackay 1998). The thinness of the overburden may expose the

fig. 13b: Frozen thermokarst, Ibyuk pingo summit, Tuktoyaktuk peninsula, spring 2004. Image is ~ 50 m across.

underlying pingo ice to thaw or melt conditions; thermokarst may ensue (**fig. 13b**) (Mackay 1998). This would be the first stage of a process leading to the eventual collapse of the pingo (Mackay 1998) **(fig. 14)**.

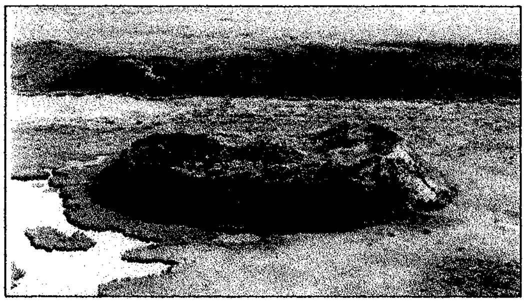

fig. 14: A collapsed pingo in the midst of a drained lake, Tuktoyaktuk peninsula; the mound might have reached 15 - 20 m in height before collapsing (Mackay 1998)

Pingo growth and development also induce circumferential stretching and tension. This tension is relieved by the formation of radial dilation cracks. Radial dilation cracks propagate from the top to the bottom of the pingo; on occasion, they may intersect with thermal contraction cracks in the lake flats next to the pingo (Mackay 1987; 1998) **(fig. 15).**

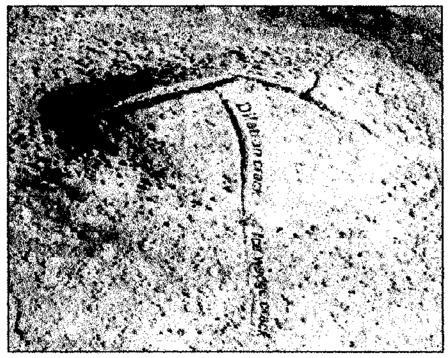

fig. 15: Dilation cracks on a small drained lake pingo converging with thermal contraction cracks on the perimeter of the pingo. Pingo is ~ 200 m in diam. (Mackay 1998).

The genesis and growth of hydraulic pingos is a function of two factors: 1. the downslope flow of intra- and sub-permafrost flow of groundwater, which creates a hydraulic gradient (**fig. 16**) (Mackay 1998); and, 2. the downslope presence of thin or discontinuous permafrost and of very coarse sediment (Cruickshank and Calhoun 1965; French 1993; O'Brien 1971). Coarse sediment facilitates the upward migration of artesian water through the permafrost and the subsequent formation of an ice core as the distance to the surface lessens. Consequently, hydraulic pingos tend to be found on lower valleyside slopes, valley bottom alluvium, alluvial fans, braided channels and outwash material (Cruickshank and Colhoun 1965; French 1993; Lasca 1969; Mackay 1998; O'Brien 1971). Dilation cracks and collapse features are commonplace amongst hydraulic pingos as well (Bennike 1998).

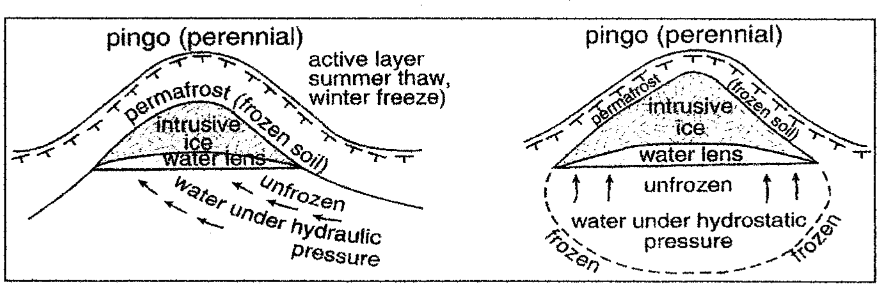

fig. 16: Diagramme of hydraulic and hydrostatic pingo formation (French 1993)

4.1.3 Large- and Small-Scale Polygonal Patterned Ground

There are two types of polygonal patterned ground, sorted and non-sorted. Sorted polygons are the product of freeze-thaw processes that separate coarse grains, cobbles and stones from fine grained material in the active layer of cold-climate sediments (Washburn 1973). Separation generates polygons in which fine material is bordered by coarse material (Washburn 1973). Most sorted polygons are ≤ 10 m in diameter (Washburn 1973).

Ice wedge polygons are a type of non-sorted polygon that is the product of thermal contraction. Ice wedge polygons tend to be larger than polygons that are sorted. Polygons ~ 30 - 60 m in diameter have been identified in the Fosheim Peninsula, Ellesmere Island (Lewkowicz and Duguay 1999). For example, polygons that are ~ 60 - 80 m in diameter are found in the flood plains of the Yamal peninsula in Siberia, only to be surpassed in size by polygons up to 100 m in diameter on the surface of sea terraces in the region (Kuzmin *et al.* 2002). The troughs bounding non-sorted polygons in the size range identified above are underlain by ice, sand or a combination of the two fills (Lachenbruch 1962; Washburn, 1973).

In a cold-climate environment, the tensile stress of frozen ground is determined by the penetration depth of surface temperatures (Maloof *et al.* 2002). Frozen ground has a low thermal conductivity. This implies that the area most susceptible to oscillations of temperature, and to thermally-induced cracking, is close to the surface (Pechmann 1980). The force of crack extension lessens with depth. Crack spacing is a function of horizontal stress relief, as determined by the distance from the crack to points of 5% stress relief on the ground normal to the crack itself (Lachenbruch 1962). For example, 5% stress relief should be achieved by a 3 m crack at a horizontal distance of 12 m, by a 6 m crack at a horizontal distance of 18.8 m and by a 9.1 m crack at a horizontal distance of 21.5 m (Lachenbruch 1962). This represents a vertical crack depth to horizontal distance ratio of ~ [(4.0 - 2.5) to 1].

Field measurements of crack depth and spacing obtained in the Brooks Range, Alaska, are consistent with this hypothesis (Pechmann 1980). Crack depth measurements for the large Siberian polygons are unavailable. However, ice wedges ~ 52 m in depth have been reported in the coastal region of the Laptev Sea, Russia (Romanovskii *et al.* 2000). If the coastal ice wedges of Siberia are an indirect benchmark of possible polygon size, then polygons ~ 130 m in diameter would not be inconsistent with formation by thermal contraction.

Thermal contraction cracks may become filled with meltwater generated by the surficial thaw of ice or snow, the sub-surficial thawing of ground ice or condensation from atmospheric vapour (Lachenbruch 1962; Mellon 1997; Washburn 1973); in extremely cold and dry environments such as the Antarctic and even eastern Greenland, the infiltrate may be sand (Bennike 1998; Lachenbruch 1962; Sletten *et al.* 2003; Washburn 1973). Upon a water-filled crack freezing, a small vertical vein of ice forms at the interface between the active layer and the permafrost underlying it; subsequent cracking, initiated at the top of the wedge, propagates upward through the active layer and downward through the permafrost (Lachenbruch 1962). Repeated cycles of cracking and infiltration transform the ice vein into a vertical ice wedge (**fig. 17**) (Lachenbruch 1962); the process that leads from crack infiltration by sand to sand wedge

fig. 17: Ice wedge, southwest of Tuktoyaktuk, exposed by coastal erosion. The man is ~ 2 m in height (spring 2004)

development is quite similar (Sletten *et al.* 2003). Isolated ice cracks in the floors of recently drained Arctic lakes may begin to appear as early as the first winter following the loss of water (Mackay 1999). The formation of polygon networks may take hundreds if not thousands of years (Plug and Werner 2002). In some instances, the formation of ground cracks and of small hydrostatic pingos has occurred within a few years of lake being drained (Mackay 1999).

The process that initiates ground cracks and the formation of ice- or sand-wedge polygons - thermal contraction - differs from the processes that initiates the formation of drained lake pingos - permafrost aggradation and freezing. However, both processes are associated with cold-climate landscapes and it is not unusual to find thermal contraction cracks or polygons evolving alongside drained lake pingos (**fig. 11**) and pingos of other types (**fig. 18**) (Bennike 1998, Mackay 1979). Along the Tuktoyaktuk coast, countless drained lake pingos are encompassed within fields of ice-wedge polygons (**fig. 11**).

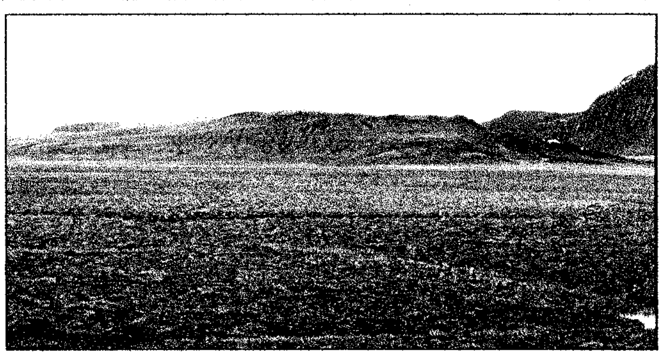

fig. 18: Middle Fjord Pingo (background), polygonal patterned ground (foreground), whether the pingo is hydrostatic or hydraulic is not known. Image is ~ 300 m across (Axel Heiberg Island, summer 2001).

4.1.4 The Gusev-Thyra Pingo Hypothesis

The presence of clustered mounds (14.3^{0}S / 184^{0}W) (**fig. 20**) whose shapes **(figs. 21 and 22)** are suggestive of terrestrial pingos has been reported in a near equatorial impact crater and possible paleo-lake named Gusev (**fig. 19**) (Cabrol *et al.* 2000, Grin and Cabrol 1998). The hypothesised mounds are located to the north of a small impact crater - Thyra - within Gusev (**figs. 19 and 20**) (Cabrol *et al.* 2000, Grin and Cabrol 1998). Using Viking image 434S09 (69 m/pixel) as a benchmark, the authors of the Gusev- Thyra pingo hypothesis suggest that many of the mounds are hundreds of metres if not kilometres in diameter. In the area of one mound summit, a depression may be indicative of pingo-like collapse (Cabrol *et al.* 2000).

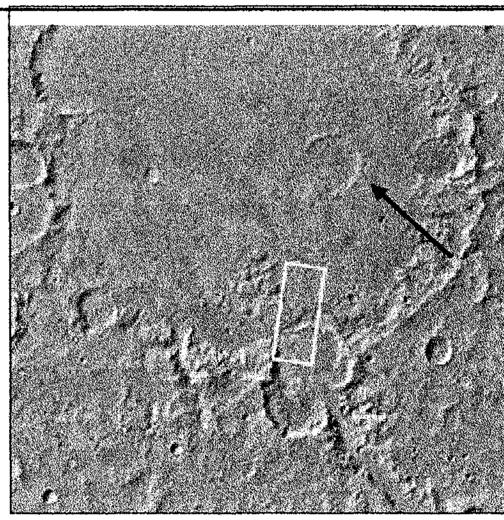

fig. 19: MOC2-58A (NASA/JPL/MSS) Ma'adim / Gusev complex. The diameter of the Gusev crater is 150 km. The fan at the mouth of Ma'adim Vallis channel as it enters Gusev crater could be indicative of fluvial discharge. The arrow points to the Thyra crater.

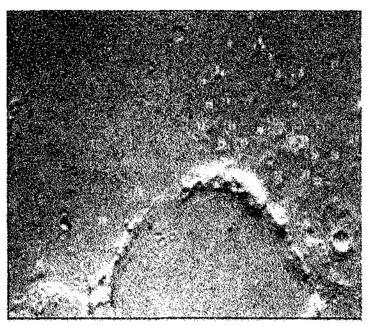

fig. 20: Viking Orbiter image 434S09; res. 69 m /pixel. Thyra mounds, numbered (Cabrol *et al.* 2000)

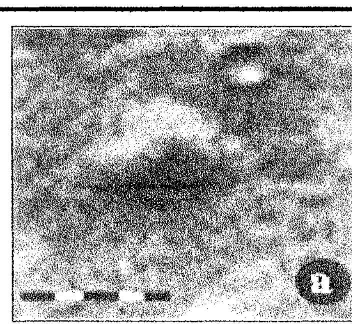

fig. 21: Enlargement of Viking Orbital image 434S09. Oval pingo-like mound north of Thyra crater, diam. ~ 600 m; height ~ 35 - 140 m; res. 69 m/pixel (Cabrol *et al.* 2000).

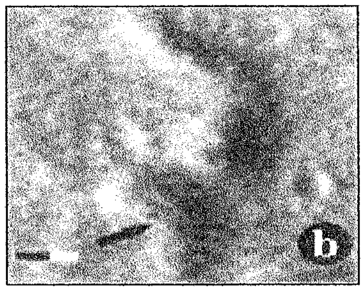

fig. 22: Elongated and sinuous pingo-like mounds north of Thyra crater. Diam. of smaller mound ~ 1500 m; height ~ 60 - 240 m. Diam. of larger mound ~ 2000 m; height ~ 60 - 240 m; res. 69 m/pixel (Cabrol *et al.* 2000).

An elaborate hierarchy of processes has been hypothesised to explain their similarity to pingos on Earth (Cabrol *et al.* 2000). The hypothesis comprises five principal assumptions. First, the pressure and heat generated by the impact formation of Gusev during the Hesperian period created an impermeable layer of melt material in the crater basin (Cabrol *et al.* 1997). From the Hesperian through to the early Amazonian period, the basin was filled periodically with open or ice-covered water (Cabrol *et al.* 1997, 2000). Second, the main source of basin water is thought to have been Ma'adim Vallis, a large channel that breaches Gusev's southeastern rim (Cabrol *et al.* 1997, 2000; Grin and Cabrol 2000) **(fig. 19)**. Third, oscillations in the discharge of water from Ma'adim Vallis into the crater were accompanied by rising rates of evaporation and sublimation as the Martian atmosphere became colder and thinner. Gradually, the basin water was lost (Cabrol *et al.* 2000; Grin and Cabrol 1997). Fourth, as the water saturated sediments lying beneath the basin and above the impermeable layer of melt material were exposed to increasingly cold temperatures they froze. Fifth, the heat and quakes associated with the formation of Thyra, a small impact crater in the Gusev basin, could have led to a localised destabilisation of the ice/water sediments and the surficial release of water (Cabrol *et al.* 2000). Alternatively, the Thyra quakes might have caused the collapse of the rampart separating Gusev from the ponded water of Ma'adim Vallis, releasing flood water into the crater (Cabrol *et al.* 2000). In time, the loss of water through evaporation or sublimation would have exposed the lake basin to freezing conditions and induced a series of events leading to the formation of hydrostatic pingos north of the Thyra crater (Cabrol *et al.* 1997, 2000; Grin and Cabrol 1997). Depressions or pits suggestive of terrestrial thermokarst that lie 50 km to the north of the mounds and possible frost heave in the area of the mounds are cited as corroborative evidence of periglacial processes at work in the basin (Cabrol *et al.* 1998, 2000, 2002).

Alternative explanations of mound formation by non-periglacial processes were considered briefly and discounted. As the crater landscape is deficient of volcanic landforms or deposition, volcanism was ruled out (Cabrol *et al.* 2000). A fluvial origin was also rejected. Some of the mounds are perpendicular to the hypothesised flow of water in the crater; other mounds are not streamlined as they would be were water action to have been the dominant erosional process at work (Cabrol *et al.* 2000).

4.1.5 Questions Concerning the Gusev-Thyra Pingo Hypothesis

Missing from the Gusev-Thyra mounds are dilation cracks. Except for one possible instance, summit cratering is not present either. Dilation cracks and summit cratering are common evolutionary features of pingos. In order to explain the general absence of these features the authors of the Gusev pingo hypothesis invoke three lines of reasoning. First, pingo growth could have come to a stop in a juvenile stage of development, prior to the onset of significant mechanical stress or failure. Second, perhaps dilation cracks did form and are present. But if they are similar in size to terrestrial dilation cracks - being a few metres in diameter - then perhaps they are too small to be resolved by the coarse Viking imagery of 69 m/pxl. Third, dust combined with a highly cemented layer of regolith could have blanketed the mounds, therein preventing the loss of core ice indefinitely through evaporation or sublimation (Cabrol *et al.* 2000). While the second explanation is not implausible, the conceptual ground on which the first and the third explanations are built is weak.

Terrestrial pingos, whose size is an order of magnitude smaller than the Martian mounds often dilate very early in their development; additionally, collapse features may arise even among small and relatively young pingos on Earth (Mackay 1979, 1998). Are there special conditions attached to the growth of pingos on Mars that exempts them from the influence of stress and tension, so that dilation and collapse is avoided even when the size of the Martian mounds exceeds by far that of the largest terrestrial analogues? Moreover, to what extent is the hypothesised existence of near-surface ice-cores dating back to the early Amazonian period reasonable? For the ice to have remained extant from the formation of Thyra to the present, the cement overburden would have had to remain immune to disaggregation through hundreds of millions of years of aeolian erosion. Even a modest loss of integrity over such a long period of time would have engendered sublimation of the ice and the subsequential collapse of the mounds. The stability of near-surface ground ice at latitudes below 40^0 is thought to oscillate extensively in conjunction with periods of high obliquity (Mustard *et al.* 2001). For the ice cores beneath the near equatorial Thyra mounds to have withstood disaggregation almost indefinitely and to have maintained their integrity through countless cycles of obliquity would be quite remarkable.

A second feature is absent from the Gusev-Thyra mound landscape: small-scale polygonal patterned ground. On Earth, the formation of hydrostatic pingos is a product of permafrost aggradation and freezing; the formation of ground cracks and ice- or sand-wedges is a product of thermal contraction. Each of these processes are associated with terrestrial cold-climate landscapes and, as noted above, it is not unusual to find thermal contraction cracks alongside hydrostatic pingos in cold-climate landscapes. In a Martian landscape formed by cold-climate processes and dotted with pingo-like mounds and other cold-climate features such as thermokarst and frost heaves, the presence of thermal contraction cracks or polygons would be expected. The absence of cracks or polygons in the Gusev-Thyra basin area is curious.

Arguably, very old polygonal patterned ground may lie buried beneath the buried beneath the surficial regolith in the area of the Thyra mounds, having been overlain by dust and debris subsequent to its formation. In their account of the Gusev-Thyra pingo hypothesis, neither the absence nor the possible relict presence of polygonal patterned ground are elaborated. At the same time, the hypothesised presence of thermokarst distal to the Thyra mounds neither validates assumptions concerning the periglacial origin of Thyra mound landscape nor of the mounds themselves.

The relative uniformity of size of the Gusev-Thyra mounds is puzzling. The drained lake landscape of Tuktoyaktuk, for example, comprises pingo scars, collapsed and partially collapsed pingos (Mackay 1979; 1998), and pingos that range in size from a few to hundreds of metres in diameter **(fig. 11).** Mound size is proportional to mound age (Mackay 1979, 1998; Bennike 1998). Large pingos are older than smaller ones. The Ibyuk pingo, which is the second largest terrestrial pingo, is thought to be ~ 1000 years old. Differences in mound size and evolution among pingos close to one another indicate that local or regional conditions suited to pingo genesis and growth have been in place over a relatively long period of time. The uniformity of large size amongst the Gusev-Thyra mounds suggests that conditions were suitable only for a relatively short period of time, with mound growth starting and coming to an end abruptly. An elaboration of these conditions is missing from the Gusev-Thyra hypothesis.

By comparison with terrestrial pingos, the hypothesised mounds north of Thyra commonly are an order of magnitude larger. When a sufficiently large pocket of pore water is placed under extremely high hydrostatic pressure beneath a plane of weakness in the deepest part of a former lake basin, very large pingos could arise. Most of the drained lakes in the area of Tuktoyaktuk are hundreds of metres in diameter. All other variables being equal, the argument is made that a large kilometres-wide basin in the area of Thyra could have engendered the development of kilometres-wide pingos (Cabrol *et al.* 2000). But caution ought to be exercised in assuming that the genesis of mounds morphometrically similar to terrestrial pingos but an order of magnitude larger than them can be explained by invoking the same morphological processes. In terrestrial geomorphology as in Martian geomorphology, similarities of form need not be synonymous with similarities of formation. For example, surficial cones that are similar in form to collapsed hydrostatic pingos have been identified in the Cerberus Plains, Mars. Rather than being the product of lake drainage and permafrost aggradation, the origin of these cones is thought to have been initiated by the surficial flow of lava over areas of near-surface groundwater (Lanagan *et al.* 2001). This hypothesis is consistent with the observation of rootless cones in Iceland, whose formation is tied to lava flows emplaced over marshy terrains (Lanagan *et al.* 2001).

Interestingly, the pingo-like mounds to the north of Thyra identified on the basis of Viking image 434S09 (69 m/pixel) are not apparent in the MOC images M0202129 (5.81 m/pixel) and M0302330 (3.48m/pixel). Equally, there is no evidence of small-scale polygonal patterned ground in the more resolved MOC images. As for the hypothesised presence of frost heave and thermokarst, the absence of specific geo-references for these features in the source articles (Cabrol *et al.* 1997 and 2000) limits the extent to which the MOC images could be scrutinised.

4.1.6 The Analogical Value of the Gusev-Thyra Crater Hypothesis

Analogically, the Gusev-Thyra pingo hypothesis is undermined by five principal weaknesses. First, the absence of polygonal patterned ground on the Gusev crater floor in the area surrounding the crater mounds is inconsistent with the cold-climate landscapes often associated with pingos on Earth. Second, other than one possible instance, the crater mounds are deficient of collapse features or crosses. This deficiency is inconsistent with terrestrial pingos. Third, the average size of the pingo-like mounds in the area of the Thyra crater is an order of magnitude larger than the average size of hydrostatic pingos on Earth. Fourth, while the morphology of the Gusev crater may be suggestive of the past presence of water, the pingo formation hypothesis is highly speculative; the hypothesis requires multiple layers of assumption that are not justified by the geomorphological field data themselves or by terrestrial analogues. Alternative theories of mound formation were considered, but not at length. Fifth, the Gusev-Thyra hypothesis is dependent upon one source of data: Viking Orbiter images whose resolution is coarse.

By contrast, the dust devil hypothesis is sustained by ground-based and orbital data that encompasses real-time geomorphological, atmospheric and thermal data points. Alternative theories do not fit the data. Like the Gusev-Thyra hypothesis, the cataclysmic discharge hypothesis is constrained by dependence upon orbital imagery and by speculation tie to events in the distant past. But all in all there seems to be a better geomorphological fit between the available data and a fluvial or mixed discharge origin than there is between the available data and the Gusev-Thyra pingo formation hypothesis. For these reasons the Gusev-Thyra hypothesis is of a lower analogical value than either the dust devil or the cataclysmic outflow hypotheses.

4.2.1 Pingos and a Periglacial Landscape in Northwest Utopia Planitia

The Utopia crater mounds bracket the latitudinal median of the crater and are concentrated in an area ~ 10 km^2 that lies ~ 2 - 3 km east of the crater centre. The proximity of the mounds to the centre of the crater may indicate of a hydrostatic origin. Had the crater been filled with water that was subsequently lost as Mars began to move away from high obliquity, permafrost aggradation, pore water expulsion, ice core formation and mound development could have occurred on the crater floor.

The geomorphological data are consistent with this scenario. For example, the MOLA tracks show that many of the Group A mounds are arrayed longitudinally on a slightly elevated plateau or terrace (**fig. 10**). The terrace is located immediately to the east of an assemblage of dendrites. The dendrites coalesce into a main trunk much as they would in a terrestrial fluvial system. Immediately to the northeast of the dendrites is a channel that is normal to the Group A plateau (**figs. 8 and 9**). Water might have been borne by the channel as it graded to the south.

I hypothesize that the terraced mounds of Group A are hydrostatic pingos that formed when the last vestiges of water in the local landscape receded, evaporated or sublimated. The loss of water would have exposed the water-saturated regolith beneath the terraces to permafrost aggradation and to increased pore water pressure. Pingo genesis might have ensued.

A few mounds are clustered to the northwest of Group A on the opposite side of the dendrites. The absence of MOLA tracks in the area of the western mounds makes it difficult to ascertain whether they are located on a plateau or a basin. But in either case, the proximity of the eastern and western mounds to possible fluvial landforms in the midst could be indicative of an origin that is related to those landforms.

The pingo-like mounds of Group B lie in the midst of an elliptical feature, possibly a small drainage basin. As indicated by the MOLA tracks (**fig. 10**), the basin grades slightly to the east and intersects the southward trending channel in the vicinity of two small, dust-covered craters. The mounds of Group B, like the mounds of Group A, could have been formed when the last vestiges of water in the local landscape drained away to the east and south or were lost through evaporation or sublimation. This would have exposed the saturated regolith beneath the basin to permafrost aggradation and increased pore water pressure. Pingo genesis could have been initiated.

The gradual loss of elevation to the east of the Group A and B mounds (**fig. 10**) is consistent with the presence of a central crater peak, partially visible in the Viking image of the crater **(fig. 23).** Central peaks are expected in impact craters of this size (Melosh 1985). Notwithstanding the eastward loss of elevation, the morphology of the southern basin and of the northern dendrite/channel assemblage suggests local confluence immediately to the west of the Group A terrace and Group B basin (**figs. 8, 9 and 10**). This might be the product of differential erosion or settling. Perhaps water collected in the area to the west of the Group A and B mounds and then followed the topography through the Group B basin on its way to the eastern channel and impact craters. Unfortunately, the low resolution (231 m/pixel) of the Viking background image (**fig. 23**) hinders the evaluation of this hypothesis.

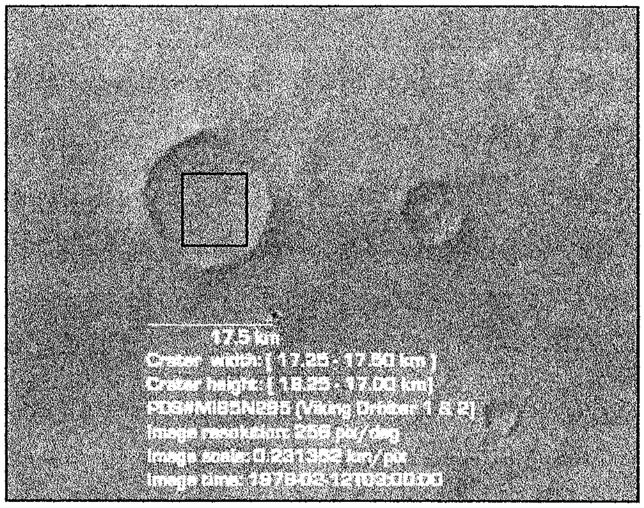

fig. 23: Viking Image M165N295, NW Utopia Planitia (res. ~ 231 m/pixel). Background view of the impact crater (on the left) highlighted by MOC image EO300299. A faded peak resulting from the impact formation of the crater is visible at the centre of the crater.

Summit depressions, possibly collapse features, are present amongst a few of the mounds (**fig. 8**). Mound cracks, that may be the result of dilation, seem to intersect polygonal cracks at the mound perimeters **(fig. 8)**. The convergence of mound-based dilation cracks with ground-based polygonal cracks is not unusual in terrestrial periglacial landscapes where pingos are found (**fig. 8**) (Bennike 1998; Mackay 1998). In a Martian cold-climate environment neither erratics, rafted in by glaciation, falling rim debris, small impact craters nor impact ejecta settling on a crater floor, would present features suggestive of summit depressions or dilation.

4.2.2 Small-Scale Martian Polygons

Large and small patterns of polygonal ground are ubiquitous on Mars (Lucchitta 1981; Kuzmin *et al.* 2003; Pechmann 1980; Seibert and Kargel 2001; Yoshikawa 2002). Generally, polygons are characterised as large when their trough to trough diameters are > ~ 250 m; many large polygons are kilometres in diameter, with some polygons being as large as ~ 20 km in diameter (Kanner *et al.* 2003; Lucchitta 1981; Pechmann 1980; Rossbacher and Judson 1981; Seibert and Kargel 2001; Weinrich and Christensen 1993; Yoshikawa 2002).

Thermal contraction theory suggests that the stress of contraction exceeds the tensile strength of frozen ground at distances measured in metres not kilometres (Lachenbruch 1962; Plug and Werner 2001). As such, it seems unlikely that the large polygons were formed by processes related directly to thermal contraction (Heisinger and Head 2000; Pechmann 1980; Rossbacher and Judson 1981; Seibert and Kargel 2001). The cooling of lava flows (Carr *et al.* 1976; Morris and Underwood 1978); tectonic rebound following the removal of the water/ice load in areas such as the Utopia Basin (Carr *et al.* 1976; Heisinger and Head 2000; Pechmann 1980) and dessication of water-saturated sediments (Morris and Underwood 1978) are some of the processes invoked by planetary scientists to explain the formation of large polygons on Mars.

Martian polygons are characterized as small if their trough to trough diameters are < ~ 250 m (Kanner *et al.* 2003; Kuzmin *et al.* 2002; Mellon 1997; Pechmann 1980; Seibert and Kargel 2001). Small-scale patterns of polygonal terrain have been identified in areas of low elevation in the mid- to high-latitudes of both Martian hemispheres (Mellon 1997; Seibert and Kargel 2001). These are areas in which ground ice or ice-cemented permafrost would be stable and might be present (Mellon 1997; Seibert and Kargel 2001). Ice-cemented permafrost is a requirement of thermal contraction and of crack formation (Lachenbruch 1962). The largest concentration of small-scale polygons is in and around the Utopia basin (Seibert and Kargel 2001). Most of the polygons in MOC image EO300299 are < ~ 250 m in diameter; some of them are slightly larger. The image is not resolved finely enough to ascertain whether the polygons are sorted or unsorted. But the size of the polygons is more suggestive of terrestrial polygons formed by thermal contraction than it is of sorted polygons formed by freeze-thaw processes.

To what extent are Martian polygons that are ~ 250 m in diameter consistent with thermal contraction theory? Recently, it has been suggested that the depth to which a fracture forms in terrestrial permafrost is contingent upon the rheological properties of the ground more than it is on the penetration depth of surface temperatures (Maloof *et al.* 2002). Deep cracks will propagate more easily in very cold, very brittle ground than in warmer ground that is less brittle. On the assumption that the Martian regolith is very cold, with temperatures below 60 K in some places, and consequently, very brittle, it has been argued that cracks as deep as ~ 100 m could form (Mangold 2004, in prep.). If the diameter of small-scale polygons is proportional to crack depth, then a crack depth of ~ 100 m in the very cold regolith of Mars could engender the formation of polygons that are ~ 200 - 300 m in diameter. The mean size of the polygons in MOC-EO300299 falls well below this threshold.

Identifying the bright material that fills the cracks of the small-scale polygons on the crater floor of MOC image EO300299 is difficult. The surficial fill could be sand or dust (Heisinger and Head 2000). The extent to which the sub-surficial fill comprises sand, dust or water ice cannot be ascertained. Terrestrially, crack infiltration by sand tends to occur in cold and highly dessicated environments. But as the crater floor landscape points to the possible presence of liquid water, the floor cracks could have been filled by water. Subsequently, repeated cycles of cracking and infiltration would have induced the growth of ice wedges, which may still be present at depth beneath the polygon troughs.

Polygon orientation also suggests past fluvio-lacustrine activity. Generally, the orientation of the polygons in MOC image EO300299 is random. However, a band of orthogonal polygons ~ 800 m in width overlies a dark-curvilinear channel-like feature that runs roughly along a north-south axis in the area to the east of the terraced mounds in Group A. The MOLA data indicates that this channel-like feature is at a lower elevation than the hypothesised terrace immediately to the west. Band orientation is normal to the contour of the channel-like feature through its reach. When terrestrial cold-climate lakes or rivers drain slowly, thermal contraction cracks form orthogonally, either normal to or parallel with the contour of the lake basin or shoreline (Lachenbruch 1962; Kuzmin *et al.* 2002). The orthogonal orientation of the polygon band in MOC image EO300299 could be a marker of past fluvio-lacustrine activity in the hypothesised channel.

4.2.3 Crater Age and Possible Sources of Water

I hypothesise that the crater-based landscape shown in MOC image EO300299 is relatively young, perhaps ~ 100,000 years old. The hypothesis is based upon five assumptions. First, the crater lies within an area of the northern plains that may have undergone re-surfacing as recently as the early Amazonian period (Tanaka *et al.* 2003). Second, the dendritic basin and fields of polygonal patterned ground in the crater are not overwhelmed with dust and debris. Third, the pingo-like mounds are crossed by what may be dilation cracks. While the scale of image resolution prevents one from ascertaining whether the cracks are open or filled, the fact that they too are not covered up by dust and debris suggests a relatively young age. Fourth, over long periods of time near-surface ground ice is subject to sublimation. Consequently, if the mounds are pingos, then the general absence of collapse features or scarring in the landscape suggests that the ice cores underlying them have not sublimated and may still be extant. Fifth, and perhaps most importantly, is the recent hypothesis relating the formation and removal of near-surface ground ice at latitudes greater than 30^0 N to episodes of high obliquity: when obliquity exceeds 30^0 (Head *et al.* 2003; Mustard *et al.* 2001).

The last instance of high obliquity may have been ~ 100,000 years ago (Head et al. 2003). The hypothesis suggests that at high obliquity water is removed from polar reservoirs and is transported to the mid-latitudes where it nucleates on dust particles in the air or on the ground; subsequently, the water

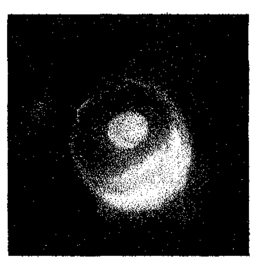

fig. 24: MOC image M2000356; frosted northern crater (71^0N, 257^0W), ~ 48 km in diameter, late spring

covers the surface like an ice-rich blanket (Head *et al.* 2003). The ice-rich blanket could be similar in appearance to the frost accumulation that occurs seasonally under contemporary conditions in sub-polar impact craters (**fig. 24**).

If the atmospheric pressure and temperature in the area of the sub-polar northern crater rose in response to increased obliquity, then the ice-rich blanket covering the crater floor could have thawed or melted. Had the atmospheric pressure and temperature been sufficiently high, meltwater might have collected on the crater floor and persisted for some time. At a lower pressure and temperature, basal melting might have led to the collection of ponded water under a cover of ice. In either case, the regolith beneath the crater floor would have warmed and the infiltration of meltwater might have taken place. When Mars receded from high obliquity, the temperature and atmospheric pressure would have fallen, leading to the loss of water in the crater basin by sublimation or evaporation. In the areas of low topography and of residual ponding a series of events leading to the formation of ice mounds and of small-scale polygons could have been initiated. Had relatively coarse sediments been present on the crater floor, this would have facilitated the initiation of these events.

The Utopia crater lies in an area that was susceptible to flooding as late as the early Amazonian period (Carr and Head 2003; Fairén *et al.* 2003). The crater rim displays evidence of deformation or breach consistent with the erosional work of water (**fig. 23**). Depending upon the velocity of the flood water, coarse sediments could have been laid down prior to the most recent episodes of obliquity. Speculation concerning whether rampart deformation was the work of water, water-ice, wind or of differential weathering, however, is constrained by the low resolution (231 m/pixel) of the Viking wide-band crater image.

4.2.4 Comparing the Utopia Planitia and Gusev-Thyra Pingo Hypotheses

Comparatively, the evidence in favour of a possible pingo presence in the Gusev crater is stronger than the evidence supportive of a possible pingo presence in the Utopia crater. The size of the mounds in the Utopia crater is consistent with that of terrestrial pingos; the size of the Gusev-Thyra mounds is too large. Small-scale polygonal ground is identifiable in the Utopia landscape; small-scale polygonal ground is not identifiable in the Gusev-Thyra landscape. Some of the Utopia mounds are crossed by cracks and others feature possible collapse scars. None of the Gusev-Thyra mounds are crossed by cracks, although a possible collapse feature may be present on one of the Gusev-Thyra mounds.

Could pingo-like mounds on Mars grow to a size that dwarfs terrestrial pingos but avoid dilation and the mechanical failure that is common among much smaller pingos on Earth? Perhaps at some point in the distant past the Gusev-Thyra mounds were crossed but became blanketed by dust and debris; perhaps crosses are present but are unidentifiable in the absence of higher resolution images. Either way, the lack of crosses compares unfavourably with the Utopia crater, where crossed mounds are discernible.

The general absence of collapse features amongst the Gusev-Thyra mounds is more difficult to explain. For the mounds to have remained inflated since their hypothesised formation in the early Amazonian period, the ice underlying them would have had to be immune to sublimation for hundreds of millions of years. By tying mound genesis to the most recent episode of high obliquity, the need to hypothesise ground ice being extant for hundreds of millions of years is avoided.

The presence of pingo-like mounds on a slightly elevated terrace or in a basin is where one would expect them to be if their geneses were tied to the loss of ponded lake water. In this regard, the analogical similarity of the Utopia mounds to the hydrostatic pingos of the Tuktoyaktuk peninsula is high. Equally, while not being an unambiguous artefact of water, the existence of small-scale polygonal patterned ground and the possibility that the polygon troughs were filled with water-ice enhances the likelihood that periglacial processes were at work in the crater basin at some point in the past. The concurrent presence of pingo-like mounds and of small-scale polygonal patterned ground in a landscape also is a marker of similarity between the Utopia crater basin and the Tuktoyaktuk coastal landscape. This marker is missing from the Gusev-Thyra crater landscape. In addition, the Gusev-Thyra pingo formation hypothesis is based upon a long, very complicated and highly speculative series of events The chronology of events required by the Utopia-crater pingo formation hypothesis is simpler and less speculative. If high obliquity is invoked, then the formation of pingos and of a periglacial landscape on the floor of the Utopia crater could mirror the formation of pingos and of polygonal patterned ground in terrestrial drained-lake landscapes. Lastly, the Gusev-Thyra hypothesis is constrained by coarse Viking imagery. By contrast, the Utopia hypothesis seamlessly integrates high resolution MOC imagery with MOLA altimetric in order to sustain its assumptions concerning landscape formation. For these reasons, the analogical value of the Utopia hypothesis is higher than that of the Gusev-Thyra hypothesis.

Chapter 5: Conclusion

The use of analogues in planetary science is paradoxical. When non-terrestrial environments or landscapes are understood incompletely, planetary scientists often invoke terrestrial analogues as a source of potential insight and knowledge. But if one's understanding of target environments or landscapes targets is incomplete, then one's ability to evaluate the relevance or value of an analogical source must be incomplete too. In those instances when the conceptual distance between planetary science and a non-terrestrial target is at its greatest, the ability to ascertain analogical relevance and meaningfulness could be at its weakest.

The use of incomplete data sets to underpin analogical hypotheses may be unavoidable in a relatively young discipline like planetary science. This notwithstanding, the viability and meaningfulness of analogical speculation is contingent upon finding a way to distinguish strong from weak and relevant from irrelevant hypotheses. The framework of analogical differentiation developed in the thesis, comprising three key criteria, is essential to meeting this end. The criteria are: 1. the extent to which data drawn from disparate sources converged in support of a hypothesis; 2. the degree to which alternate hypotheses had been considered; and, 3. the measure of reconcilability between the data captured in the field and the expectations derived from data and theory obtained from the analogical source. Three analogical hypotheses focused on Martian geomorphology were evaluated on the basis of the evaluative framework: the dust devil, cataclysmic discharge and crater-based pingo hypotheses.

The evolution of the dust devil analogue exemplified the transition from data-less speculation and hypothesis construction to data-based explanation in the development of a scientific theory. In the 1960's and early 1970's the genesis of global dust storms on Mars was understood poorly. Images of the Martian surface were of a low resolution and knowledge of atmospheric boundary conditions were sparse. However, drawing upon their knowledge of terrestrial aeolian processes in dry desert environments planetary scientists suggested that dust devils could be a plausible mechanism for initiating dust upliftment under conditions of low-atmospheric pressure and low-velocity surface winds. In time, complementary streams of data gained from the Viking Landers and Orbiters converged in support of the dust devil hypothesis. As the depth and breadth of the data pool grew, the analogical paradox discussed above dissipated and disappeared. Alternative hypotheses carried no conceptual weight by comparison.

The origin of the massive and possibly ancient equatorial discharge channels on Mars still is a mystery. Fluvial break-out on a scale of ~ 1.4×10^9 m^3 s^{-1}, which is thought to have formed Kasei Valles, is without parallel on Earth and on Mars. The largest known terrestrial discharge, linked to the formation of the Channeled Scablands, is thought to be at least two scales of magnitude lower. Even the channel forming discharge of Cerberus Fossae, is three orders of magnitude lower than that the channel forming discharge of Kasei Valles.

A number of general hypotheses have been posited to explain fluvial episodes of very high magnitude on Mars. One of the leading hypotheses suggests that a global cryosphere intermittently has delivered buried (sub-permafrost) water under pressure from the poles to the equator. Other hypotheses connect aquifer break-outs to volcanism or to the impact of large bodies on the Martian surface. An evaluation of these hypotheses awaits the acquisition of more detailed data of the Martian surface and of the geology of Mars at depth. Questions concerning whether the discharge at Kasei Valles was fluvial, glacial or mixed also remain unanswered, as do questions concerning the origin of the discharge itself. For these reasons, the outflow channel and cataclysmic origin analogue is less strong that the dust devil analogue.

On analogical grounds, the Gusev-Thyra pingo hypothesis is problematic. To the credit of its authors, the hypothesis was the first attempt to elaborate the possible genesis and development of pingos in a Martian impact crater. Engaging as it was, the plausibility of the hypothesis was constrained by five main factors. First, the images invoked in support of the hypothesis were of a low resolution - ~ 69 m/pixel -; higher resolution images were unable to identify the pingo-like mounds. Second, the pingo-like mounds were an order of magnitude larger than terrestrial analogues, raising questions about the analogical value of terrestrial pingos to these large Martian mounds. Third, the pingo-like mounds, in general, seemed to lack summit and dilation cracks that are ubiquitous amongst terrestrial pingos. Fourth, landforms such as polygonal patterned ground that are often side-by-side with pingos in cold climate landscapes were absent from the low and high resolution images of the Thyra-Gusev area. Fifth, the genesis of the Martian mounds was contingent upon a sophisticated and highly speculative series of events; data supportive of the events was sparse.

By contrast, the landscape of the Utopia crater comprises an assemblage of features and mounds that is reminiscent of the Tuktoyaktuk peninsula in northern Canada. All of the Tuktoyaktuk pingos are coastal and many of them formed as the result of coastal recession. The pingo-like mounds of the Utopia crater are adjacent to possible fluvial features, as seen in the northwest quadrant of MOC-EO300299. Moreover, the mounds could have arisen at the most recent occurrence of high obliquity, with the climate induced collection, dissipation and loss of water in the crater basin. Topographically, as indicated by the MOLA altimetric tracks, the areas in which the mounds are present are consistent with a drained lake pingo formation hypothesis. Mound size and shape, evaluated on the basis of high resolution imagery, is consistent with terrestrial analogues. The presence of summit depressions and of mound crosses that intersect the polygonal cracks in the surrounding landscape also is suggestive of pingos in cold-climate environments, so is the shape and size of the polygonal patterned ground itself. Orthogonal polygons to the east of the mounds suggest a possible fluvial channel long past.

Admittedly, none of these points are unequivocal in their support of a drained lake pingo hypothesis. However, as a body of evidence these points are consistent with the presence of pingos and a periglacial landscape in northwest Utopia Planitia. Alternative hypotheses are not obvious. For this reason, the Utopia Planitia pingo hypothesis must be ascribed a higher analogical rank than the cataclysmic discharge hypothesis. On the other hand, neither the pingo nor the discharge hypothesis has attained the maturity or the meaningfulness of the dust devil hypothesis.

When relict landscapes are studied on Earth, geomorphologists gain analogical understanding by studying active landscapes that share a common genesis. The analysis of Martian geomorphology is not as straightforward. Notwithstanding aeolian processes such as the ones responsible for dust devil formation and some small-scale examples of fluvial discharge or mass wasting, the analysis of Martian landscapes and landforms takes place largely in the absence of contemporary geomorphological activity. The shortfall is overcome, in part, by synthesising the available Martian field data with data derived from terrestrial analogues.

By developing a set of guidelines with which to differentiate good from bad analogical hypotheses, I have sought to do two things: 1. establish a firmer philosophical footing for analogical reasoning; and, 2. facilitate the acquisition of meaningful answers to basic questions concerning Martian geomorphology.

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