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THE UTILITY OF GEOTHERMAL ENERGY ON MARS

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The exploitation of geothermal energy has been absent from previous considerations of providing power for settlements on Mars. The reason for this is the prevailing paradigm that places all of Mars' volcanic activity in the remote past and hence postulates a crust that is frozen to great depths. It is argued in this paper that this view may be true in general, but false in particular. Geological evidence is reviewed that suggests that magmatism may have been active on Mars until recent times and may hence still be ongoing. Thus, the presence of significant, localized, hyperthermal areas cannot be ruled out on the basis of the low mean heat flows predicted by global heat flow models. The possibility of the presence of useful geothermal fields is further strengthened by observations of fluvial outflows that seem to have been associated with certain magmatic extrusions and which therefore hint at favourable groundwater conditions. Such a geothermal energy source would be of great potential economic value, being of use for the generation of electricity and direct heating for industry and habitation. The addition of this energy option to those of solar, wind and nuclear, cannot but enhance the prospects of a martian civilization that must start afresh, without an equivalent to the Earth's stock of fossil fuels.

All things are an exchange for fire, and fire for all things, even as wares for gold and gold for wares.

Heraclitus of Ephesus

1. INTRODUCTION

Mars promises to be both a generous and challenging place for future explorers to visit. Generous, because it is the only known extraterrestrial locality possessing an accessible abundance of the material pre-requisites of life; challenging, because this endowment tempts us toward a longer-term strategy where manned visits evolve into a permanent and self-sufficient presence.

The validity of exploiting indigenous resources on Mars to support manned exploratory missions is now widely accepted. Using martian sunlight and wind to generate auxiliary power, martian volatiles as feedstocks for life support systems and the manufacture of fuels, and martian soils and rocks for construction, will enhance the duration, flexibility and safety of missions to Mars [1-3]. This, however, is "living off the land" in a restricted sense, since it is only made possible with an expensive technological infrastructure manufactured on and supplied from the Earth. For martian settlements to progress towards self-sufficiency–as they must do to be realistic at all–this dependence on a net subsidy from the Earth must eventually be eliminated and replaced by a relationship of two independent trading economies [4].

A fundamental requirement of any ecosystem or economy is an internal flow of energy. In addition, for such systems to be viable over the long term and for growth to be possible, energy resources must be harnessed profitably–that is, more useful energy must be liberated than work consumed in the process of liberation. Thus, there must be a continuing supply of *net energy* and the higher the net energy ratio (useful energy provided/work expended in provision) the better [5]. Net energy provision is thus crucial to the feasibility of the settlement of Mars and is far from being a trivial question. Mankind only has the experience of building one technological civilisation–our own–made possible by the net energy provided by the combustion of our planet's rich stock of fossil fuels. Oil, coal, natural gas, and the oxygen-rich atmosphere in which to burn them, are not present on Mars. In settling Mars therefore humanity will not just be confronted by the alien rigours of Mars itself, but will have to face the challenge of providing an alternative energetic basis for civilisation.

In this paper, proposed methods of generating power on Mars are briefly discussed before embarking on a more detailed discussion of the potential of martian geothermal energy. Consideration of this option has probably been neglected until now because of the prevailing paradigm of Mars as a geologically dead and deep-frozen world. However, it will be argued that this viewpoint, whilst true in general, may be false in particular. Hyperthermal areas probably still exist on Mars and might be profitably "mined" for their heat.

2. OPTIONS FOR POWER SUPPLY ON MARS

Terrestrial civilisation relies on four power sources for almost all its consumption of primary energy. These are, in descending order: the combustion of fossil fuels; the combustion of biomass (mostly fuelwood); hydroelectric power; and nuclear fission. Some details of these sources (applicable to the late 1980's) are given in Table 1. Also listed are a variety of alternative primary energy sources that currently either play a minor, or non-existent, economic role, but which are under consideration as future replacements for fossil fuel. A rough impression of the net energy provided by these systems (whilst ignoring arguments over hidden subsidies etc) can be gained by looking at the quoted cost of the generation of electricity–in general, the cheaper the price, the greater the relevant net energy ratio.

TABLE 1: *A Comparison of Energy Sources (Late 1980's)*

Energy Source	Typical Cost of Electricity Generation	Typical Unit Sizes	World Primary Energy Use	Application to Mars?
Fossil fuels	4 - 6 ¢ / kW hr	500 - 1000 MWe per large power station	75.6%	No
Hydropower	~ 3 ¢ / kW hr	1000 MWe per large dam	5.5%	No
Biomass	~ 5 ¢ / kW hr[1]	< 100 MWe	14.7%[2]	No
Nuclear fission	~5 ¢ / kW hr	500 - 1000 MWe per large power station	4.1 %	Yes
Tidal energy	> 8 ¢ / kW hr	0.4 - 240 MWe per barrage[3]	Negligible	No
Ocean thermal energy conversion (OTEC)	12 - 25 ¢ / kW hr	10 - 100 MWe per large plant[4]	None	No
Solar thermal	~ 9 ¢ / kW hr	10 - 100 MWe per large plant[4]	Negligible	Yes
Photovoltaics	25 - 35 ¢ / kW hr[5]	0.03 - 6.5 MWe per large installation[3]	Negligible	Yes
Wind	6 - 15 ¢ / kW hr	0.1 - 0.5 MWe per turbine[6]	Small	Yes
Geothermal	3 - 10 ¢ / kW hr	10 - 100 MWe per large plant	0.1%	?
Solar power satellite (SPS)[7]	?	5000 MWe per large satellite	None	Yes
Nuclear fusion[7]	?	?	None	Yes

[1] *Advanced gasification power generation close to plantation (not yet widely practiced).*
[2] *Mostly inefficient fuelwood combustion in thirdworld countries.*
[3] *Existing pilot plants.*
[4] *Present pilot plants are mostly of lower capacity.*
[5] *Expected to fall to 11-15 ¢/kWhr by 2000 and lower into the 21st century.*
[6] *Wind farms consist of a number of such turbines.*
[7] *Not yet developed.*
Data mostly culled from Ref. [6].

When considering power generation on Mars, we are faced with a double problem. Firstly, Mars does not have a natural, uncontained, biosphere which provides *gratis* life-support. Artificial life-support, whether entirely mechanical, or bioregenerative, is a complex and energy intensive process. Estimates of the electrical power consumption on Mars to support human beings vary from on-paper calculations for a temporary 8-man outpost which obtain a figure as low as ~ 1.2 kWe/person [7], to the experience of running Biosphere 2 which needs an enormous ~ 100 kWe/person [8]. This compares to the ~ 11 kW/person and the ~ 3 kWe/person consumption of primary and electrical energy respectively of the averageAmerican. The reality of living and prospering on Mars will probably involve a per capita power consumption between these 1-100 kWe/person extremes. The former is much too low as it does not include realistic heating requirements and the demands of permanent habitation and growth, including those of industry and the quality of life. On the other hand, we might reasonably expect future enclosed habitats to be much more economical and practical than Biosphere 2, which was not designed with efficient energy use in mind.

On the Earth, direct fuel use is economically very important. On Mars, it is not an option and fuels and oxidisers must be synthesised from basic raw materials [3,9]. Thus, a reasonable estimate for the per capita power consumption of a permanently established martian population might be arrived at by assuming a demand for electricity similar to the per capita *primary* energy consumption of the first world nations, multiplied by a factor reflecting the need to synthesise alternative energy carriers, and incremented further due to the needs of artificial life-support. Such a calculation would embody the needs of basic survival, industry and a fair standard of living. The published figure that perhaps comes closest to reality is the calculated electrical power demand of the 150-man Mars base designed by the Japanese Ohbayashi corporation, intended specifically as a beachhead for permanent settlement [10]. Although their calculations were not fully displayed in the cited reference, their estimate of an all inclusive power demand of ~ 20-50 kWe/person has an air of plausibility. If we assume this to be realistic, then we might reasonably expect a growing civilisation on Mars needing a supply of electrical energy about 2-5 times as great as the consumption of primary energy of the first world nations of the Earth.

The second problem inherent in the energetics of martian settlements is that, looking back at Table 1, it is seen that only one of the big four power sources is likely to be available, namely nuclear fission. To be brought into operation, nuclear power requires an elaborate infrastructure in place. Nuclear fuels must be prospected, mined, purified and then consumed in reactors that are themselves the products of sophisticated manufacturing. Spent fuel must be properly disposed of, or reprocessed, further adding to the work involved. Thus, in order to commence the progression towards self-sufficient energy use, martian settlers must have access to more inelaborate and available energy sources, before large-scale indigenous nuclear power comes on line.

The two power sources often mentioned in this regard are solar and wind power [2,11,12]. However, whilst these sources are undoubtedly available on Mars and might serve well to provide auxiliary power for outposts or pioneering settlements, they are not suitable as the energetic basis of a vigorous civilisation–especially in view of the much greater relative demand for electricity. The prices given for solar-thermal, solar-photovoltaic and wind power in Table 1 show that these systems (especially solar) are not fully competitive with fossil fuels due to the high cost of manufacturing generating equipment, such as solar cells and wind turbines. Prices however are falling and should continue to do so in the next century, but even if solar and wind power should become economic on the Earth it does not mean they will become so on Mars, where additional factors are against them. Martian sunlight is an average of 43% as intense as terrestrial sunlight, and even when lesser cloud cover is accounted for, solar arrays on Mars will need roughly double the area as a similarly rated one on Earth. Since the martian atmosphere at the planet's surface is only about 1% the density as that on Earth, a similarly rated wind turbine on Mars must have rotor blades ten times the diameter as turbines built to work on the Earth, or must operate in winds that average 4.6 times the speed. In addition, both solar and wind power are categorised as being "intermittent renewables"–they never run out, but are only intermittently available and are thus unsuited to provide a base-load power supply.

What of the other power supply options listed as appropriate for Mars in Table 1? Deuterium is abundant on Mars and so there exists plenty of fuel for nuclear fusion. But fusion is an unproven concept and will likely face the same bootstrapping problems suggested previously for fission. Solar Power Satellites (SPS) will be suitable for the provision of base-load electricity as they can be sited in permanent sunlight [13]. Even given the weaker sunlight at Mars, the Ohbayashi designers considered SPS as the best method of providing their settlement with a reliable power supply [10]. However, SPS is also an unproven concept (although certain to be viable) and has the disadvantage of being sited remote from the settlement, in space.

This leaves just one remaining contender in Table 1–geothermal energy–heat emanating from the planetary interior and found in useful form as hot underground waters. This has five attractive features: it is an intrinsic energy resource; it is suitable for a base-load supply; in addition to electricity generation, it can be used to provide thermal energy directly; the technology is comparatively mature; and, if a quality hydrothermal reservoir can be found, then power is potentially very cheap to generate. Experience has shown that geothermal electric power plants are extremely reliable and flexible, being on-line 97% of the time, compared to 75% and 65% for coal-fired and nuclear plants respectively. They can be constructed in modular increments and hence upgraded in capacity when necessary: 0.5-10 MWe plants can be up and running in as short as six months and clustered facilities generating > 250 MWe in just 2 years [14].

However, four conditions must pertain in order for there to exist an exploitable geothermal field (ignoring, for the moment, the potential of hot dry rock); these are [15]:

(1) A powerful source of natural subterranean heat

(2) An adequate water supply

(3) An aquifer of permeable reservoir rock

(4) A cap rock

On Mars though, item 1 is particularly problematic in view of the prevailing paradigm of the planet being cooled to great depths. Theoretical models of the mean global geothermal heat flow on Mars [16-18] estimate it to be about 0.03-0.04 W/m^2, compared to an average of 0.06-0.08 W/m^2 on the Earth. Looking at the problem from the point of view of this mean flow does indeed render martian geothermal power an unlikely prospect, as it places the 100°C isotherm as deep down as 10 km, even at the equator. However, heat leaking out of the Earth is far from isotropic and exhibits enormous variations between localities. A model that predicted merely the mean heat flow of the Earth to be, say, 0.065 W/m^2 would not predict the existence of local "lows" in forearc regions of just 0.03 W/m^2, "highs" of 0.09 W/m^2 in backarc regions, and "superhighs" in immediate volcanic areas as high as 0.6 W/m^2 [19]. Even though Mars does not possess plate tectonics, its history has been dominated by volcanism. Rocks of igneous origin are thought to be exposed over some 58% of its surface– not all of them dating back to the primordial times [20]. It is perhaps therefore not unreasonable to propose that martian heat flow too might exhibit some local variation and that, given the possible abundance of subterranean water [21-24], exploitable geothermal fields might still be present.

Is it reasonable therefore to dismiss the potential of geothermal power production on Mars out of hand? Not necessarily. This paper thus proceeds to assess the possible existence of present day hyperthermal areas on Mars and the future uses of martian geothermal energy, should it turn out to be viable.

3. POSSIBLE HYPERTHERMAL LOCALITIES ON MARS

If it were easy to drill boreholes to an arbitrary depth, then hot rock could be reached from anywhere on the surface of Mars. However, economic and practical constraints dictate that a good geothermal field is underlain by relatively shallow, hot strata. This requires an anomalously high heat flow, implying the presence of a young igneous intrusion beneath the site–a body of ascending magma that may or may not ultimately reach the surface. A crucial question to ask therefore is whether magmatic activity is still extant: for the more commonplace it is, the better the prospects for geothermal power production.

Theoretically, anywhere on Mars could be underlain by a fresh magma body but, as on the Earth, most of these heat sources would not manifest dramatically at the surface. The presence of such "hidden" sources is often difficult to infer in the absence of detailed on-site observations. However, it may be that our current data set can act as a meaningful guide to where at least some present day martian hyperthermal areas might be situated. This is because the most obvious *external* manifestations of internal heat are volcanism and possibly outburst flooding–and features relating to both of these processes have been extensively imaged from orbit. It follows therefore that *a search for hyperthermal areas on Mars should start by examining the planet's youngest igneous and fluvial terrain, assuming that some of their magmatic centres may still be active or dormant, as opposed to long-extinct.*

Martian geology is currently divided into three major chronostratigraphic divisions, the *Noachian*, *Hesperian* and *Amazonian* Systems (in order of decreasing age). These are further subdivided into *Lower* and *Upper*, and in the case of the Noachian and Amazonian, *Middle* Epochs. *Upper Amazonian* (UA) surfaces are dated as the most recent, having a superposed density of impact craters > 2 km-diameter of less than 40 per 10^6 km^2. They cover ~ 7% of the planet's surface, with 32% of them characterised as being of volcanic and 12% of fluvial origin [20]. This implies that ~ 3.1% of the surface of Mars (an area of ~ 4.5 million km^2) is covered in "young" igneous rocks or fluvial sediments. This is a substantial area, comparable in size to half the USA.

Dating a surface on Mars is done by counting the local crater density and then calculating the time required to generate those craters by using an impact flux model scaled relative to the Moon. Comparing crater densities can give a good impression of the relative age of various surfaces, but unfortunately, the model-dependent part of the procedure leads to substantial variations between different timescales in estimates of absolute age. Thus, although Upper Amazonian surfaces are the youngest (in fact Mars can still be said to be within the UA), the absolute age of its junction with the Middle Amazonian is uncertain. The Neukum-Wise chronostratigraphic model dates the Upper Amazonian Epoch between 0 - 700 million years old [25]; whereas the Hartmann-Tanaka model reckons the UA to be shorter, lasting the previous 0 - 250 million years [26]. Resolving the age of a given martian feature to within the time span of this Epoch is even more problematic, especially if the feature is too small to provide statistically reliable cratering data. On a formation that is already very sparsely cratered, uncratered patches of essentially zero age are difficult, or impossible to distinguish.

This means that even if UA rocks are "young" in a relative sense, it is possible that most of them could still be hundreds of millions of years old. *On the other hand, a more recent or contemporaneous origin for some of them cannot be ruled out.* Indeed, it seems unlikely that *all* magmatic activity on Mars would have ceased in just the last 4 - 15% of the planet's history. This point of view receives some support from the evidence provided by the SNC meteorites (assuming they do originate, via impact ejection, from Mars). Those of the Shergottite group appear to have crystallised from lavas as recent as 160 Myr to several hundred Myr ago [27,28]. In other words, they are Upper Amazonian rocks quite possibly much younger than the UA-MA boundary. An age of 160 Myr is equivalent to just 3.5% of martian geologic time. The possibility that martian rocks this young might have reached the Earth by such an improbable route argues strongly, on statistical grounds, both for the likelihood that magmatic activity is ongoing and that its products may not be exceptionally rare. In a reconstruction of the resurfacing record of Mars, Tanaka *et al.* [29] conclude that the rate of resurfacing has fallen over the total span of the planet's history from ~ 1 km^2/yr to ~ 0.01 km^2/yr, as volcanism changed from widespread to local activity. However, given the average UA resurfacing rate, and the fact that lava flows on Mars are usually bigger than on the Earth, they estimate that a substantial lava flow has been extruded somewhere on the planet once every ~ 10^4 years for the past few hundred Myr.

The implications of the Upper Amazonian geologic record are clear: Mars *is* a more quiescent planet than the Earth, but not totally so. Local magmatic activity, extrusive or merely intrusive, may still persist. As Tanaka *et al.* [20] have stated, *"Although such processes have waned during the past 2 Gyr... faulting, volcanism and flooding may all occur in the future."*

With a view to identifying recent geologic activity, a number of detailed studies have been done of Upper Amazonian localities, but before reviewing these it is useful to consider the planet-wide distribution of such areas. This can be done by referring to the USGS 1:15,000,000-scale geologic maps of Mars prepared by Scott *et al.* [30]. These display a wide variety of geologic units which are correlated by their crater frequency distributions to the three time-stratigraphic systems in an accompanying chart. A key describing map units (which are coded both by colour and a formal letter sequence) is also provided, which gives a general interpretation of their composition and origin. These maps therefore give an overview of the areas of interest here and the relevant data is summarised in Table 2. It is apparent that UA volcanic and fluvial rocks to not occur at random. In fact they are almost exclusively located in the planet's northwest quadrant, from longitude 220° in Elysium eastward to longitude 20° in Acidalia Planitia and north of 15°S and south of 50°N. Such is the clustering of such outcrops in adjacent geographic areas that one can surmise the existence of a distinct province of recent anomalous heat flow on Mars, including Elysium, Amazonis Planitia, Arcadia Planitia and Tharsis.

3.1 Cerberus Plains

One of the youngest regions on Mars showing evidence of substantial volcanic/fluvial activity are the equatorially located Cerberus plains in SE Elysium. These cover a large area of > 10^6 km^2 from longitude 220° eastward to 168° (an east-west distance of almost 3000 km) and are up to 700 km wide (north-south) near longitude 195°. They are almost uncratered and in low to medium resolution images appear smooth, with lobate albedo patterns and embayment relations with older terrain. Whatever it was that re-surfaced this area, it appears to have filled a topographic low, centred on 5°N, 190°W, south of the Elysium volcanic assemblage and then overflowed northeastwards down channels near 11°N, 179°W onto Amazonis Planitia.

In the USGS maps, most of the Cerberus plains area is designated as Unit *Achu*–"younger channel and flood-plain material." However, a more detailed study by Plescia (which also includes parts of adjacent Units *Aps* and *Apk*) suggests an origin by flood volcanism [31,32]. High resolution images of certain areas show distinct lava flow textures such as pressure ridges, festooning and digitate flow margins. Plescia explains the associated water-cut features to the east by suggesting that the lavas flooded into western Amazonis via channels carved by a previous fluvial episode. This fluvial episode and the subsequent volcanism may have been causally linked.

The thickness of the re-surfacing material is substantial. Judging from the distribution of older terrain protruding through the deposits, Plescia estimated that the central flows must be at least 400 m thick, thinning out to ~ 10 m thick individual flows towards the margins. This amounts to a visible release of ~ 10^5 km^3 of lava and ~ 10^{16} kg of water, assuming a 1%wt content of water within the extruded magma. It is likely that much more melt than this was generated and intruded at shallow depths. The water itself adds up to a ~ 10 m depth averaged over the Cerberus area–perhaps sufficient to explain the associated fluvial geomorphology to the east. Plescia suggests that the lavas erupted at high rates for fairly brief periods, fed by rising mantle plumes. Scaling from rates of flood basalt extrusion estimated from the Earth and Moon, he calculated that the total time for emplacement of the entire formation could have been as short as 7 years or as long as 4 million years. This assumed one continuous eruption. In reality there was likely to have been interruptions in activity and periods of quiescence that would have further drawn out the process.

TABLE 2: *Upper Amazonian volcanic and Fluvial Terrain*

Geologic Assemblage	Map Unit	Locations	Crater densities > 2 km - diameter/10^6 km^2	Intepretation
Arcadia Formation	Aa_5	Central & southern Arcadia Planitia; central Acidalia Planitia	~ 20 [1]	Dark, fresh appearing lava flows; small volcanic cones.
	Aa_4	Central & southern Arcadia Planitia	20 - 40	Dark, fresh appearing lava flows; small volcanic cones
Medusae Fossae Formation	Amu	South of Olympus Mons, westward along southern Amazonis Planitia.	20 - 50	Pyroclastic deposits, or aeolian debris.
Cerberus Plains Formation[2]	Achu	South & southeast Elysium	~ 20	Flood lavas or fluvial sediments or both.
	Achp			
	Aps	South Elysium		Undefined origin.
Other channel systems[3]	Ach	North edge of Tempe Fossae; northern Arcadia Planitia.	~ 20	Fluvial sediments.
Tharsis Montes Formation	At_6	Plains flanking Arsia, Pavonis & Ascraeus Mons and caldera fill.	20 - 40	Lava flows from fissures.
Olympus Mons Formation	Aop	Plain flanking southeast of Olympus Mons.	20 - 30	Lava flows from fissures; isolated fluvial features.[3]
	Aos	Olympus Mons sheild.	30 - 40	Lava flows.
Eastern Volcanic Formation	[4]	Western flank of Hecates Tholus.	< 30[5]	Airfall ash deposit.

[1] *The USGS maps do not distinguish terrain with a >2km crater density of <20/10^6 km^2. Some regions in this Table are virtually uncratered.*
[2] *The Cerberus plains are not distinguished as an Assemblage in the USGS maps. It is so here because of the alternate flood lava model of Plescia [31].*
[3] *These channels are small compared with those of the Cerberus Plains.*
[4] *Not included in the USGS maps. The Hecates Tholus dome is of Hesperian age (Unit Hhet), but Mouginis Mark et al. [33] claim an UA age for deposits on the western flank.*
[5] *Different cratering statistics given in [33], but age estimated as younger than Olympus Mons caldera.*

The sources of lavas in a flood basalt province are often difficult to find as fissure vents are buried by their own lava. However Plescia concluded that the geomorphology of the western part of Cerberus near 200°W changed to being more akin to "plains-style" volcanism, characterised by a sequence of overlapping tube-fed low shields, extending over broad areas. Here, he was able to nominate certain features as being lava-source constructs, but only on images with poor detail due to low resolution and high-sun conditions (see Plate 1).

The Cerberus plains are undoubtedly very young and they overlie Unit Aa_4 of the Arcadia formation in the east (itself very sparsely cratered). Despite this geological youth however, it is only possible currently to date them in absolute terms to being younger than 250-700 Myr. If they are only tens of millions of years old, then it is possible that heat flow in this area remains substantially elevated over the global mean. In fact, it may be that the activity under the Cerberus plains is not extinct, but merely in repose. The only features that are seen to post-date the lava flows are the Cerberus Rupes–a WNW-trending fracture system. In this regard, it is worth noting that graben formation due to crustal extension on the Earth (which may or may not be analogous) is often associated with magmatic activity.

If the Cerberus plains are of volcanic origin, then it demonstrates that late in martian history sufficient heat remains in the mantle to generate surface hotspots of considerable extent and massive outpourings of low viscosity lava. The fact that the outpouring of these lavas was also associated with the release of water adds to the possibility of useful geothermal fields remaining at the site to this day.

3.2 Hecates Tholus

Hecates Tholus is the northernmost of the three large volcanic constructs of Elysium and is thought to be the oldest. Its shield is mapped as Unit *Hhet* (Upper Hesperian) and is thus roughly 2-3 billion years old. Its southern flanks were buried about a billion years later by LowerAmazonian lava flows from Elysium Mons. At face value therefore, we might reasonably expect Hecates Tholus to be long extinct and cooled to considerable depths.

Mouginis Mark *et al.* [33] however have drawn attention to a remarkable asymmetry in the distribution of craters on this volcano. To the west of the summit and down slope some 75 km, there appears an almost complete absence of superposed impact craters and an obscuration of the sinuous channels that cover the rest of its flanks. This re-surfacing is evidently very young, younger it is suggested than 300 million years–the estimated date of the collapse of the Olympus Mons caldera (Unit *Aos*).

The explanation may be that we are observing an air-fall deposit of volcanic ash, emplaced following a Plinian-style explosive eruption. To have obscured the pre-existing topography, the depth of this pyroclastic mantle must be at least ~ 100 m and implies a volume of ash of ~ 65 km^3 and a mass of ~ 7×10^{13} kg–of a similar magnitude to the masses of air-fall deposits on the Earth. In a detailed model of the proposed eruption, Mouginis Mark *et al.* proposed that the ash could have been emplaced in a single 20-30 day eruption, or a number of shorter events separated in time by < 0.1 Myr. If water was the driving volatile, then the minimum depth of magma storage would have been

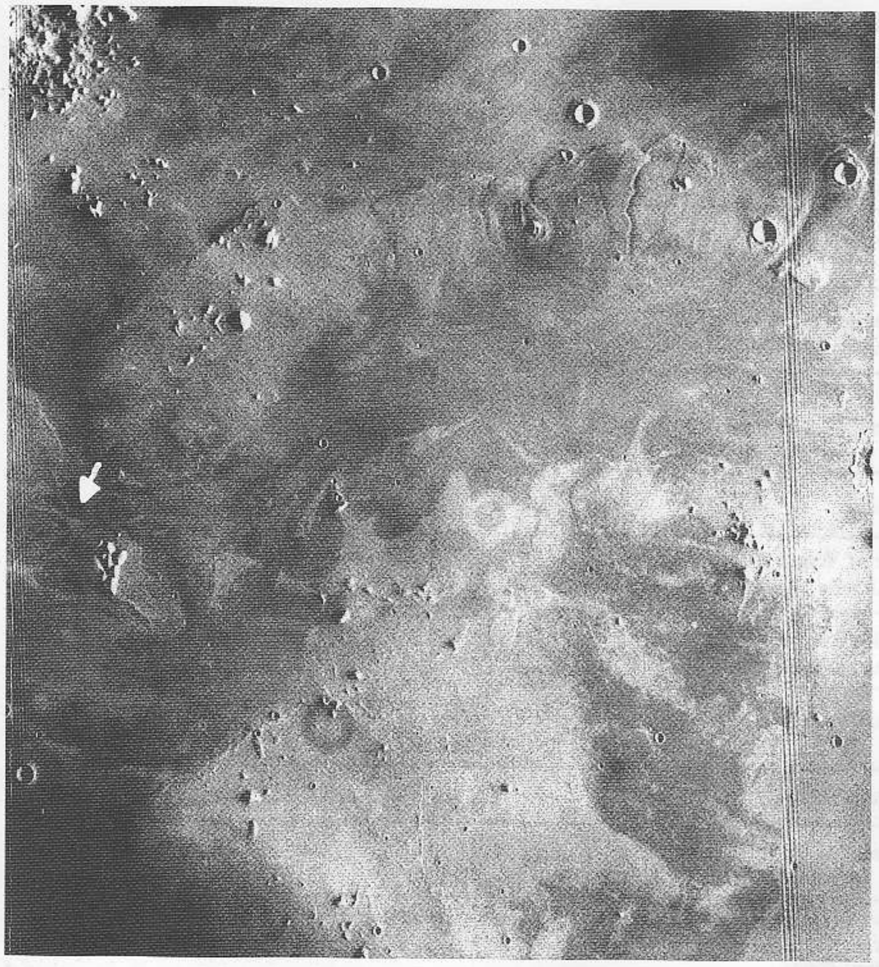

Plate 1.

Part of the western expanse of the Cerberus Plains, showing albedo patterns suggestive of recent lava flow over wide areas, submerging a more rugged terrain beneath. The bright circular feature with radiating flows to the west of the inselberg in the left of the frame (marked by an arrow), has been interpreted by Plescia [31] as a low shield vent. Viking frame: 385S42; at 6°N, 207°W; image width: 375 km; resolution: 233.4 m/pixel.

Photo courtesy of NSSDC

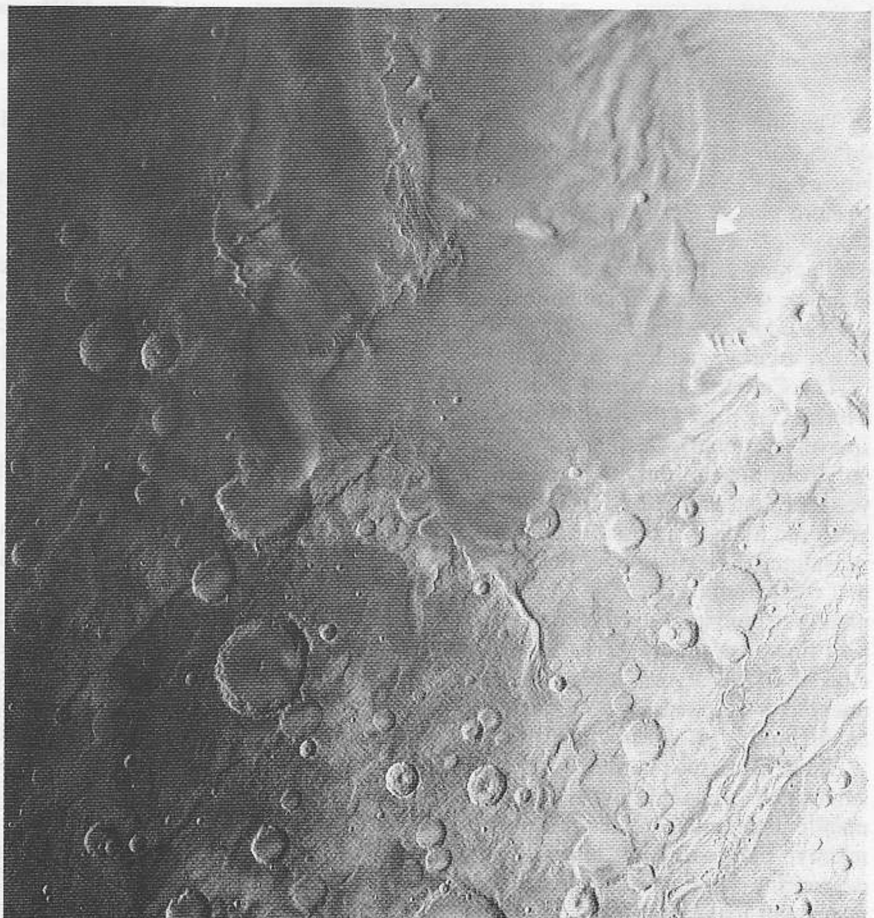

Plate 2.

Plains-Uplands boundary in the region of 3°S, 157°W showing smooth, amost uncratered, Upper Amazonian terrain towards the top of the image, interpreted by Scott and Tanaka [34] as ignimbrite deposits. They suggest the depression marked by the arrow may represent a collapsed magma chamber beneath a source vent. Viking frame: 606A62; image width: 750 km.

Photo courtesy of NSSDC

200-4000 m: heat conducting into the adjacent volume could have melted any ground ice present, setting up a hydrothermal circulation that could have incorporated extra water into the magma.

The extraordinary implications of this observation, and more subtle variations in crater density over the whole shield, is that Hecates Tholus has been intermittently active for in excess of hundreds of millions of years. Although this is unknown for volcanoes on Earth, it is perhaps possible on Mars where the absence of plate tectonics fixes the crust in place over mantle hotspots for as long as they last. It may be therefore that Hecates Tholus is not extinct at all, but dormant still, and hot within.

3.3 Medusae Fossae Formation

A pyroclastic origin for Amazonian deposits of a much greater extent has been proposed by Scott and Tanaka [34]. The rocks in question are those of the Medusae Fossae formation, exposed along the border between the highlands to the south and Amazonis Planitia–within an area roughly delineated by a triangle drawn between the volcanoes Apollinaris Patera, Biblis Patera and Olympus Mons. They consist of smooth or gently undulating level sheets, that in some areas of apparently poor lithification, show signs of having been eroded by the wind (see Plate 2). Features diagnostic of lava flows are absent and Scott and Tanaka proposed that these rocks are ignimbrite units–sheets of partially welded volcanic ash and pumice resulting from recurrent explosive eruptions.

These eruptions must have been on an enormous scale, even taking into account the fact that pyroclastic clouds should travel further on Mars than on the Earth before depositing their load. The thickness of the proposed ignimbrites, which follow but subdue underlying topography, is estimated to be as much as 2-3 km. Their total area covers ~ 2.2×10^6 km^2, comprising an estimated volume of ~ 3.85×10^6 km^3 of pyroclasts! However Medusae Fossae rocks vary quite widely in age and are dated to throughout the Amazonian System. Only about a third of the exposures appear to be Upper Amazonian in age and are found predominantly from the centre to the east of the assemblage.

In their detailed study, Scott and Tanaka subdivided the ignimbrites into seven Units based on a number of geomorphological criteria, Units 6 and 7 (of roughly equal area) being the Upper Amazonian exposures and hence corresponding to the USGS map Unit *Amu*. The rocks of Unit 6 are seen to overlie several of the aureole deposits of Olympus Mons but are embayed by younger plains lava flows. Those of Unit 7 however, appear to be as young–or younger–than the most recent Tharsis lava flows, as well as being some of the thickest ignimbrites in the entire formation. The two largest outcrops of Unit 7 (tracts of land over 300 km across) are located at the intersection due south of Olympus Mons and west of Biblis Patera, and due east of Nicholson crater. It is interesting to note that both of these areas show the presence of elongate collapse structures–depressions that Scott and Tanaka suggested may have formed by roof collapse over shallow magma chambers, about 7-10 km below the surface.

If this interpretation of the origin of the Medusae Fossae formation is broadly correct, then one can speculate meaningfully over a 2 billion year history of the area. The ignimbrites were formed as a result of repeated, large-volume, eruptions, interspersed in time by the incursion of lava flows from the plains to the north, and Tharsis and Olympus Mons to the east. These different styles of volcanism would have reflected differing mineralogical and volatile compositions of the magma at source–that rising beneath southern Amazonis presumably being more silicic, and hence more viscous and liable to explosive release. As activity has continued for so long, and as some of the most substantial ignimbrites appear to be the youngest, it is far from certain that all magmatism beneath this region has ceased. The central and eastern stretches of the Medusae Fossae formation might thus be a good place to prospect for anomalous heat flow, starting in particular with those caldrons that hint at magma chambers beneath.

3.4 Northwestern Tharsis

Nowhere else on Mars is evidence for persistent volcanism more spectacular and widespread than in the Tharsis region where igneous rocks covering > 7×10^6 km^2 have been accumulating more or less continually since Upper Hesperian times. Extensive lava flows flanking the shields of the three massive volcanoes of the Tharsis bulge, Arsia, Pavonis and Ascraeus Mons are dated as Upper Amazonian in age (Unit At_6), as is the material filling their calderas [30].

The very youngest features in this region however are thought to occur in northwest Tharsis, associated with Olympus Mons. The shield of this massive construct is also of the Upper Amazonian (Unit *Aos*), but more recently formed than this are considered to be the plains at the base of the Olympus Mons escarpment (Unit *Aop*), surrounding it from the northeast to the south. These have been interpreted as consisting of many overlapping lava flows, aggregating to a depth of several kilometres, extruded from faults and fissures beneath the volcano and appear to represent the most recent large-scale formation in the region. Whilst it would be wise to eventually investigate Tharsis as a whole for its geothermal potential, the plains comprising sequence *Aop* appear particularly promising on two counts. Not only do they provide a clue to where heat flow was highest in the recent past, but they also show geomorphological evidence for the release of what may have been hydrothermal fluids.

Isolated, fluid-cut, channels in northwest Tharsis have been studied and described by Mouginis Mark [35] who considers it most likely that their origin was due to the erosive action of flowing water, rather than lava. Three such small fluvial outflows are located on Unit *Aop* and thus postdate even this youngest of Tharsis terrain. The best imaged system is located at 16°N, 129°W–within 15 km of the Olympus Mons escarpment–and appears to originate from an arcuate graben (see Plate 3). The channel system itself is 85 km in length and divides into three main segments of width 300-1600 m, with braided floors and streamlined islands. Some distributaries end in deltas and what may be sink holes or ponds where water presumably evaporated or percolated underground. The channels seem to be quite shallow (~ 23 m mean depth) and the surface area of the entire system is ~ 50 km^2, involving the removal of ~ 1.15 km^3 of surface material. The estimated volume of water required to cause this erosion is 3-12 km^3.

Such geologically recent flooding is somewhat puzzling as models that predict the presence of water on Mars today from long-term stability criteria indicate that the equatorial crust should be desiccated to significant depths [36]. Mouginis Mark [35] therefore considered the most likely explanations for the channels either to be the melting of ice lenses deeper than ~ 1 km by an igneous intrusion, or the tectonic release of the contents of a deep groundwater system via faults caused by the great mass of Olympus Mons loading the surrounding plains. Both of these models imply that thermodynamically useful fluids may still be present at relatively shallow depths beneath these plains. Obviously, if the flooding has been associated with high heat flow then the potential of the site as a geothermal field would be much enhanced. Perhaps if there are any hyperthermal

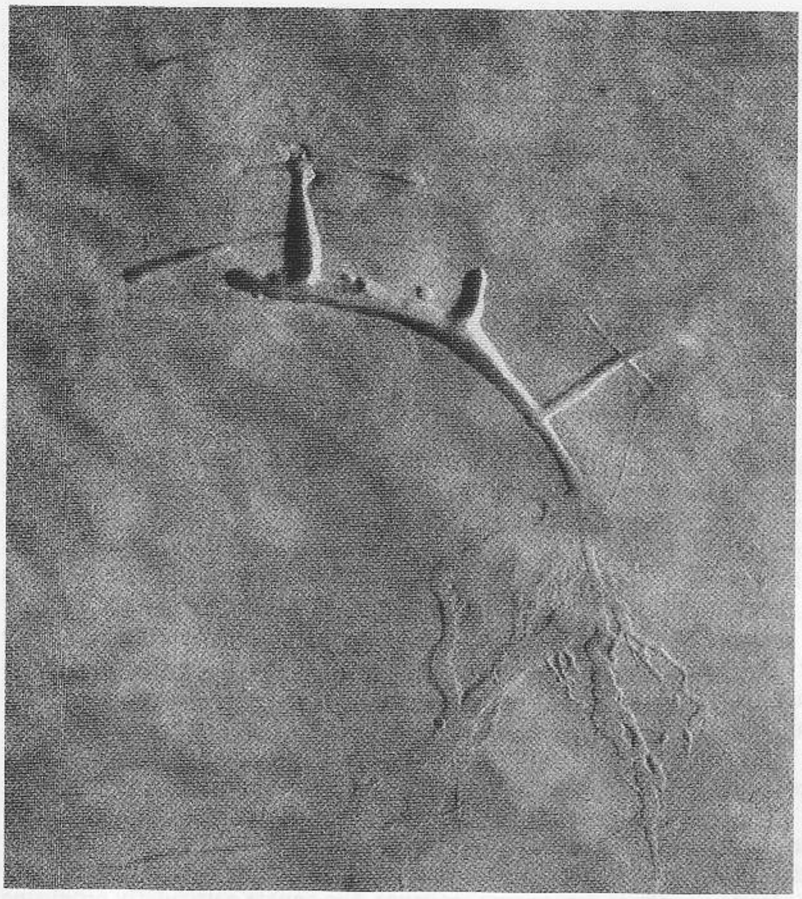

Plate 3.

Geologically recent flooding on Mars [35]. Water appears to have been released from this arcuate graben located 15 km to the east of the Olympus Mons escarpment, pointing to an interaction between groundwater and a submerged heat source. viking frame: 468S53; at 16°N, 129°W; image width: 23 km; resolution: 24 m/pixel.

Photo courtesy of NSSDC

areas remaining on Mars it might be here–at the foot of the greatest volcano in the Solar System.

3.5 Valles Marineris

On the Earth, volcanism is commonly associated with tectonic rifting, but in the large Valles Marineris rift system on Mars obvious volcanic features such as shields and lava flows are absent. Nevertheless, a detailed survey of the interior deposits of the central Valles Marineris area by Luchitta has revealed a variety of more subtle features of possible volcanic origin–some of which may have been formed recently [37,38]. The most compelling evidence comes in the form of dark patches which can been seen from high resolution Viking images to line up with tectonic structures.Those in Ophir and Candor Chasmata are found mainly at the base of scarps found on interior layered deposits, whereas those in the north of Coprates Chasma occur adjacent to and along the faults at the base of trough walls.

These dark markings in Coprates Chasma point most persuasively to a recent volcanic origin, extending discontinuously along its northern boundary fault line for 200 km. The fact that they juxtapose so well with such large-scale structures argues against their being the result of aeolian deposition. Moreover, they appear not to be derived from exposed volcanic sills or dykes eroded by the wind as they lie on top of landslide deposits which would have buried such outcrops on the canyon floor (see Plate 4). The presence of pyroclastic deposits seems to explain all the features of the patches the best: their wispy appearance implies explosive jetting of material; their colours are similar to slightly weathered basalt powder; and their low albedoes are similar to those of pyroclastic mantles identified on the Moon. The extrusion of lava may also be indicated in some areas beneath those patches visible in the Chasma wall which have shed dark streaks downhill and into adjacent gullies.

That these Coprates patches are extremely young seems indicated by a number of criteria:

(1) their morphological crispness and feathery outlines;

(2) their superposition on Upper Amazonian landslide deposits (Unit *As*); and

(3) their dark colour. The latter is significant because dark igneous deposits on Mars would generally be expected to lighten with age due to oxidative weathering and mantling with dust. By estimating the rates of these processes between wide bounds, Luchitta calculated that these deposits could have been formed as recently as 30 years to 1.5 million years.

If volcanism associated with the Valles Marineris is as young as this then it is unlikely to be totally extinct and large fluxes of magmatic heat may still be leaking out from beneath the canyon floors. The presence of adequate groundwater for geothermal power purposes cannot be assessed from the current data, however the explosive nature of the local eruptions implies that the magma at least was, or perhaps still is, not lacking in volatiles.

3.6 Possible Cryptovolcanic Locations

It has been noted above that 4.5 million km^2 of Mars is geologically characterised as Upper Amazonian in age and of volcanic or fluvial origin. These surfaces represent the overt evidence of recent anomalous heat flow. Additional significance can be ascribed by their geographic location–all of them

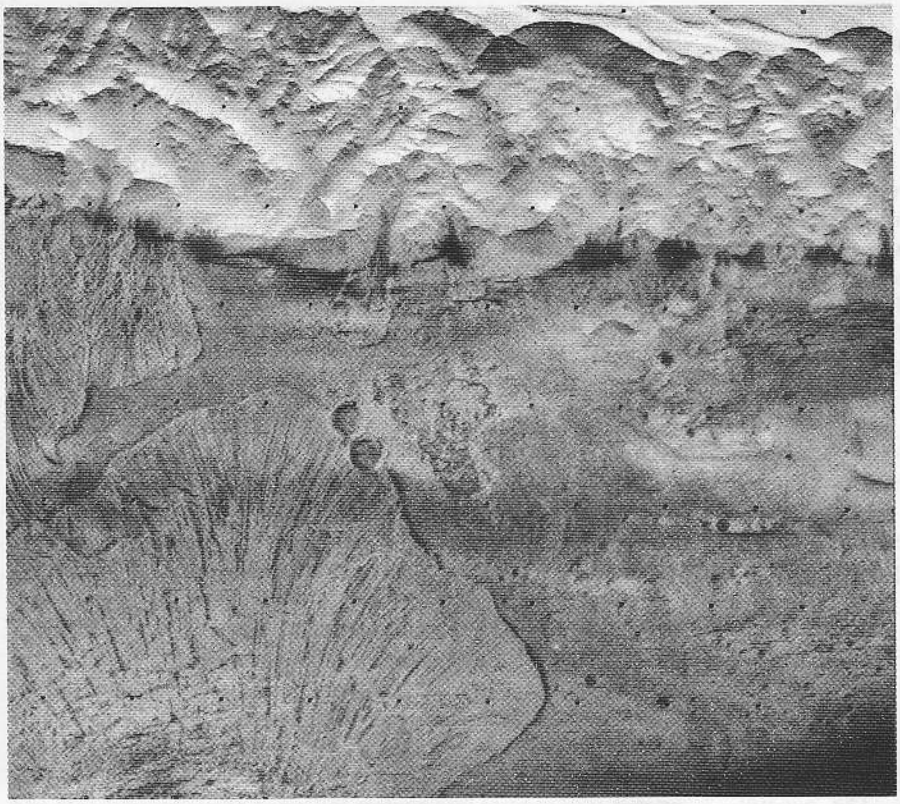

Plate 4.

The Coprates Chasma floor at 12°S, 67°W, showing the 7 km high north wall of the chasma at the top of the image and a landslide deposit extending from the south. A band of wispy dark patches are seen running along the fault trace at the base of the wall and may represent explosive volcanic vents of recent origin [38]. Viking frame: 80A01; image width: 80 km.

Photo courtesy of NSSDC

cluster into one distinct province between roughly 20-220°W and 50°N-15°S, an expanse of about 40 million km^2, equivalent to 28% of the total planetary area. Amazonian volcanism, that younger than about two billion years, seems to have concentrated here, perhaps as the surface manifestation of long-term heat loss from a mantle "superplume" beneath. The fact that this proposed "anomalous heat flow province" (AHFP) seems to have been active for so long, and into geologically recent times, makes it perhaps unlikely that all magmatism has ceased. Moreover, the overt signs of volcanism that are visible *almost certainly understate the activity that has actually occurred* as considerably more magma than the amount released to the surface could have been intruded at shallow depths. Such "cryptovolcanism"–shallow volcanic intrusion without eruption–is common on the Earth and it is noteworthy that whilst all commercial geothermal fields are associated with regions of present day, or Miocene to Quaternary volcanic activity (< 20 Myr old), not all are sited close to volcanoes [15]. In fact, some of the most productive geothermal fields, such as Larderello in Italy and the Geysers in California, draw their power from hidden magmatic sources.

Whilst cryptovolcanism could occur anywhere on Mars, it is most reasonable to invoke its possibility within the proposed anomalous heat flow province. However, except where resolvable outburst flood features have been created by magmatic intrusion (such as reviewed in Section 3.4) Viking images can provide no direct evidence of this process. However, certain geological environments on the Earth can be indicative of cryptovolcanism [15] and have analogues within the AHFP on Mars.

(1) *Rift Valleys and Large Grabens.* These tectonic structures are caused by tension and thinning within the crust resulting in the downfaulting of large longitudinal blocks. Often, the relative pressure release that results at depth results in a rise of magma in compensation. The possible association of martian grabens with recent volcanic activity has already been mentioned in the contexts of the Valles Marineris and Cerberus Rupes. However, the AHFP contains many more such tectonic structures, on a variety of scales, which could have been accompanied with cryptovolcanism. Another complex graben system that might merit investigation for heat flow anomalies are the Ceraunius Fossae, which appear to have fractured Noachian rocks in Lower Amazonian time, but which also appear to have had something to do with much later fluvial activity [35].

(2) *Turbidite Areas.* Cryptovolcanism is particularly favoured under areas buried beneath thick plastic sediments, such as silts deposited underwater. This is because clays may flow into fault spaces in the hard bedrock beneath, sealing them against the rise of upwelling magma. Rising intrusions with insufficient energy therefore may come to rest at the soft rock/hard rock boundary. This might particularly apply on Mars where the lower gravity results in lesser buoyancy forces.

Both Larderello and the Geysers are examples of turbidite-area geothermal fields and may have their martian analogues. Substantial areas of the northern plains are included in the AHFP, as well as Chryse Planitia with its prominent Hesperian outflow channels. Large thicknesses of water-lain sediments may have been deposited in these localities–especially if the hypothesis of the past existence of a martian Boreal Ocean is correct [39]. That Upper Amazonian volcanism has occurred on the northern lowlands is indicated by the uncratered lava flows and small volcanic cones imaged in Arcadia and Acidalia Planitia (Units Aa_4 and Aa_5). The occurrence of cryptovolcanism, sealed beneath the sediments of large adjacent areas and undetected by the Vikings, is a distinct possibility.

3.7 Hyperthermal Localities on Mars: An Opposing Conclusion

The fact that volcanic and fluvial activity on Mars has, for the past two billion years, been largely confined to one quadrant of the planet, and the fact that it has continued into the recent geologic past, strongly suggests that the occurrence of present day hyperthermal areas cannot be ruled out by arguments based on mean *global* heat flow calculations. The escape of heat from the interior of Mars has evidently been very patchy over most of the planet's history and it seems more likely than not that this state of affairs should still pertain at present. Thus, whilst the deep frozen Mars paradigm may be valid at global resolution, it may break down with the gaining of detail at regional, or lesser, scales.

In the opinion of this author, our present geologic data are–on balance–supportive of the possibility of locating hyperthermal areas on Mars, rather than the opposite notion of a uniformly cold crust. It is therefore certainly worth investigating Mars further, with the specific intention of prospecting useful geothermal resources.

4. A MODEL OF A GEOTHERMAL FIELD ON MARS

So as to characterise the nature of the geothermal resources we might expect to find on Mars, a simple model of a martian geothermal field is presented in this Section. The general features of such a field, and the method of its exploitation–a concept known as the "geothermal loop"–are sketched in fig 1. Essentially, heat conducted from a high-energy source beneath raises the temperature of groundwater within a confined aquifer. These hot fluids can be tapped by drilling bore holes down to their location and, depending on such factors as the reservoir temperature, pressure and permeability, the flow obtained at the well head is either in the form of hot water, superheated steam, or a two-phase mixture. At the surface, the enthalpy of these fluids can either be used for direct heating or the generation of electricity (discussed in Section 5). The cooled residual water is then injected back into the aquifer to be re-heated and re-circulated.

This description is somewhat stylised and there are many variants of it on the Earth. It could also serve however as a prototype of a geothermal field on Mars as its main characteristics could be duplicated there. Judging by such geomorphological features as the valley networks and outflow

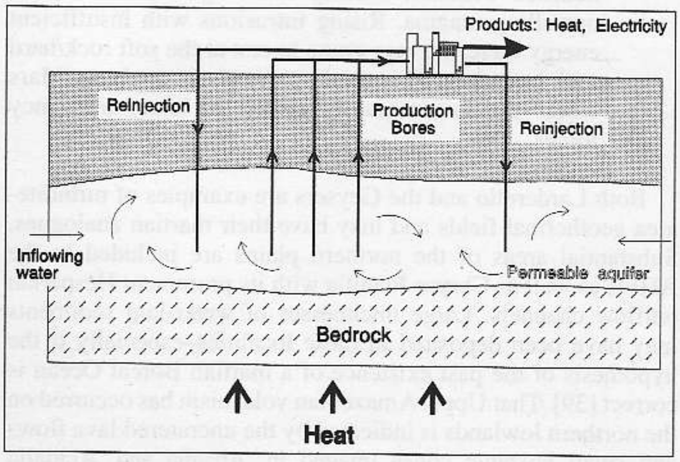

Fig. 1 The Geothermal Loop. Exploitation of geothermal energy by the extraction of heated groundwater and its reinjection into the aquifer (after Ref. [41]).

channels, the martian regolith is thought to be both porous and permeable (highly so in some areas [40]) and to possess a groundwater system, possibly of global extent [24]. Aquifers on Mars are automatically sealed by the cryosphere (the upper layers of crust below freezing) and so a "cap rock" of sorts would be ubiquitous that might actually confine groundwater at low elevations under artesian pressure. The greatest doubt lies in the presence of geothermal heat anomalies–but it has been noted above that these too may still persist in some places.

Of course, there will be systematic differences between the version of fig. 1 that applies to the Earth and the one applying to Mars. The lower temperature of the surface on Mars (>60 K colder) means that, for a given surface heat flow, suitable reservoirs are going to be at greater depths: bore holes must therefore be systematically deeper and more expensive and a greater quantity of useful heat will be lost during fluid extraction by conduction into surrounding cold rock. However, a mitigating factor here is that low temperature fluids on Mars are thermodynamically more useful–a supply of water at the equivalent of waste-water temperatures on the Earth (< 30-40°C) would still be precious on Mars. The lesser martian gravity has a number of consequences. Pressure is less at a given depth and so for a given fluid temperature, there is a greater likelihood of a situation where vapour pressure is found to exceed the hydrostatic pressure: all other things being equal, steam-dominated reservoirs (prized for electricity generation) may thus be relatively more common. Pumping from water-dominated reservoirs will require less energy, but since pressure gradients and buoyancy forces will be less, fluid circulation and hence natural recharge by inflow from adjacent areas will be more sluggish. Re-injection of waters will thus be even more important on Mars, not just to maintain its circulation, but to conserve its supply as recharge of the aquifer as a whole through precipitation over areas where it outcrops on the surface will not occur.

Some simple mathematical modelling can provide approximate estimates of the potential heat resources available beneath the martian surface and the depths where useful fluids might be located. The magnitude of the vertical heat flow q W m^{-2} is related to the crustal temperature gradient dt/dz K m^{-1} by Fourier's law of heat conduction:

$$a = k\frac{dt}{dz} \tag{1}$$

where k is the thermal conductivity of the rocks in W m^{-1} K^{-1}.

From this it follows that, assuming a constant temperature gradient, the depth z beneath the surface to a given temperature $t(z)$ is:

$$z = k\frac{t(z) - t_s}{q} \tag{2}$$

where t_s is the surface temperature.

In order to proceed from here, it must be noted that–as on Earth–the character of rocks will vary from place to place, influencing properties such as their specific heat and column mass. However, since order of magnitude accuracy suffices for this study, it is sufficient to assume homogeneity and, over the depths being considered, a constant temperature gradient. The constants chosen to define this mean crustal rock are a density of 2700 kg m^{-3} and a specific heat capacity of 839 J kg^{-1} K^{-1}. From these one can calculate [41] that the cooling of 1 km^{3} of rock by 1 K releases heat energy of 2265 TJ. We thus define a quantity known as the *specific crustal heat* to be: Q_s = 2265 TJ km^{-3} K^{-1} or 71.83 MWyt km^{-3} K^{-1}.

The energy released by a given volume of rock, cooled by a given increment, will be the same anywhere on Mars. *However it is advantageous to work hyperthermal areas because they contain a much greater total heat which will be accessible at shallower depths.* This total crustal heat can be gauged by plotting a graph of temperature versus depth [41]. The area under the curve (expressed in km K) multiplied by Q_s gives the total crustal heat above surface temperature available beneath each km^2 of land surface. However not all this heat will be attainable or useful for geothermal power production. Rocks of a certain minimum temperature t_{min} must be reached and there will be a depth limit z_{max} beyond which heat mining is impractical. This limits the heat available for practical purposes to the

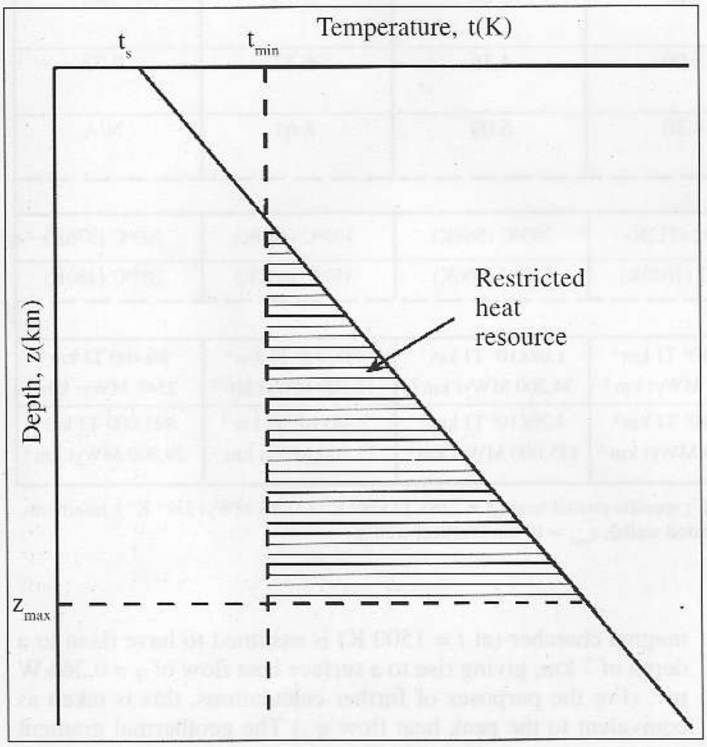

Fig. 2 Definition of the Restricted Heat Resource: that heat contained in rocks above a certain useful tempertaure (t_{min}) down to a certain attainable depth (z_{max}).

area defined by the shaded zone in fig. 2.

This heat–that per km^2 of surface, at attainable depths, above a minimum useful temperature, is called the *restricted heat resource* (Q_r TJ km^{-2}) and is here calculated as:

$$Q_r = Q_s \frac{(z_{max} - z(t_{min}))\,(t(z_{max}) - t_{min})}{2} \qquad (3)$$

where $z(t_{min})$ is the depth at which the minimum useful temperature is encountered and $t(z_{max})$ is the temperature at the maximum attainable depth. These are obtained from the following equations:

$$z(t_{min}) = k\frac{t_{min} - t_s}{1000q} \qquad (4)$$

$$t(z_{max}) = \frac{z_{max}q}{k} + t_s \qquad (5)$$

where the factor of 1/1000 in Eq. 4 converts $z(t_{min})$ from m to km.

The restricted heat resource Q_r thus gives the maximum amount of useful heat available beneath the surface. However, this upper limit would never be approached in practice. A feasible heat mining project on Mars would aim to extract a quantity of heat perhaps equivalent to Q_s multiplied by a few degrees–not by a uniform cooling of the crustal column, but by cooling the aquifer rocks by a greater magnitude.

In order to complete the model, values of its "constants" must be assigned. In line with our previous assumption of crustal homogeneity, we chose a uniform value of thermal conductivity equal to k = 2 W m^{-1} K^{-1} [22] and perform calculations appropriate to tropical locations (~ 50% the planetary area) where mean surface temperature is $t_s \approx$ 220 K. Assuming a water supply at a temperature as low as 30°C is economically useful on Mars and, assuming further that there is a 30°C drop in temperature between reservoir and well-head, then the minimum useful rock temperature that must be reached is t_{min} = 60°C. Geothermal fluids from commercial fields on the Earth are usually obtained from depths of 0.5 - 2 km; on colder Mars though, such reservoirs will inevitably be deeper down. Since the current state of the art in borehole drilling allows penetration to 10 km for vertical wells and 6 km for deviated wells [41], z_{max} is set to each of these depths and calculations of Q_r are done for both. A depth limit in another sense is approximately represented by z_{max} = 10 km, in so far as porosity this far down is expected to tend to zero due to self-compaction of the megaregolith by the weight of rock above [22,24].

Application of this model to what might be regarded as "average Mars crust" is instructive. Here, the heat flow is set to the global mean of q = 0.03 W m^{-2} derived by others [16]. The temperature gradient is therefore dt/dz = 15 K km^{-1} and the depth of the 0°C isotherm is ~ 3.5 km and that of the t_{min} isotherm ~ 7.5 km. Temperatures only rise to 100°C at 10 km depth. The restricted heat resource above 6 km is zero, but that above 10 km is ~ 10^5 TJ km^{-2}, equivalent to ~ 3000 MWyt km^{-2}. Perhaps surprisingly therefore, *warm water between 60° - 100°C might be available almost anywhere beneath the martian tropics, even if the pessimistic deep frozen Mars paradigm is true.* However, depths that have to be drilled to in order to obtain these fluids are great and into strata where porosity is tending to a minimum. A low enthalpy geothermal reservoir with these characteristics on the Earth would be totally uneconomic. Whether it would be so on Mars, where any supply of liquid water would be highly prized, is debateable–however it would certainly be less than ideal.

Hyperthermal areas on Mars heated by extant magmatism are thus extremely desirable but since such hotspots will be geologically transient, it is helpful to add a time dimension to the model. The decline of heat flow following the waning of magmatic activity from its peak is assumed to obey the following empirical formula:

$$q(T) = \frac{q_0}{\sqrt{T}} \qquad (6)$$

where T is time in million-year units and q_0 is the peak heat flow. For oceanic crust on the Earth, the above relation is observed to hold for T = 3 - 120 Myr with q_0 = 0.473 W m^{-2} [42]. How applicable such a relation would be for Mars is unknown as the cooling of magma bodies is a complex issue and the geologic setting would be different: values of $q(T)$ derived here therefore should be treated with caution.

The results of modelling the characteristics and evolution of

TABLE 3: *Results of the Martian Geothermal Field Model*

Area Type	Average crust	Active hotspot	Waning hotspot	Waning hotspot	Waning hotspot	Waning hotspot
Age: T / Myr	> 150	0 - 1	5	10	20	50
Heat Flow: q / (Wm^{-2})	0.03	0.366	0.164	0.116	0.082	0.052
Thermal Gradient: (dt/dz) / (K km^{-1})	15	183	82	58	41	26
Depth of 0°C isotherm: $z(273\ K)$ / km	3.53	0.29	0.65	0.91	1.29	2.04
Depth of 60°C isotherm: $z(t_{min})$ / km	7.53	0.62	1.38	1.95	2.76	4.35
Depth of 100°C isotherm: $z(373\ K)$ / km	~10	0.84	1.87	2.64	3.73	5.88
Depth of 200°C isotherm: $z(473\ K)$ / km	N/A	1.38	3.09	4.36	6.17	9.73
Depth of 300°C isotherm: $z(573\ K)$ /km	N/A	1.92	4.30	6.09	8.61	N/A
Temperature at:						
$t(z_{max} = 6\ km)$	37°C (310K)	1045°C (1318K)	439°C (712K)	295°C (568K)	193°C (466K)	103°C (376K)
$t(z_{max} = 10\ km)$	97°C (370K)	>1227°C (>1500K)	767°C (1040K)	527°C (800K)	357°C (630K)	207°C (480K)
Restricted heat resource::						
$Q_r(z_{max} = 6\ km)$	0	6.0x10^6 TJ km^{-2} 190,000 MWyt km^{-2}	1.98x10^6 TJ km^{-2} 62,900 MWyt km^{-2}	1.08x10^6 TJ km^{-2} 34,200 MWyt km^{-2}	488,000 TJ km^{-2} 15,500 MWyt km^{-2}	80,400 TJ km^{-2} 2548 MWyt km^{-2}
$Q_r(z_{max} = 10\ km)$	1.03x10^5 TJ km^{-2} 3280 MWyt km^{-2}	1.82x10^7 TJ km^{-2} 578,000 MWyt km^{-2}	6.90x10^6 TJ km^{-2} 219,000 MWyt km^{-2}	4.26x10^8 TJ km^{-2} 135,000 MWyt km^{-2}	2.44x10^6 TJ km^{-2} 77,200 MWyt km^{-2}	941,000 TJ km^{-2} 29,800 MWyt km^{-2}

Assumptions: Surface temperature t_s = 220 K; thermal conductivity k = 2 W m^{-1} K^{-1}; specific crustal heat Q_s = 2265 TJ km^{-3} K^{-1} (71.83 MWyt km^{-3} K^{-1}); minimum useful rock temperature t_{min} = 60°C; maximum penetration depth z_{max} = 6 km (deviated wells), z_{max} = 10 km (vertical wells).
N/A = not aplicable, value outside of parameter space.

an idealised geothermal field, loosely based on Plescia's description of the formation of the Cerberus plains [31-32], are displayed in Table 3 and fig. 3. Before magmatic activity begins, the area is assumed to be typical of "average Mars crust"–a megaregolith consisting of impact brecciated rock and interbedded sediments and lava flows with a mean porosity ranging from 20-50% at the surface and tending to zero at 10 km depth. Thermal characteristics are as described previously (Table 3, column 1; fig. 3a) with temperatures rising to 0°C at 3.5 km depth and to 100°C at the megaregolith base. The top kilometre of crust is assumed to be desiccated by a process of ground ice sublimation and polar redeposition [36], but ground ice could still be present between z = 1 - 3.5 km and groundwater in aquifers beneath.

Crustal tension in the Cerberus plains region leads to rifting, the sinking of faulted blocks and the rise of magma from below. Local heat flow rises by over an order of magnitude and isotherms rise steeply, melting ground ice and elevating the water table. Where convecting hydrothermal systems intersect the surface, thermal springs emerge–in some places with sufficient energy to cause outburst flooding, further ground subsidence, and resurfacing with alluvial sediments. Eventually–and assisted by the pre-existing faulting–basalt erupts through fissures, in a series of pulses and in a number of locations, burying the previous landscape under several hundred metres of lava.

The situation beneath such an eruptive centre, immediately following the climax of its activity (T = 1 Myr) is illustrated in fig. 3b and quantified in Table 3, column 2. The roof of a basalt magma chamber (at t = 1500 K) is assumed to have risen to a depth of 7 km, giving rise to a surface heat flow of q = 0.366 W m^{-2}. (For the purposes of further calculations, this is taken as equivalent to the peak heat flow q_0.) The geothermal gradient has risen to a very high 183 K km^{-1} such that, even though the surface temperature remains at 220 K (except adjacent to discharging vents), the permafrost cap has been reduced in thickness to just ~ 300 m. Below this, down to ~ 800 m, rocks of between 0° - 100°C are encountered and further down to ~ 1.9 km temperatures range between 100° - 300°C. So long as groundwater and permeable strata are present, the prospects of the recovery of conventional geothermal power from such an environment would be excellent. Fluids of a variety of temperatures and phases are likely to be found at comparatively shallow depths, allowing geothermal power to be applied to its full spectrum of potential uses. The restricted heat resource beneath such an area would be enormous: ~ 190,000 MWyt km^{-2} down to 6 km and ~ 578,000 MWyt km^{-2} down to the base of the megaregolith. This latter value is > 170 times greater than the Q_r calculated for average Mars crust.

The quality of a geothermal field will decline over the next few million years following the cessation of magmatic activity. The model calculations for 5 - 10 Myr show that by this time the contents of the magma chamber have solidified. However, heat flows remain quite high at > 0.1 W m^{-2} and thermal gradients (whilst 100 degrees less than previously) are still > 50 K km^{-1}. The depth of the cryosphere remains less than a kilometre and so the additional drilling required to reach useful temperatures, when compared to equivalent operations on the Earth, is not all

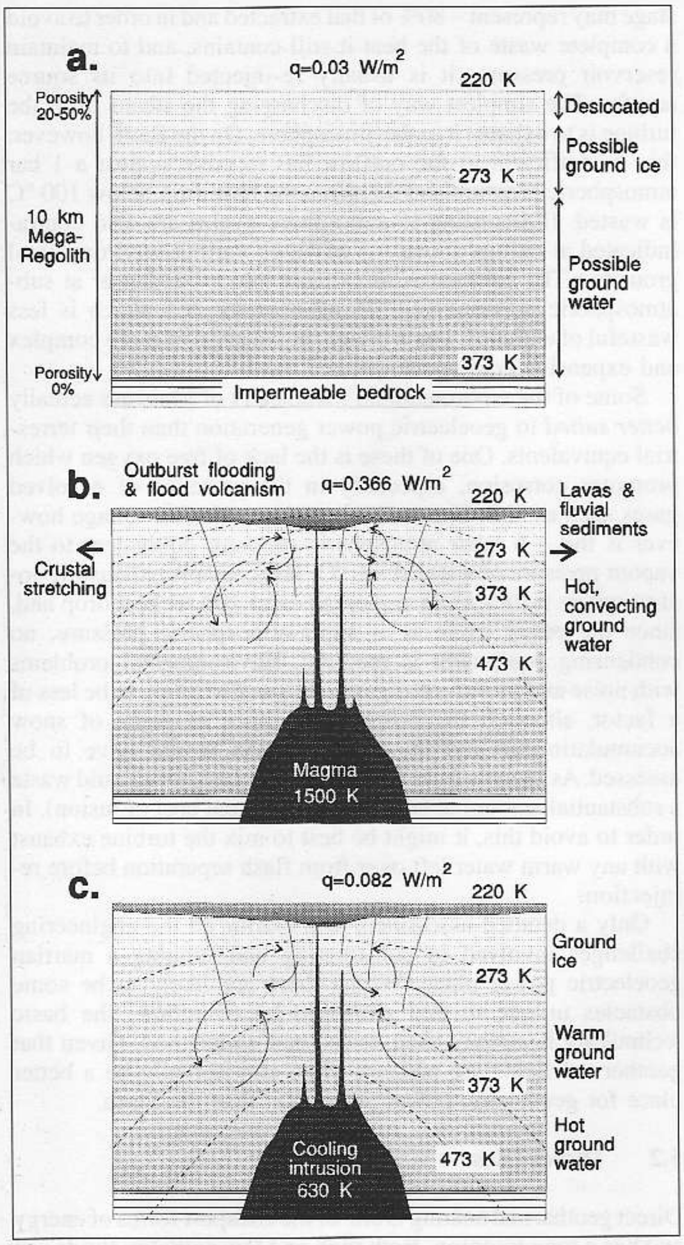

Fig. 3 Schematic of the Martian geothermal field model.
a. Average Martian crust.
b. Immediately following the peak activity of flood volcanism.
c. The field after ~ 20 Myr of decline (See also Table 3).

that great. Warm water would be encountered below ~ 1.4 - 2 km and hotter fluids deeper than ~ 2- 3 km. Restricted heat resources, whilst several times less than initially, are still large: between 135,000 - 219,000 MWyt km^{-2} down to 10 km, 41 - 66 times greater than average crustal Q_r. Such areas therefore still have good potential for producing geothermal power.

After 20 Myr of decline, the model predicts a hyperthermal area with a heat flow of ~ 0.08 W m^{-2}–similar to the crustal average for the Earth. Even though Q_r $(z=10\ km)$ is ~ 24 times the martian crustal average, useful temperatures are now found quite deep down and isotherms are spreading out with the reduction in temperature gradient (see fig. 3c). Warm waters would be obtained from between ~ 2.7 - 3.7 km and higher enthalpy fluids (if recoverable at all) from considerably greater depths. By 50 Myr, heat flow has fallen to less than the terrestrial average and, whilst still elevated in martian terms, Q_r is only ~ 9 times greater and useful temperatures have to be sought deeper than ~ 4.4 km. Whilst heat mining is theoretically possible from such sites (or even from "average Mars crust", as noted above) it may be that conventional geothermal power production would be impractical or uneconomic, especially if the characteristics of aquifers at the depths required do not permit an adequate rate of fluid recovery. However, artificial methods of reservoir stimulation, such as proposed for exploiting "hot dry rock" on Earth, might significantly enhance the utility of mildly hyperthermal areas on Mars (see Section 6).

We might therefore conclude from this simple model of a martian geothermal field that volcanic or cryptovolcanic hotspots less than ten million years old offer a good potential for the production of geothermal power. If Tanaka *et al.* [20] are correct and the rate of extrusive magmatism is one event every ~ 10,000 years then one might expect on the order of ~ $10^7/10^4 = 1000$ such hotspots on Mars. Allowing for repeated eruptions might reduce this number by a factor of perhaps 10-100, including cryptovolcanic sources though would increase it. What fraction of these hotspots would also occur in combination with an adequate ground water supply is uncertain, but where conditions are suitable, boreholes of several kilometres depth would access energy resources of thousands of megawatt-years (thermal), below each square kilometre of surface, in the form of hot fluids. Such fluids could be used by a growing martian civilisation in a wide variety of ways.

5. USES OF GEOTHERMAL ENERGY ON MARS

Depending on their geological setting, geothermal fluids are obtainable at a range of temperatures and flow rates. Reservoirs are categorised as being of *low enthalpy* if between 30 - 120 °C and *high enthalpy* if above [43-44]. The former supply warm waters from which the sensible heat can be recovered and the latter provide hot pressurised water, two-phase mixtures, or steam which yield latent heat in addition. Undesirable fluid characteristics can include a rich content of dissolved solids or non-condensible gases that might cause scaling or corrosion of equipment. A variety of production technologies and utilisation strategies are therefore required for the optimum recovery of heat. The engineering details of these are lengthy and it suffices here to argue in general terms for the wide potential utility of geothermal power on Mars.

Such power is obtained from geothermal fluids either by the *direct* use of their heat content, or the *indirect* transformation of that heat into electricity [44]. On the Earth, geoelectric generation is perhaps of disproportionate importance because direct heat applications are constrained to the vicinity of the resource site itself, whereas electricity is readily transportable over large distances. On the other hand, direct use benefits from a much greater conversion efficiency (the ratio between useful energy output and the thermal energy released from the cooled geofluid) which may be up to 90% for applications such as heating, but less than 20% for geoelectric power. Moreover, on colder Mars, low enthalpy fluids that can only be exploited directly are intrinsically more useful and the site-specific nature of direct heat applications may be less of a constraint since there are no pre-existing centres of civilisation. Settlements on Mars are likely to be founded adjacent to that planet's richest natural resources–geothermal resources included.

5.1 Indirect Uses: Geoelectricity

A robust and reliable source of electricity will be required by all martian settlements. Such power can be generated from high enthalpy geothermal fluids either by driving a turbine directly with geothermal steam, or with an organic working fluid vaporised via heat exchangers by hot pressurised geothermal waters (see fig. 4) [44-46]. The former method is the most commonly practised, but is most suitable for use with geothermal fluids above ~ 150 °C; the latter "binary cycle" is more efficient at generating power at lower temperatures. Typically, one production well must be drilled per ~ 10 MWe output for power stations rated between ~ 1 - 100 MWe. Assuming a demand of 20 kWe/person on Mars (discussed in Section 2), one such plant would provide for the needs of 50 - 5000 people.

Geothermal wells that produce dry steam are the most convenient for generating electricity as the vapour can be piped through a demister straight to the turbine inlet. The more commonly occurring hot pressurised water or two phase flows however require steam to be separated before utilisation. The fluid is piped to a separator vessel where it is flashed by a pressure release that optimises the flow rate and enthalpy content of the output steam. If the thermodynamics are favourable, the residual hot water is then put through further flash cycles, each one producing a lower pressure steam that is also conveyed to the turbine. The water resulting from the last flash

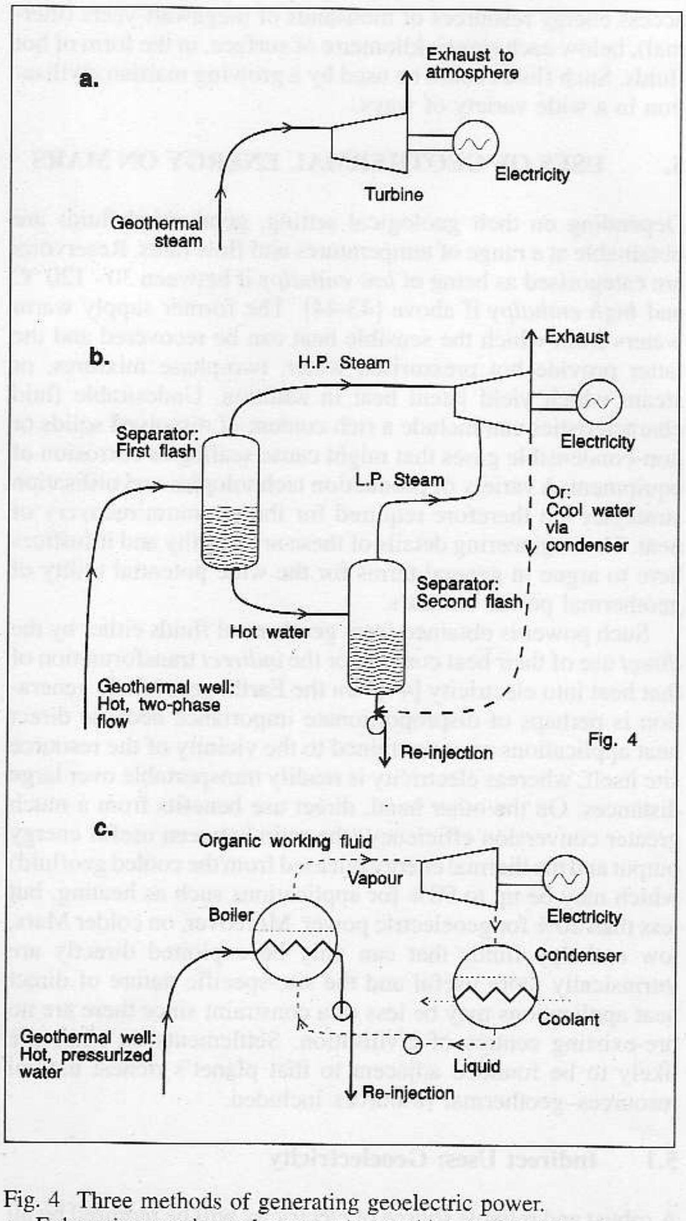

Fig. 4 Three methods of generating geoelectric power.
a. Exhausting geothermal steam *via* a turbine to the atmosphere.
b. Separating steam from a two phase flow with multiple flash cycles.
c. The Binary Cycle - using geothermal water to heat a secondary working fluid.

stage may represent ~ 80% of that extracted and in order to avoid a complete waste of the heat it still contains, and to maintain reservoir pressure, it is usually re-injected into its source aquifer. The simplest way of discharging the steam from the turbine is to exhaust it to the atmosphere. On the Earth however, this is inefficient as the outflow has to push against a 1 bar atmospheric pressure and therefore the heat drop below 100 °C is wasted. (Exhausting-to-atmosphere cycles are also contra-indicated at ratings above ~ 5 MWe on various environmental grounds.) The solution is to exhaust into a condenser at sub-atmospheric pressure (e.g. 75 mbar at 45 °C) which is less wasteful of enthalpy, but is bought at the price of more complex and expensive equipment.

Some of the environmental parameters of Mars are actually *better suited* to geoelectric power generation than their terrestrial equivalents. One of these is the lack of free oxygen which promotes corrosion, especially in the presence of exsolved gases such as H_2S. The most obvious martian advantage however is the ~ 6 mbar atmospheric pressure–equivalent to the vapour pressure of water at ~ 0 °C. Thus, simple exhausting-to-atmosphere turbines can exploit an extra 100 °C heat drop and, since the entire cycle is at supra-atmospheric pressure, no condensing equipment is required. Environmental problems with noise and malodorous gases etc are also likely to be less of a factor, although the potential nuisance of drifts of snow accumulating around the power station would have to be assessed. As it cools from 0 °C to -60 °C, this snow would waste a substantial amount of heat (including latent heat of fusion). In order to avoid this, it might be best to mix the turbine exhaust with any warm water left over from flash separation before re-injection.

Only a detailed assessment will clarify all the engineering challenges involved in constructing and running a martian geoelectric power plant. Whilst there are likely to be some obstacles unique to that planet to be overcome, the basic technology is already tried, tested and understood. Given that geothermal fields are present, Mars may actually be a better place for geoelectric power generation than the Earth.

5.2 Direct Uses

Direct geothermal heating is one of the cheapest forms of energy and has a long tradition. Both high and low enthalpy fluids can potentially serve a wide range of applications [47-49] and some of these are listed against the necessary fluid temperature in the *Líndal diagram* shown in fig. 5 [48]. It should be noted than an analogous diagram for Mars will have much in common but will not be identical. Some of the entries in fig. 5 will not be relevant to Mars; similarly, there will be uses found for direct geothermal heating on Mars that are not needed on the Earth.

High enthalpy fluids are applicable to industrial processes that benefit from a supply of saturated steam, such as in the manufacture of a wide variety of chemicals (including ethanol, hydrogen peroxide and vitamin C), paper, textiles and plastics. Other potential uses include food processing, water distillation, salt production, mineral extraction, air conditioning, and cement setting [48]. Although applicable however, geothermal steam has rarely been adopted for these processes in practise, simply because of the inconvenience of co-locating industries at geothermal sites and the fact that geothermal technological solutions are less familiar than those involving heating by fuel oil or electricity. On Mars however, civilisation will be making a fresh start in the absence of fossil fuels and pre-existing centres of power demand. Industries will have to be configured to suit the natural resources available. If geothermal steam is discovered to be one of those natural resources, then it undoubtedly

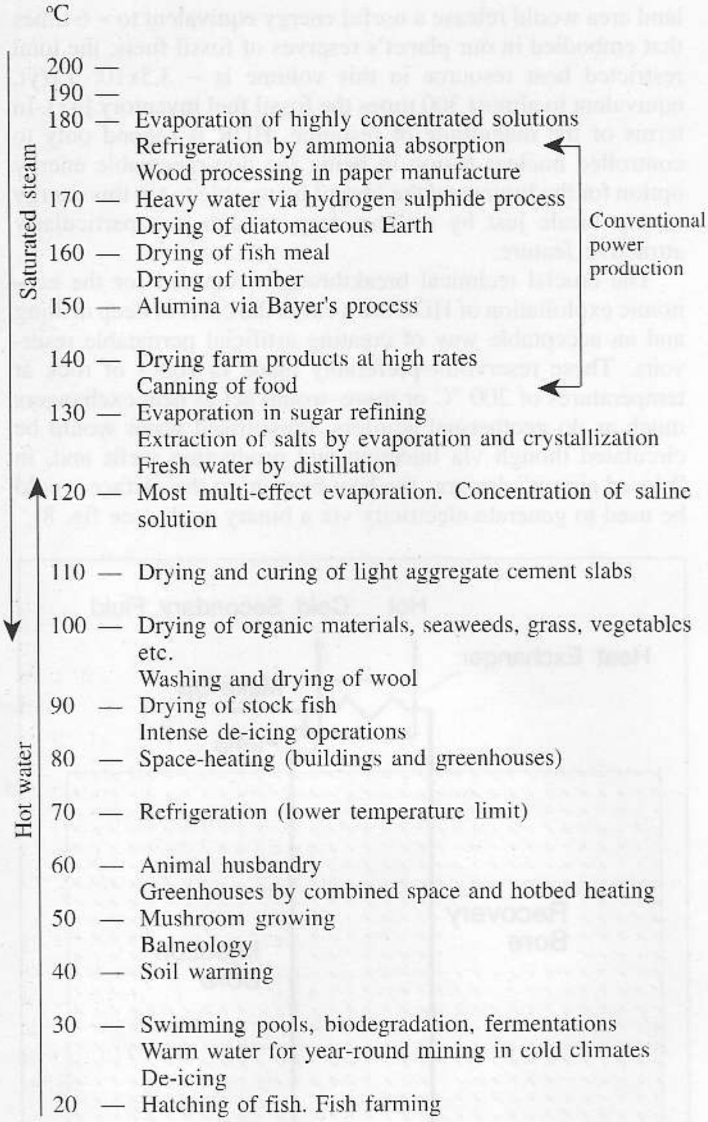

Fig. 5 The Lindál Diagram. A temperature spectrum of potential direct geothermal heating applications (after Ref [48]).

increases the technological options for martian industry and opportunities for growth.

Low enthalpy geothermal systems that yield hot water are relatively more common than steam systems and are expected to be even more so on Mars because of generally lower heat flows and surface temperatures. Such resources are of little practical use for geoelectrical generation and are best suited for direct applications. Fortunately, such applications abound (see fig. 5) and certain peoples such as the Japanese and Maori have taken advantage of hot springs for bathing and cooking since pre-history. Today, well known examples of the direct use of low enthalpy geothermal energy are district heating in Iceland and greenhouse heating in Hungary [47,49]. Most impressively, the city of Reykjavík is almost entirely heated by ~ 435 MWt of geothermal waters pumped from three nearby fields at a rate of ~ 1970 kg s^{-1}. The system provides about 1.5 m^3 of piping hot water for each of 120,000 people per day and is designed to meet the heating load at -10 °C outside temperature. Water at an initial mean temperature of 95°C is distributed and passes through radiators and heated floors and is of such good chemical quality that it can be used directly for washing and bathing. The rejection temperature from the system is 35 °C.

Geothermal heating is used on a smaller scale throughout Iceland as described in this fascinating paragraph from a relevant paper [47]:

"Since about 1930 elementary and secondary boarding schools in the rural areas of Iceland have whenever possible been sited at locations where geothermal energy is available. In these centres the school buildings and living quarters for the pupils and staff are geothermally heated. They are also as a rule equipped with a swimming pool, and are self-supplying with vegetables (tomatoes, cucumbers, cauliflowers etc.) grown in their own hot houses. There are now many such schools in various parts of the country, and quite often they are used as tourist hotels during the summer holidays. Quite often these centres have formed the nuclei of new service communities in the rural areas."

The analogy between this description of isolated communities in Iceland and the vision of settlements on Mars–which must be similarly self-sufficient and the nuclei of growth to come–is most striking. Evidently, the experience of settling Iceland could have significant relevance to that of settling certain areas of Mars. A large proportion of the basic energy needs for a martian society will be for heating. On most of the planet this will have to be done with electrical power, but where geothermal fluids are present a direct heating option is at hand that may be simpler, more efficient and inexpensive (see fig. 6). The fact that low enthalpy reservoirs are likely to be much more common on Mars than their high enthalpy counterparts does not compromise the feasibility of exploiting geothermal energy. The naturally occurring energy distribution may admirably match the demands of the martian heat market.

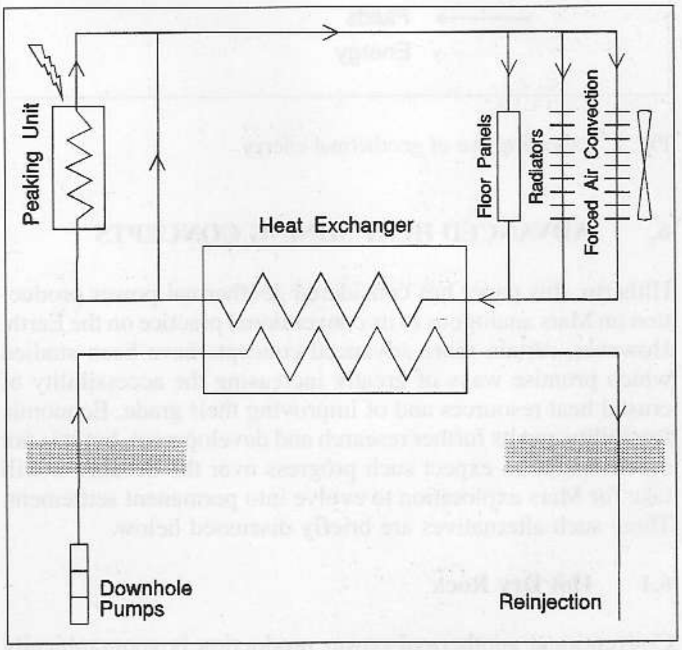

Fig. 6 Direct use of geothermal energy for base-load habitat heating. Peak loads might be handled by electrically powered auxiliary heaters connected in series.

5.3 Cascading Use

In order for martian pioneers to prosper, it may be crucial for them to maximise the efficient use of any given resource. Geothermal energy is attractive in this regard as its wide range of applications allow the temperature drop between production and re-injection wells to be exploited to the full. Uses can be *cascaded*, where the waste water from high temperature processes can be fed the those needing fluids at a lower temperature. Theoretically, a good high enthalpy geothermal field could be used to power a chain of applications from the top to the bottom of the Líndal diagram.

This general strategy of maximising the benefits of the geothermal loop is illustrated in fig. 7. Specific examples of cascading might be where the water separated from flash cycle electricity generation is passed to a binary cycle generator (figs. 4b + 4c) or used for direct heating of habitats and greenhouses (fig. 4b + 6). Many other combinations will be possible that, if creatively integrated into a martian economy, further enhance the attractiveness of geothermal projects on Mars.

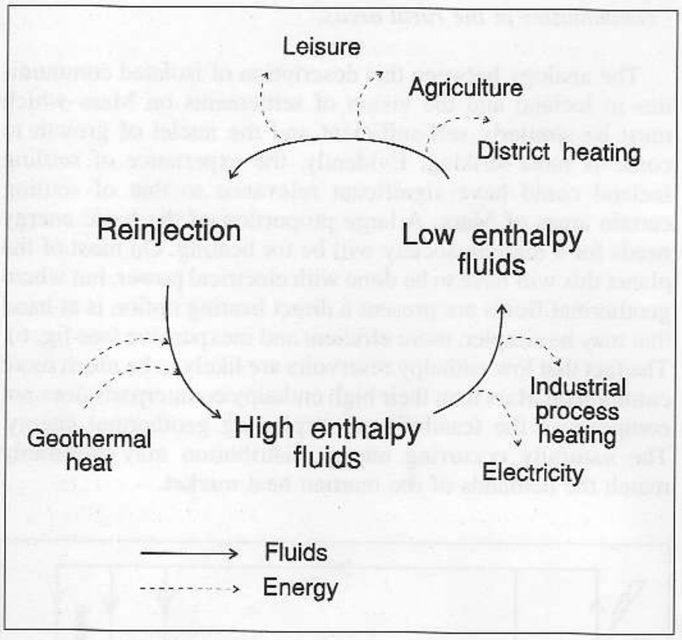

Fig. 7 Cascading use of geothermal energy.

6. ADVANCED HEAT MINING CONCEPTS

Hitherto, this paper has considered geothermal power production on Mars analogous to its conventional practice on the Earth. However, certain more advanced concepts have been studied which promise ways of greatly increasing the accessibility of crustal heat resources and of improving their grade. Economic feasibility awaits further research and development, but it is not unreasonable to expect such progress over the decades it will take for Mars exploration to evolve into permanent settlement. Three such alternatives are briefly discussed below.

6.1 Hot Dry Rock

Conventional geothermal power production is geographically constrained by its reliance on permeable rocks and a natural water supply. Heat energy however is available anywhere beneath a planet's surface if its crust is penetrated to sufficient depths. For every site where groundwater conditions are favourable, there are many more where the rocks beneath may be hot, but which are also relatively impermeable and dry. An economic way of exploiting this "Hot Dry Rock" (HDR) resource vastly enhances the scope and potential of heat mining [41,50]. For example, it has been calculated that an average cooling by 1 °C of the top 10 km of crust beneath two thirds of the Earth's land area would release a useful energy equivalent to ~ 6 times that embodied in our planet's reserves of fossil fuels; the total restricted heat resource in this volume is ~ 3.5×10^6 TWyt, equivalent to almost 300 times the fossil fuel inventory [41]. In terms of the magnitude of resource, HDR is second only to controlled nuclear fusion in being the non-renewable energy option for the future and the idea of being able to tap this energy at any locale just by drilling deep enough is a particularly attractive feature.

The crucial technical breakthroughs required for the economic exploitation of HDR are a cut in the costs of deep drilling and an acceptable way of creating artificial permeable reservoirs. These reservoirs–preferably made in zones of rock at temperatures of 200 °C or more–would act as heat exchangers much as do geothermal aquifers. Pressurised water would be circulated though via injection and production wells and, in "closed circuit" designs, the heat brought to the surface would be used to generate electricity via a binary cycle (see fig. 8).

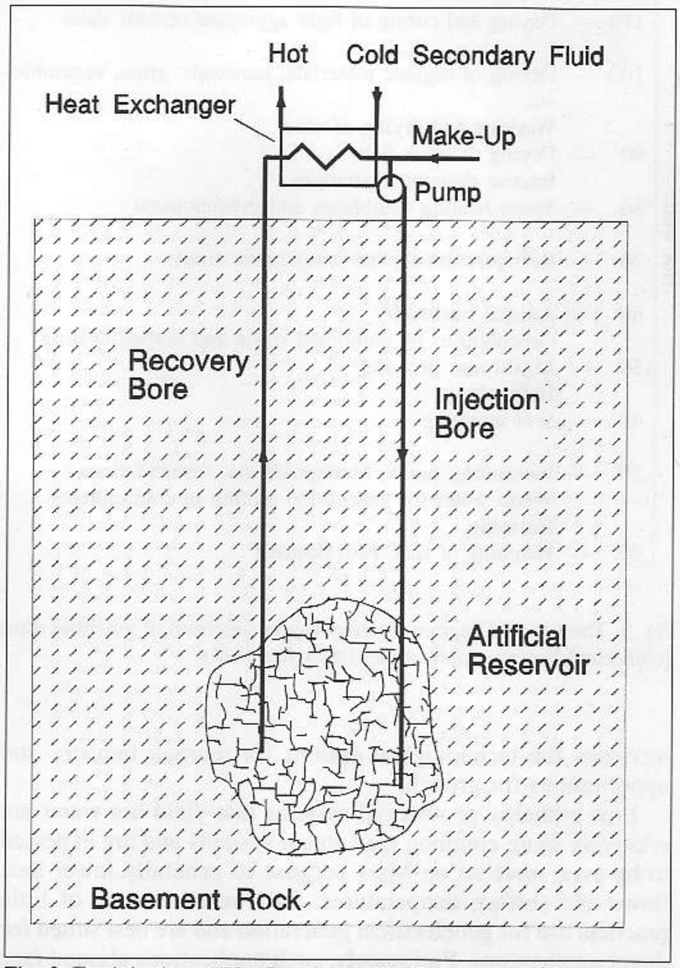

Fig. 8 Exploitation of Hot Dry Rock. Fluid is circulated through, and heat recovered from, an artificial zone of permeable rock.

The central problem is therefore one of creating permeability where none exists–of fracturing rocks at depth in a way that optimises their heat transfer and fluid transmissivity characteristics. Techniques of doing this are currently being experimented with and include [41]:

(1) *Hydraulic pressurisation*: pumping water under pressure to "jack" open natural joints.

(2) *Explosive fracturing*: detonating a chemical explosive of modest intensity to generate radial cracks.

(3) *Rapid gas pressurisation*: igniting a propellant or gas generating system.

(4) *Thermal stressing*: the injection of pulses of hot and/or cold fluids.

The first two methods are presently receiving the greatest attention. Research is also required into the long-term operation of HDR reservoirs–in particular such potential problems posed by the permanent loss of working fluid to surrounding strata and the clogging of conduits by the alteration products of aqueous rock chemistry. Currently such a long-term flow test is underway at Fenton Hill in New Mexico, where the first experimental HDR geoelectricity (~60 kWe) was generated from a 150 °C working fluid in 1980 [41].

A mature technology to exploit HDR on Mars would similarly expand the scope and potential of martian geothermal energy. Even though, at mean global heat flow, the top 10 km of the martian crust is throughout below 100 °C, the restricted heat resource of the tropics is still an enormous ~ 2×10^5 TWyt. Reliable rock fracturing practice greatly improves the prospects of putting this low grade heat to good use (direct uses would be best–see the lower half of fig. 5) as well as in more thoroughly extracting high grade heat from hyperthermal areas, or from below the megaregolith, where naturally occurring geologic and groundwater conditions are unsuitable. An obvious problem in this regard is in the supply of working fluid when none is available beneath the site. Water does exist on Mars and so the economics of martian heat mining would to an extent be based on the proximity of hot rocks and deposits of ice or groundwater.

6.2 Nuclear-Stimulated Geothermal Techniques.

Between 1959-1970, the use of nuclear explosives with respect to geothermal power production was the subject of several studies conducted under the aegis of the now defunct Plowshare programme. No proposals were proceeded with, but they are worth a brief mention here if we accept the possibility that the civil uses of nuclear explosives may be less politically and environmentally sensitive several decades hence and on another planet. Basically these hybrid nuclear-geothermal concepts can be divided into two categories:

(1) those where the energy to be "mined" is derived primarily from a nuclear explosive, and

(2) those where it originates from naturally occurring hot rock.

A nuclear explosive cannot be readily used for other than destructive ends as its energy release is almost instantaneous. This difficulty can be overcome however if this energy is converted to heat and stored, so it can be tapped at a more gradual rate. Rocks store heat well and thus the idea behind nuclear-geothermal concepts of the first kind was to use buried nuclear detonations to excavate cavities and deposit large amounts of thermal energy at safe depths, whereupon it could be exploited in more or less conventional ways by introducing a working fluid. Since the cost of a nuclear device is only a shallow function of yield, electrical generation using the residual heat from explosions of > 1 Mt was calculated to be competitive with fossil fuels. The problem with this concept is that the thermodynamic quality of the reservoir would degrade rapidly in the presence of groundwater–the loss of heat by mass transfer to surrounding cooler strata causing the temperature within the high temperature zone to rapidly fall to the boiling point. One proposed solution was to detonate the explosives within salt domes as these are anhydrous and allow isothermal storage of heat at 800.4 °C–the melting point of salt [51]. However extraction of heat at this high a grade appeared only to be possible if the roof of the cavity remained largely intact and introduced working fluids (air, H_2, CO_2 and steam were variously suggested) had unrestricted access to a lake of molten salt pooled at its base. This is perhaps unlikely, although the technique cannot entirely be ruled out as being of practical and economic worth. It is thought that extensive evaporite deposits, and perhaps therefore large thicknesses of salt, might be present on Mars [52].

Ideas moved on from that of mining deposited nuclear heat when it became appreciated that if detonations took place within hyperthermal areas the recoverable heat from the volume of rock fractured by the blast would be much greater than that released by the explosive [53]. In fact, Plowshare experiments have demonstrated that nuclear explosives are rock-fracturing tools *par excellence*. The shock wave generated by a contained detonation crushes surrounding strata and excavates a spherical cavity which then usually caves in, forming a rubble chimney progressing upwards roughly 4½ times its initial radius. These broken columns of rock make ideal large-scale heat exchangers, with advantages of size, ease of creation, and in their hydraulic and structural properties, over artificial permeable zones made by "acceptable" means (see Section 6.1). Nuclear explosives are therefore the best known method of "stimulating" Hot Dry Rock for the recovery of its energy content–making geothermal power feasible in previously impractical locations (see fig. 9).

One example used to illustrate the concept of nuclear-stimulated geothermal power production involves the detonation of a 1 Mt device below the safe containment depth of 1.4 km (which would be ~ 2 km on Mars) in rock at 350 °C [54]. Calculations suggest that the event would create a transient

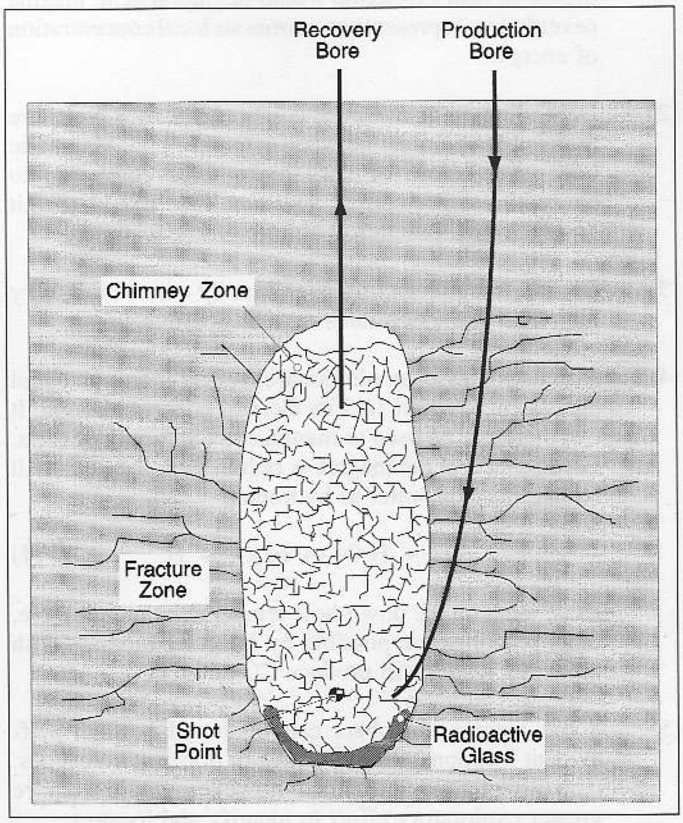

Fig. 9 Recovery of heat from the rubble chimney created by a contained nuclear detonation.

cavity ~ 70 m in radius, which would collapse forming a rubble chimney ~ 300 m high; surrounding this central structure, rock would be extensively fractured out to a distance of ~ 200 m. The total volume of the permeable zone would thus be ~ 4×10^7 m^3, from which ~ 620 MWyt of energy, of a grade adequate for geoelectricity, would be available. Only 127 MWyt of this heat would come from the nuclear device itself, a fraction of the total of ~ 20%. Heat recovery and power generation would be carried out in a closed circuit by recycling pressurised water through the reservoir and running it through heat exchangers and a binary electric generator at the surface. In this way, the risk of surface radioactive contamination via the working fluid (itself modest since most fission products would be vitrified and insoluble) would be reduced still further.

But for the hysteria that surrounds the very mention of the word "nuclear" at the present time, one is tempted to recommend further research into nuclear techniques of stimulating geothermal power production on Mars. If geothermal heat is not present, then nuclear explosives can emplace it. If permeable rocks are not present at a given hyperthermal site, then nuclear explosives can create these too. Nuclear explosive fracturing might make it feasible to circulate fluids through layers deeper than 10 km, where a near-inexhaustible HDR energy resource will be available anywhere on Mars.

6.3 Magma Exploitation

Where magma chambers lie at accessible depths it may be possible to tap their heat content directly, as opposed to the conventional practice of recovering it after it has conducted into superposed solid rocks [41-55]. There are five distinct advantages of doing this.

(1) The cooling of just 1 km^3 of molten rock from 1200 °C to 60 °C releases ~ 82,000 MWyt. Although such a degree of heat extraction would be impractical, magma nevertheless represents an enormous local concentration of energy.

(2) Depending on its chemical composition, rock melts are found at temperature between 600 - 1300 °C. Magmatic heat is therefore of very high grade compared to conventional geothermal sources. This would permit geoelectricity generation at high efficiencies.

(3) Because magma can transfer heat by convection, very high heat extraction rates may be possible.

(4) Magma possesses an additional chemical energy potential equivalent to about 1/12 its thermal energy potential. It can therefore be used to manufacture a variety of fuels. For instance, if the magma is rich in Fe^{2+}, then this will reduce injected water to hydrogen:

$$2\,FeO + H_2O \rightarrow Fe_2O_3 + H_2 \qquad (7)$$

Depending on the down-hole temperature and pressure, other reactions are possible by injecting biomass with the water which will produce CO and CH_4.

(5) Some magma chambers can be found beneath self-evident locations, such as active or dormant volcanoes. (Cryptovolcanic intrusions however would require greater exploratory effort to identify and locate.)

On the Earth, many magma chambers are known to occur in the top 10 km of crust. They are more common however in the lower 5 km as their buoyancy, and hence rate of ascent, increases as they rise due to expansion of their volume and exsolution of gases. Their restricted heat resource has been conservatively estimated to be ~ 7000 TWyt, much of this being concentrated in the geological environment near tectonic plate boundaries [41]. On Mars, we might reasonably expect accessible magma bodies to be much rarer, but not necessarily completely absent as magmatic activity may not be wholly extinct (as discussed in Section 3). Any of the localities within the anomalous heat flow province detailed in Table 2 could potentially be underlain by still molten, or partially molten, rock as, during the early stages of a volcanic cycle, magma is intruded into the shallow subsurface (as shown in fig. 3b). At first sight, it is difficult to imagine the penetration of molten rock with any equipment that could remain functional. However, the technology to do this is under development and lava at 1100 °C in Hawaii has already been safely penetrated to a depth of 33 m. This is done by projecting very high velocity water jets in advance of the drill encasing it within a chilled finger of rock. So long as the bore walls are maintained at below 700 °C, it is estimated that they would be stable down to depths of ~ 10 km.

The current concept of magma exploitation involves the creation of an open down-hole heat exchanger. This would be done by injecting water into the magma where it would form a bulb of solidified, but highly permeable rock with a large surface area for heat transfer. Water would flash to steam in this zone and would be removed via a pipe concentric with the injection bore (see fig. 10). As convection within the magma chamber would be promoted by this process, the most efficient way to operate the system would be to circulate water at a rate where the wall thickness of the heat exchanger tends to a constant and heat is supplied at the same rate that the working fluid removes it. Attainable power outputs per well of 25-45 MWe have been estimated [55].

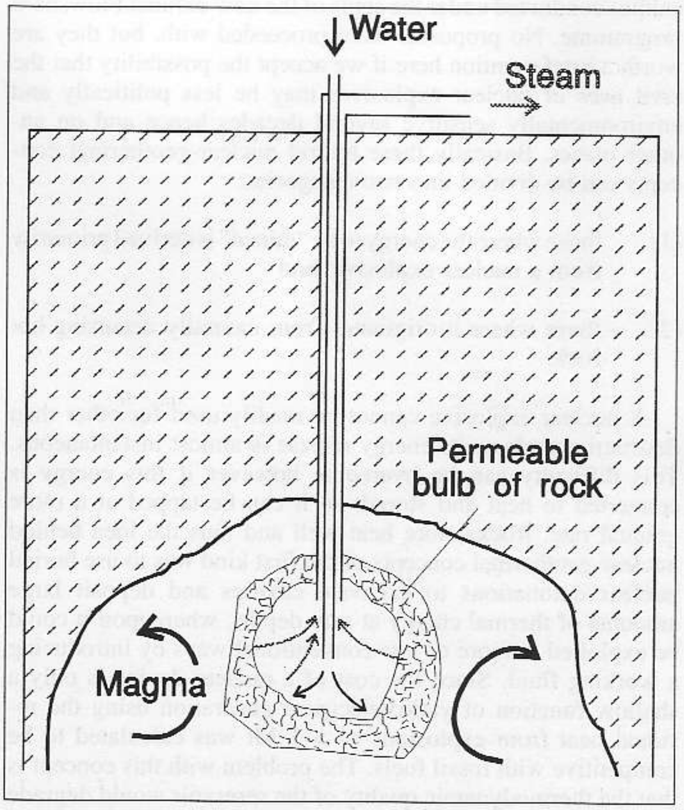

Fig. 10 A downhole heat exchanger created by injecting water into magma. Steam is recovered via a pipe concentric with the injection bore (after Ref. [41]).

Because of the lower martian gravity, buoyancy forces are less and thus magma chambers that reach shallow depths will be systematically larger than those on the Earth. Any discovery of an accessible direct magma resource on Mars therefore is likely to provide a long term potential for generating many megawatts of thermal, electrical and chemical energy. As with HDR however, the economics of exploiting magma energy will depend partly on a good water supply (unless CO_2 suffices as a working fluid). The simple fact that it is easier to transport water downhill, and that any water table will be closer to the surface in basin areas, suggest that power production centres for all advanced heat mining concepts will be favoured at low topographic elevations. Hotspots beneath the lowlands of Arcadia Planitia and the Cerberus Plains (between about -1 to -2 km below the planetary mean radius) may thus be better places to start heat mining than anywhere on the heights of Tharsis.

7. CONCLUSIONS

Theoretical models of global heat flow are not adequate as a basis to rule out the present day existence of geothermal hotspots on Mars. Indeed, geomorphological evidence is perhaps supportive of their realism as volcanic and fluvial activity appears to have been ongoing–albeit at a declining rate–into relatively recent geological time.

The economic exploitation of geothermal energy on Mars is therefore a distinct possibility. The concept depends crucially though on narrowing down the order of magnitude uncertainty in the absolute age of the most recent magmatism. Hyperthermal areas brought about by activity less than ~ 10 Myr old, associated with a groundwater supply, will be needed for the conventional production of geothermal power. Exploitation of areas of lesser heat flow may be possible, but will require the sort of technology currently under development for exploiting Hot Dry Rock–deeper wells and possibly the creation of artificial zones of permeability through which to circulate an introduced working fluid.

Only a thorough on-site exploration of Mars will reveal its true geothermal potential. Already, there are clues of where to start investigating: 3.1% of the planet's surface appears to be of the youngest geological age and of volcanic or fluvial origin; these rocks outcrop within a larger province comprising the regions of Elysium, Amazonis, Arcadia and Tharsis. As these features all occur in just one quadrant of Mars, they may be genetically linked to the presence of a mantle super-plume below. Thus, there is a potential for the discovery of cryptovolcanic hotspots anywhere beneath this region–a huge expanse of land, roughly a quarter of the planetary area.

Pioneering martian settlements will undoubtedly rely on substantial energy subsidies from the Earth in the manner of both imported fuels and generation infrastructure. However, in order to become self-reliant over the long-term, martian civilisation will have to move towards exploiting indigenous energy fluxes with domestic technology. The greater the choice of energy sources, the more secure settlers can feel about their future prosperity.

Geothermal energy may well be one of these available options. It will not be practical to harness at the very beginning of settlement, neither might it be a major economic feature of a mature planetary civilisation–but as a stepping stone between the two it could play an important role. Settlements sited in geothermal areas would have access to an abundant energy supply that, in some ways, is more reliable, efficient and secure than that gathered from the sun or wind. Not only will electrical power be made available, but also a supply of hot water for a multitude of direct uses.

Some of the first permanent martian communities could spring up around such geothermal oases. By the latter half of the next century, the spa towns of Mars might even be known for offering the best of life on the high frontier.

8. ACKNOWLEDGEMENTS

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