CONCRETIONS IN EXHUMED CHANNELS NEAR HANKSVILLE UTAH:

IMPLICATIONS FOR MARS

Jonathan D. A. Clarke[1] and Carol R. Stoker[2]

[1] Mars Society Australia, c/o 43 Michell St Monash, ACT 2904, Australia, phone 61-4184-01612/Australian Centre for Astrobiology, Ground Floor, Biological Sciences Building Sydney, NSW, Australia (corresponding author)
[2] NASA Ames Research Center, Moffett Field, California 94035, United States of America.

Mars analogue concretions & exhumed channels, Utah

Abstract

The landscape near Hanksville, Utah, contains a diversity of Mars analogue features. These included segmented and inverted anatasomosing palaeochannels exhumed from the Late Jurassic Brushy Basin Member of the Morrison Formation that hosts abundant small carbonate concretions. The exhumed and inverted channels closely resemble many seen on the surface of Mars in satellite imagery and which may be visited by surface missions in the near future. The channels contain a wealth of palaeoenvironmental information, but intrinsically difficult terrain would make their study challenging on Mars. We show that an unexhumed channel feature can be detected geophysically, this may allow their study in more easily accessed terrain. The concretions morphologically and in their surface expression parallel the haematite "blue berries" that are strewn across the surface of Meridiani Planum on Mars. They are best developed in poorly cemented medium to coarse channel sandstones and appear to have formed early in the diagenetic history.

Introduction

Satellite images of Mars have revealed numerous fluvial channels dating from the Late Noachian through to Early Hesperian (Howard *et al.* 2005, Irwin *et al.* 2005, Mangold *et al.* 2008, Burr *et al.* 2009, Newsome *et al.* 2010), many of which have been exhumed and inverted through denudation (Pain *et al.* 2007, Williams *et al.* 2009). Relief inversion is common on Earth during landscape evolution and many examples are known (Pain and Ollier 1995). Properly interpreted, such features provide insight into the martian water cycle, fluvial hydrology, and processes and rates of landscape evolution. Examples of such features have been considered as landing sites for future unmanned Mars missions such as the *Curiosity* Mars Science Rover, (Rice and Bell 2010, Marzo *et al.* 2009).

Mars analogue concretions & exhumed channels, Utah

Images from Mars Exploration Rover *Opportunity* have revealed a widespread unit of sandy lacustrine and aeolian evaporitic sediments containing haematite concretions (Klingelhofer *et al.* 2004, McLennan *et al.* 2005, Sefton-Nash and Catling 2008) formed during diagenesis and now being concentrated by aeolian deflation into a lag of wind-rippled sand (Soderblom *et al.* 2004). Haematite concretions have been reported from terrestrial aeolian sandstones and acidic salt lakes and have been used as Mars analogues (Chan *et al.* 2004, Morris *et al.* 2005, Benison and Bowen 2006, Benison *et al.* 2007). Such features provide insight into the subsurface physical and chemical environment during their formation.

In this paper we describe a new location that provides an analogue to exhumed and inverted martian channels and for concretions located on the edge of the Colorado Plateau in Utah. We will characterise these features and document their geologic and geomorphic context and describe their significance compared to similar, previously documented occurrences of inverted and exhumed relief and concretions. Lastly, we will argue that this study provides a good analogue for the level of investigation that can be achieved with a human surface mission on Mars.

MDRS and Morrison Formation geologic setting

The study area is located near Hanksville, Utah, on the edge of the San Rafael swell (Figure 1). The site is the location of the Mars Desert Research Station (MDRS, Persaud *et al.* 2004), a facility established by the Mars Society for analogue research in the disciplines of engineering, planetary science, astrobiology, and human factors, and as a platform for education and outreach programs.

Mars analogue concretions & exhumed channels, Utah

The region (Western Regional Climate Center 2010) has an arid climate, over a 56 year period (1948-2005) Hanksville received an annual average precipitation of 141.22 mm, of this14.73 mm (10.4%) occurred as snow. Precipitation was highest in August to October. The hottest month was July, with an average daily maximum of 37.1^o C and a daily minimum of 16.3^o C. The coldest month was January, with an average daily maximum of 5.2^o C and a minimum of -10.9^o C. Monthly minima are below freezing from November to March. The study area lies between the altitudes of 1340 and 1400 m.

The stratigraphy of the area (Table 1) consists of a dissected succession of near flat-lying Cretaceous and Jurassic sandstones and shales. The main unit studied is the Jurassic Morrison Formation, in particular the uppermost Brushy Basin Member (Hintze and Kowallis 2009).

The landscape consists of mesas and scarp-bounded surfaces resulting from erosion of the flat lying succession of alternating units of greater and lesser resistance to erosion. Clay-rich units being more easily eroded and sandstones are less. The sandstone surfaces form smooth plains and the clay-rich materials mostly dissected slopes. In the immediate vicinity of MDRS the Brushy Basin Member forms a dissected plain of cracking clays (Clarke and Pain 2004). Fluvial channels are exposed on the steep slopes or are being exhumed as inverted relief. It is these features that we put forward as new Mars analogues.

Methods

Study methods consisted of air photo interpretation, geological documentation of the inverted and exhumed channels and the concretions associated with them, ground

Mars analogue concretions & exhumed channels, Utah

penetrating radar surveys of the best exposed and most accessible example of a partially exhumed channel, and sampling of outcrops by hand and using a Shaw Backpack Drill. In the laboratory, samples were analysed for mineralogy using XRD with a TERRA field portable XRF/XRD (In Xitu Inc., Sarrazin *et al.* 2005) and cross checked using a Portable Infra-Red Mineral Aanalyser, or PIMA (Thomas and Walter 2002). The PIMA II, manufactured by Integrated Spectronics, utilizes SWIR, and has 601 contiguous spectral bands between 1,300 and 2,500 nm. The PIMA detects minerals containing OH^-, H_2O, CO_3^{3-}, PO_4^{2-}, and SO_4^{2-}. Mineral identification by spectral matching is automated and takes about a minute per sample. The instrument can be used in either the field or in the laboratory. Thin sections of concretionary units were half-stained with Alazarin red and Potassium ferrocyanin to show their carbonate mineralogy and then examined using a polarising transmitted light microscope.

Exhumed channel observations

Fluvial channels are composed of more permeable sediments such as sands and gravels than their floodplains or valley sides which are more likely composed of silts and clays. Their greater permeability results in high rates of fluid flow and greater likelihood of cementation compared to their flanking materials. Lowering of the landscape through denudation processes such as mass wasting, fluvial dissection, or aeolian deflation will exhume the channels, leaving the more indurated examples as ridges in the landscape, inverting the former topography (Ollier and Pain 1995). In the study area Jurassic palaeochannels in the Brushy Basin Member has been exhumed in this manner, leaving numerous segmented sinuous ridges. The resistant sandstones and conglomerates of the channels form cap rocks that protect the underlying floodplain clays from erosion.

Mars analogue concretions & exhumed channels, Utah

Eventually the cap rocks are removed by scarp retreat, leaving isolated boulders, the clay ridge then being vulnerable to erosion.

The best developed and most accessible examples of these channels (Figure 2) has been given the informal name of "Kissing Camel Ridge " (KCR) by previous people who have worked in the area, possibly due to the rock formations on its crest. The channel that forms the ridge is partly exhumed from the surrounding floodplain shales, allowing its buried component to be explored using geophysics.

Fluvial facies

The Brushy Basin Member of the Late Jurassic Morrison Formation was deposited in a foreland basin setting draining highlands to the west and a marginal to enclosed evaporitic basin to the east. The depositional climate was arid to semi-arid environment (Demko and Parrish 1998, Demko *et al.* 2004). In the study area, palaeocurrents indicate flows in a generally north-easterly direction (Figure 3). The sediments contain a major contribution of weathered volcanic ash, expressed as residual glass shards, bentonite beds, and abundant smectites in the floodplain facies.

Deposition was dominated by anastomosing fixed fluvial channels (Miall and Peterson 1989, Kjemperud *et al.* 2008). Sand and gravel channels 20 to 100 m wide and two to 15 m thick, composed of cross-bedded sandstone, are embedded in floodplain deposits of shale (Figure 4). The fixed channels are possibly the result of both gallery vegetation and very cohesive banks rich in smectic clays from the weathering of volcanic ash (bentonites). Adjacent to the channels are levee bank deposits of fine sands and siltstone showing planar to ripple lamination (Figure 4). Interbedded with the floodplain shales are

Mars analogue concretions & exhumed channels, Utah

thin (<1 m) lenticular to laterally extensive sand and sandstone beds generally white in colour (Figure 6, 8). These are interpreted as crevasse splay deposits. The beds have erosional to planar bases and are either massive or parallel laminated. Palaeosols are common, recognised by prominent brown and white mottling and root impressions (see Demko *et al.* 2004 for further details).

Meandering river channels are a minor architectural theme of the Brushy Basin Member of the Morrison Formation. The meandering channels are typically thin (<2 m) and are laterally extensive (100-200 m in width). Apart from the overall thinness of individual units and width to thickness rations of ~100:1, meandering channel units are generally characterised by lateral accretion surfaces visible in the best outcrops, sometimes mirrored lateral accretion surfaces are visible as the cliff face cuts across a bend. Some published descriptions of these facies can be found in Miall and Peterson (1989).

In the Hanksville area floodplain clays in the Brushy Basin Member are only weakly indurated to form shales. Sandstones are the most variable in induration. Fine-grained sandstones are generally the most weakly indurated and conglomerates the greatest, however even with individual units, cementation can vary over distances of decimetres. Crevasse splay deposits of fine sand tend to have more weakly cemented to weakly nodular to blocky induration, although exceptionally permeable horizons may also be well indurated. Fractures in both shales and sandstones have acted as preferential fluid pathways and are therefore more extensively cemented. Fluids appear to have been oxidising, and the deposition of reduced iron minerals occur as halos surround fossil wood or dinosaur bones indicates. Cements are most commonly carbonate, with some

silica, especially in the more indurated units. The concretionary units (Figure 6) occur within this diagenetic spectrum over a strike distance of at least 11 km.

Subsurface investigations

Previously, seismic refraction had been carried out on a parallel traverse to the GPR (Shiro and Ferrone 2010). The preliminary work gave encouraging indications that a channel feature could be geophysically mapped in the subsurface. We followed up this work with a ground penetrating radar (GPR) survey. Under favourable conditions GPR can provide high resolution information on sedimentary architecture and has been used to describe the characteristics of other Cretaceous units of the region (c.f. Corbeanu *et al.* 2001). We used the CRUX GPR (Kim *et al.* 2006), an instrument developed for future Space Flight Missions, to profile the inferred extension of the KCR palaeochannel beneath the cap of Dakota Formation. This GPR operates at a frequency of 800 Mhz and has a nominal penetration depth of 5 m and a resolution of 15 cm. The instrument was pulled by hand on a small cart. The two GPR profiles clearly show the upper edges of the buried palaeochannel as inverted hyperbola, showing the validity of GPR in delineating such a buried feature (Figure 5).

Mineralogy

Mineralogy detected by XRD is dominated by quartz and calcite (Table 2), the former presenting the detrital grains in the sandstone, the later the cement. Calcite is more common in the concretions than in the unconcreted sandstone. Dickite and barite were present in XRD traces of two different samples, these also are probably also cement phases.

Mars analogue concretions & exhumed channels, Utah

The PIMA II detected both calcite and montmorillonite in all the samples (Table 3). Anhydrite was detected in several samples, but with lower confidence in identification. Note that the percentages are approximate and are only recorded for the minerals the instrument is able to detect. In the MDRS area these are carbonates, sulphates, and clays. Non-hydrous silicates such as quartz and feldspar, are not detected.

Concretions

The concretions are 3-10 mm in diameter, most commonly 5 mm. They are spherical to sub-angular, most commonly sub-rounded. Occasional irregular concretions are present. Occasional doublets formed when two grow close enough to merge, rarely concretions can amalgamate to form multi-nucleate masses. When exposed on a freshly broken surface the concretions are white in colour. They weather purplish or brown. XRD analysis shows the presence of calcite.

The distribution of the concretions is strongly controlled by depositional facies (Table 4), they are most common in medium-grained channel sandstones, less common in fine-grained or pebbly channel sandstones. Degree and nature of cementation also appears a factor, concretions occur mostly in moderately indurated sandstones cemented by calcite, they are absent from poorly cemented sandstones and those that have been well cemented by silica.

Distribution of the concretions in the host rocks is not related to individual beds and depositional fabrics, but rather they are more or less evenly spaced. However, on a larger scale some beds contain more than others, and there are patches of concretion-rich sandstone next to concretion-poor sandstone. Early faults act as permeability barriers,

with concretions common on one side and not the other (Figure 6D). Similar brown-weathering carbonate occurs in veins (Figure 6C).

Because they are more indurated than the surrounding sandstones, the concretions tend to weather out of the rock. In the process the surface of the concretions acquires a purplish or brownish colour, suggesting traces of manganese and iron in the carbonate. The liberated concretions are reworked by slope processes to form deposits mantling slopes and as lags within rills and gullies.

Petrography

Microscopic examination of the concretionary sandstones shows that they are composed of medium grained, well rounded and well sorted sandstones (Table 5). The sandstones are Quartzose arenites in the classification of Crook (1960). The grains were composed of 95% quartz, including 9% chert, with minor feldspar, both potassium feldspar and plagioclase. There is a trace of amphibole, largely replaced by calcite. The predominantly sedimentary provenance is consistent with a derivation from the folded Palaeozoic rocks to the west (Williams and Hackman 1971)

The cements are composed of poikilotopic calcite enclosing multiple sand grains. Each crystal is circular to ellipsoidal in cross section, suggesting that in three dimensions the crystals are spheroids. Crystal size is 3-10 mm, overlapping that of the concretions. We conclude therefore that the concretions are composed of single crystals of calcite. The cement away from the concretions consists of thin clay coatings, probably the montmorillonite detected by PIMA, and calcite. Representative micrographs are shown in Figure 7.

Mars analogue concretions & exhumed channels, Utah

Inverted and exhumed channel discussion

Significance of the channels at the MDRS site

There have been no previous studies of inverted or exhumed channels from the Brushy Basin Member and previous studies at the MDRS site (e.g. Battler *et al.* 2006, Clarke and Pain 2004) did not refer to them. However there is an extensive literature on the similar exhumed and inverted channels of the slightly younger Cedar Mountain Formation some 70 km to the north east, near Green River (see Williams e*t al.* 2009, Harris 1980, and references therein). The two occurrences are compared in Table 6. Apart from the slightly younger age, the main difference between the two is that the Green River channels are somewhat more continuously exposed and were deposited by meandering rather than anastomosing streams.

Mars analogue relevance

Satellite images of Mars have revealed that numerous inverted and exhumed fluvial channels are present on the martian surface (e.g. Newsome *et al.* 2010, Pain *et al.* 2007, Williams *et al.* 2009, Burr *et al.* 2009).

Table 7 places the MDRS channels in the context of others that have been discussed as Mars analogues and their martian counterparts. Inverted and exhumed channels on Mars different markedly in morphology, including basalt (Luchitta 2005) and sediment filled (e.g. Bhattacharya *et al.* 2005), single (Newsome *et al.* 2010, Pain *et al.* 2007) and anastomosing channels (Burr *et al.* 2009), fans and deltas (Bhattacharya *et al.* 2005, Pain *et al.* 2007, Burr *et al.* 2009), and fixed (Newsome *et al.* 2010) and migrating high

Mars analogue concretions & exhumed channels, Utah

sinuosity (Bhattacharya *et al.* 2005) channels. Therefore a diversity of terrestrial analogues are needed.

As anastomosing fixed channels, the MDRS examples, although segmented, are among the best terrestrial analogues yet identified for those of the Aeolis region on Mars (Burr *et al.* 2009), as illustrated in Figure 8. The complex terrain and segmentation of the exhumed and inverted channels at the MDRS site also provide superb exposure and access to study the detailed fluvial architecture.

Finally, although we did not investigate this aspect, palaeochannels are prime locations for the preservation of microfossils and, when inverted and exhumed provide excellent sampling sites (references). Exhumed and inverted channels on Mars can also be expected to host such remains, if they exist. Terrestrial palaeochannels have also provided refugia for organisms as climates shift from equitable to more arid over timescales of tens of millions of years and formerly surface organisms adapt to habitats in the sedimentary pores (reference).

Concretion discussion

Significance of the concretions at MDRS

Clifton (1957) said "The origin of concretions is a geologic puzzle". Their origin is often obscure and the evidence from them contradictory (Selles-Martinez 1996).   However, detailed analysis of their context, fabric, mineralogy, and chemistry allows some conclusions to be drawn about their formation and significance.

Mars analogue concretions & exhumed channels, Utah

We infer that the distribution of concretions in Brushy Basin Member at the MDRS field site is strongly controlled by the hydrology which in turn is controlled by the depositional architecture. More work is needed in the field to map out the extent of the concretions.

The timing of the concretions is therefore interpreted as occurring during burial, subsequent to early cementation and early fracturing, but prior to final infill of porosity by cement. More work is needed, in particular petrographic studies, to determine the relative timing relationships.

Mars analogue value

Vast numbers of small spherical haematite concretions are a striking feature of the Burns formation at Meridiani Planum seen by the *Opportunity* rover (Klingelhofer *et al.* 2004, McLennan *et al.* 2005, Sefton-Nash and Catling 2008). A number of terrestrial examples are proposed as analogues, most notably those from the aeolian Navajo Sandstone (Chan *et al.* 2004), altered volcanic breccia at Mauna Kea (Morris *et al.* 2005), Western Australian salt lakes (Benison and Bowen 2006, Benison *et al.* 2007), and from the marginal marine sandstones in the Dakota Formation at MDRS (Battler *et al.* 2006). As with all analogues, these examples have both similarities and differences to the martian feature they are intended to counterpart. Table 8 shows these similarities and differences with respect to host rock texture, mineralogy, and facies, along with concretion mineralogy, sphericity, texture, dimensions, and extent. From Table 8 the best analogues are those in the Navajo Sandstone, followed by those in the WA salt lakes concretions, Brushy Basin Member, and Dakota Sandstone, with the Moana Kea concretions last.

Mars analogue concretions & exhumed channels, Utah

With regards to host rock textures, the Navajo, WA, Dakota, and Brushy Basin provide the best analogues, all occurring in sands. Regarding host mineralogy the WA and Moana Kea are the best, each individually reflecting one aspect of the main compositional lithologies at Meridiani, sulphates and altered basalt respectively. The combined aeolian and salt lake depositional environment at Meridiani are best represented by the end member analogues on Earth, with the Navajo concretions forming in dune sands and the WA concretions in acidic sulphate-rich salt lakes. The Meridiani haematite mineralogy is best reflected by the Navajo and WA concretions. Morphologically, the Brushy Basin concretions are the most similar in sphericity and size. With respect to internal fabric the Navajo concretions show the greatest similarities being internally homogeneous to concentric, this is shared by some of the Moana Kea and WA concretions. Dimensionally, the concretions of the Brushy Basin Member most resemble those of Meridiani. In terms of extent, both the Dakota and Bushy Basin concretionary units resemble those on Mars in extending for at least 10 km laterally. Lastly, in terms of geomorphic behaviour, both the Navajo and Brushy Basin concretions are significantly harder than their host rocks and weather out in a manner analogous to those on Mars.

Which of these analogues is the best therefore depends on the property being investigated. The Navajo concretions are the best with regard to mineralogy and fabric and share with the WA examples a similarity in depositional environment. The WA concretions are the only ones associated with sulphates and the Moana Kea with basaltic volcanics. The concretions in the Brushy Basin Member are however the best analogues in terms of their extent, sphericity, and surface expression (Figure 9).

Mars analogue concretions & exhumed channels, Utah

Only haematite concretions have been found on Mars to date. However the detection of carbonate in deltaic sediments in Jerezo Crater (Murchie *et al.* 2009) hints at carbonate-overprinted of sediments on the planet, at least locally. Whether the carbonate occurs as distributed cement, weathering-related overprint, or as discrete concretions, as is the case of the Brushy Basin Member concretions at the MDRS field site, remains to be seen. However the carbonate cements and concretions at MDRS illustrates the characteristics of diagenetic carbonates in rocks otherwise dominated by weathered volcanic products.

Astrobiological Applications and Implications

A key part of assessing the astrobiological potential of a site requires knowledge of the history of water activity. This information is encoded in the depositional and diagenetic history. Well exposed features such as inverted palaeochannels provide opportunities to access the exposures to acquire such information as depositional environment, water density drying deposition, and subsequent fluid history. In addition, terrestrial inverted channels are also excellent locations to find fossils (Macphail and Stone 2004) and can provide subsurface refugia to surface biota driven underground by increasing aridity (Finston *et al.*2007). Terrestrial inverted and exhumed palaeochannels therefore also provide targets for astrobiological research and the development of technologies and methodologies to look for evidence of past like on Mars in such features.

Lessons for Future Exploration

Understanding of such features is important as they occur in sites proposed as targets for future missions such as Mars Science Laboratory (*Curiosity*) (Rice and Bell 2010, Marzo *et al.* 2009) and they contain a wealth of information about martian processes including

fluvial hydrology, water chemistry, fluid flow, and constraining landscape evolution. However, exhumed and inverted channels typically have steep-sided exposures, often covered in rubbly deposits, making access difficult (Figure 10). Astronauts, even though hampered by pressure suits, may well find it easier to traverse such slopes than autonomous or remotely controlled vehicles. However unexhumed channels may be more easily accessed provided they can be located by geophysical meand

We also have shown that geophysical techniques, specially GPR are able to locate such channels in the subsurface, at least when adjacent to known exposures, allowing access from above using drills, if required. Although avoiding the problems of traversing difficult terrain, field experience (Shiro and Ferrone 2010) has shown that the handling and deployment of such complex instruments and tools will likewise be greatly facilitated by direct human presence

Future work

Investigations of the site are continuing. These include analysis of textures and materials recovered from drill core, petrography of thin sections, and further examination of the mineralogy of sediments, concretions and soils using both XRD and infrared spectroscopy. We expect these studies to reveal further details of the diagenesis and fluid history of these sediments and their relevance to Mars analogue studies. We also hope to revisit the site and map out the extent of the concretions in locations at greater distances from MDRS.

Conclusions

Mars analogue concretions & exhumed channels, Utah

We conclude that the inverted relief at MDRS an excellent example of some types of inverted and exhumed relief at Mars. They are particularly close analogues to the inverted anastomosing channels of Aeolis (Burr *et al.* 2009). Studying the MDRS channels assists in understanding the processes of sedimentation and landscape evolution that shape such features, predicts the detailed features that will be encountered when they are explored at ground level by future Mars missions, and provide testing grounds for the technology and instrumentation required for their study.

The Concretions at MDRS are a partial analogue to concretions discovered at Meridiani on Mars by the *Opportunity* rover. They are particularly good analogues with respect to size, shape, distribution, extent, and in their geomorphic expression as they weather out of the substrate and concentrated as surface lags.

Lastly, we emphasise that the area surrounding MDRS has considerable Mars analogue value, the presence of the concretions and inverted and exhumed channels adds to a diverse suite of analogues that includes sulphate soils, bedded sulphate evaporites, and gullies. All these features occur in close proximity to the station itself, which designed and equipped to simulate many of the aspects of a Mars station. The area is an ideal location for both specialised and highly integrated studies of Mars analogues and their exploration.

Acknowledgements

Mars analogue concretions & exhumed channels, Utah

Mars analogue concretions & exhumed channels, Utah

References

Battler, M. M., Clarke, J. D. A., and Coniglio, M. 2006. Possible Analog Sedimentary and Diagenetic Features for Meridiani Planum Sediments Near Hanksville, Utah: Implications for Martian Field Studies In Clarke, J. D. A. (ed.). Mars Analog Research. American Astronautical Society Science and Technology Series 111, pp. 55-70

Benison, K.C., and Bowen, B.B., 2006. Acid saline lake systems give clues about past environments and the search for life on Mars: Icarus 183, pp. 225–229.

Benison, K.C., Bowen, B.B., Oboh-Ikuenobe, F.E., Jagniecki, E.A., Laclair, D.A., Story, S.L., Mormile, R.M. and Hong, B.-Y. Sedimentology of acid saline lakes in southern Western Australia: newly described Processes and products of an extreme environment. Journal of Sedimentary Research 77, pp. 366–388.

Bhattacharya, J.P., Payenberg, T.H.D., Lang, S.C., Bourke, M., 2005. Dynamic river channels suggest a long-lived Noachian crater lake on Mars. Geophysical Research Letters 32, doi:10.1029/2005GL022747. L10201.

Burr, D.M., Enga, M.T., Williams, R.M.E., Zimbelman, J.R., Howard, A.D., and Brennan, T.A. 2009. Pervasive aqueous paleoflow features in the Aeolis/Zephyria Plana region, Mars. Icarus 200, pp. 52–76.

Chan, M.A., Beitler, B., Parry, W.T., Orno¨, J., and Komatsu, G. 2004. A possible terrestrial analogue for haematite concretions on Mars, Nature 429, 731– 734.

Mars analogue concretions & exhumed channels, Utah

Clarke, J. D. A. and Pain, C. F. 2004. From Utah to Mars: regolith-landform mapping and its application. *In* Cockell, C. C. (ed.) Mars Expedition Planning. American Astronautical Society Science and Technology Series, 107, pp. 131-160.

Clifton, H.E., 1957. The carbonate concretions of the Ohio shale. Ohio J. Sci., 57(21), pp. 114-124.

Corbeanu, R. M., Wizevich, M. C., Bhattacharya, J. P., Zeng, X., and McMechan, G. A. 2001. Three-Dimensional Architecture of Ancient Lower Delta-Plain Point Bars Using Ground-Penetrating Radar, Cretaceous Ferron Sandstone, Utah. AAPG Studies in Geology 50, pp. 427-449.

Crook, K.A.W. 1960. Classification of arenites. Am. Jour. Sci 258, pp. 419-428.

Demko, T. M., Currie, B. S., Nicoll, K. A. 2004. Regional paleoclimatic and stratigraphic implications of paleosols and fluvial/overbank architecture in the Morrison Formation (Upper Jurassic), Western Interior, USA. Sedimentary Geology 167, pp. 115–135

Demko, T. M. and Parish, J. T. 2001. Paleoclimatic setting of the Upper Jurassic Morrison Formation. Modern Geology 22, pp. 283-296.

Finston, T. L., Johnson, M. S., Humphreys, W. F., Eberhard, S. M., and Halse, S. A. 2007. Cryptic speciation in two widespread subterranean amphipod genera reflects historical drainage patterns in an ancient landscape. Molecular Ecology 16, 355–365.

Harris, D.R., 1980. Exhumed paleochannels in the Lower Cretaceous Cedar Mountain Formation near Green River, Utah: Brigham Young University Geology Studies 27, pp. 51–66.

Heim, J.A., Vasconcelos, P.M., Shuster, D.L., Farley, K.A. and Broadbent, G. 2006. Dating paleochannel iron ore by (U-Th)/He analysis of supergene goethite, Hamersley province, Australia. Geology .34(3), pp. 173–176

Hintze, L. H. and Kowallis, B. J. 2009. The geologic history of Utah Brigham Young University Geology Studies Special Publication 9.

Howard, A. D., Moore, J. M. and R. P. Irwin, R. P. 2005, An intense terminal epoch of widespread fluvial activity on early Mars: 1. Valley network incision and associated deposits, Journal of Geophysical Research 110(E12S14), doi:10.1029/2005JE002459.

Irwin III, R, P., Howard, A. D., Craddock, R. A., and Moore J. M. 2005. An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development, Journal of Geophysical Research 110(E12S15), doi:10.1029/2005JE002460.

Kim, S.S., Carnes, S.R., Haldemann, A.F., Ulmer, C.T., Ng, E., and Arcone, S.A. 2006. Miniature Ground Penetrating Radar, CRUX GPR. Presentation to IEEE Aerospace Conference, Big Sky, Montana, March 6-9, 2006. Address when accessed http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/38905/1/06-0566.pdf

Klingelhofer, G., Morris, R. V., Bernhardt, B., Schroder, C., Rodionov, D.S., de Souza, P.A., Yen, A., Gellert, R., Evlanov, E.N. Zubkov, B., Foh, J., Kankeleit, E., Gutlich, P.,

Mars analogue concretions & exhumed channels, Utah

Ming, D.W. Renz, R., Wdowiak, T., Squyres, S.W., Arvidson, R.E., and McLennan. S.M. 2004. Jarosite and hematite at Meridiani Planum form Mossbauer spectrometer on the Opportunity rover, Science 306, pp. 1740– 1745.

Kjemperud, A. V., Schomacker, E. R., and Cross, T. A. 2008. Architecture and stratigraphy of alluvial deposits, Morrison Formation (Upper Jurassic), Utah. AAPG Bulletin 92 (8), pp. 1055–1076.

Lucchitta, B.K. 2005. Light layer and sinuous ridges on plateau near Juventae Chasma, Mars. Abstracts of the 36th Lunar and Planetary Science Conference, Abstract 1500.

Macphail, M. K. and Stone, M. S. 2004. Age and palaeoenvironmental constraints on the genesis of the Yandi channel iron deposits, Marillana Formation, Pilbara, northwestern Australia. *Australian Journal of Earth Sciences* 51, pp. 497–520

McLennan S.M., Bell, J.F., Calvin, W.M., Christensen, P.R., Clark, B.C., de Souza, P.A., Farmer, J., Farrand, W.H., Fike D.A., Gellert, R., Ghosh, A, Glotch, T.D., Grotzinger, J.P., Hahn, B., Herkenhoff, K.E., Hurowitz, J.A., Johnson, J.R., Johnson, S.S., Jolliff, B., Klingelhofer, G., Knoll, A.H., Learner, Z., Malin, M.C., McSween Jr., H.Y., Pocock J., Ruff, S.W., Soderblom, L.A., Squyres, S.W., Tosca, N.J., Watters, W.A., Wyatt, M.B., and Yen, A. 2005. Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. Earth and Planetary Science Letters 240, pp. 95–121.

Maizels, J.K., 1987. Plio-Pleistocene raised channel systems of the western Sharqiya (Wahiba), Oman. In: Frostick, L., Reid, I. (Eds.), Desert Sediments: Ancient and Modem. Geological Society London Special Publication 35, pp. 31–50.

Mangold, N., Ansan, V., Masson, P., Quantin, C., and Neukum, G. 2008. Geomorphic study of fluvial landforms on the northern Valles Marineris plateau, Mars, Journal of Geophysical Research 113(E08009), doi:10.1029/2007JE002985.

Marzo, G.A., oush, T. L., Lanza, N. L., McGuire, P. C., Newso, H. E., Olilla, A. M., and Wiseman, S. M. 2009. Mineralogy of the inverted channel on the floor of Miyamoto Crater, Mars. Abstracts 40th Lunar and Planetary Science Conference, abstract 1236.

Miall, A.E. and Turner-Peterson, C. 1989. Variations in fluvial style in Westwater canyon Member, Morrison Formation (Jurassic), San Juan Basin, Colorado Plateau. Sedimentary Geology 63, pp. 21-60.

Morris, R.V., Ming, D.W., Graff, T.G., Arvidson, R.E., Bell, J.F., Squyres, S.W., Mertzman, S.A., Gruener, J.E., Golden, D.C., Le, L., and Robinson, G.A. 2005. Hematite spherules in basaltic tephra altered under aqueous, acid-sulfate conditions on Mauna Kea volcano, Hawaii: Possible clues for the occurrence of hematite-rich spherules in the Burns formation at Meridiani Planum, Mars. Earth and Planetary Science Letters 240, pp. 168–178.

Morris, R. C. and Ramanaidou, E. R. 2007. Genesis of the channel iron deposits (CID) of the Pilbara region, Western Australia', Australian Journal of Earth Sciences, 54(5), pp. 733 – 756

Murchie, S. L., Mustard, J.F., Ehlmann, B.L., Milliken, R.E., Bishop, J.L., McKeown, N.K., Dobrea, E.Z.N., Seelos, F.P., Buczkowski, D. L., Wiseman, S.M., Arvidson, R.E., Wray, J.J., Swayze, G., Clark, R.N., Des Marais, D.J., Alfred S. McEwen, and Bibring,

J.-P. 2009. A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter, Journal of Geophysical Research 114(E00D06), doi:10.1029/2009JE003342.

Newsome, N. E., Lanza, N. L., Ollila A. M., Wiseman, S. M., Roush, T. L., Marzo, G. A., Tornabene L. L., Okubo, C. H., Osterloo, M. M., Hamilton, V. E., and Crumpler, L. S. 2010. Inverted channel deposits on the floor of Miyamoto crater, Mars. Icarus 205, pp. 64–72.

Pain, C.F., Clarke, J.D.A., Thomas, M., 2007. Inversion of relief on Mars. Icarus 190, pp. 478–491.

Persaud, R., Rupert-Robles, S., Clarke, J. D. A., Dawson, S., Mann, G., Waldie, J., Piechocinski, S. and Roesch, J. 2004. Expedition one: a Mars analog research station thirty-day mission. *In* Cockell, C. C. (ed.) Mars Expedition Planning. American Astronautical Society Science and Technology Series, 107, pp. 53-88

Rice, M. S. and Bell, J. F. 2010. Geologic mapping of the proposed Mars Science Laboratory (MSL) landing ellipse in Eberswalde Crater. Abstracts 41st Lunar and Planetary Science Conference, Abstract 2524.

Sarrazin, P., Blake, D., Feldman, S., Chipera, S., Vaniman, D., and Bish, D. Field deployment of a portable X-ray diffraction/X-ray fluorescence instrument on Mars analog terrain. Powder Diffraction 20(2), pp. 128-133.

Sefton-Nash, E. and Catling, D. C. 2008. Hematitic concretions at Meridiani Planum, Mars: Their growth timescale and possible relationship with iron sulfates. Earth and Planetary Science Letters 269, pp. 365–375.

Selles-Martinez, J. 1996. Concretion morphology, classification and genesis. Earth-Science Reviews 41, 177-210.

Shiro, B.R. and Ferrone, K.L. 2010. In Situ geophysical exploration by humans in Mars analog environments. Abstracts 41st Lunar and Planetary Science Conference, Abstract 2052.

Soderblom, L.A., Anderson, R.C., Arvidson, R.E., Bell, J.F., Cabrol, N.A., Calvin, W., Christensen, P.R., Clark, B.C., Economou, T., Ehlmann, B.L., Farrand, W.H., Fike, D., Gellert, R., Glotch, T.D., Golombek, M.P., Greeley, R., Grotzinger, J.P., Herkenhoff, K.E., Jerolmack, D.J., Johnson, J.R., Jolliff, B., Klingelhofer, G., Knoll, A.H., Learner, Z.A., Li, R., Malin, M.C., McLennan, S.M., McSween, H.Y., Ming, D.W., Morris, R.V., Rice., J.W., Richter, L., Rieder, R., Rodionov, D., Schroder, C., Seelos, F.P., Soderblom, J.M., Squyres, S.W., Sullivan, R., Watters, W.A., Weitz, C.M., Wyatt, M.B., A. Yen, A., and Zipfel, J. 2004. The soils of Eagle crater and Meridiani Planum, Science 306, pp. 1723– 1726.

Thomas, M. and Walter, M. R. 2002. Application of Hyperspectral Infrared Analysis of Hydrothermal Alteration on Earth and Mars. Astrobiology 2(3), pp. 335-351.

Western Region Weather Center 2010. Climate data for Hanksville Utah. Address when accessed http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?uthank

Mars analogue concretions & exhumed channels, Utah

Williams, P. L. and Hackman, R. J.1971(comp.). Geology of the Salina quadrangle, Utah, USGS geological map I-591-A.

Williams R. M. E., Irwin, R. P., and Zimbelman, J. R. 2009. Evaluation of paleohydrologic models for terrestrial inverted channels: Implications for application to martian sinuous ridges. Geomorphology 107, pp. 300–315.

Table 1

Stratigraphy of the Jurassic and Cretaceous near Hanksville

AGE	GROUP	FORMATION	MEMBER	THICKNESS (m)
Cretaceous	Mesa Verde			300+
		Mancos Shale	Musak Shale	600-800
			Emery Sandstone	250
			Blue Gate Shale	1400
			Ferron Sandstone	250
			Tununk Shale	575
		Dakota Sandstone		0-50
		Cedar Mountain		0-125
Jurassic		Morrison Formation	Brushy Basin	60-225
			Salt Wash	30-235
	San Rafael Group	Summerville		200
		Curtis		0-80
		Entrada		475-780
		Carmel		310-99
	Glen Canyon Group	Navajo Sandstone		800-1100
Triassic		Kayeata		350
		Wingate Sandstone		320-370

Mars analogue concretions & exhumed channels, Utah

Table 2

XRD analyses of concretions and matrix

Sample ID	Material	Quartz (%)*	Calcite (%)	Other %
202	concretion	40	60	none
202	matrix	90	10	none
215	concretion	35	65	none
215	matrix	85	ND	10
295	ND	85	ND	Dickite 15
439	Concretion	25	75	none
459	Concretion	60	40	none
463	Concretion	60	40	none

All values are as computed by the JADE ™ software and rounded to nearest 5%.
Relative accuracy is estimated at 20% of value shown.

Table 3

PIMA analysis of concretions and matrix

Sample	Material	Montmorillonite %	Calcite %	Other phases detected
215	Concretion	39	38	Anhydrite
215	Concretion	57	43	
215	Concretion	38	43	Anhydrite
215	Matrix	64	36	
215	Matrix	43	34	Anhydrite
457	Concretion	68	32	
457	Concretion	67	26	
457	Concretion	66	29	
463	Concretion	65	35	
463	Concretion	72	28	
463	Concretion	33	32	Anhydrite
463	Concretion	68	32	

Mars analogue concretions & exhumed channels, Utah

Table 4

Sandstone provenance

Quartz 95%	Feldspar 3%	Clay grains 1%	Amphiboles <1%
Vein 85%	K-spar 1.5%		
Chert 9%	Plagioclase 1.5%		
Metamorphic 1%			

Table 5

Facies Context of Concretions

Lithology	Structures	Degree of cementation	Concretion abundance	Interpreted environments
Conglomerates	Cross-bedding	High	Absent	Very high energy channel
Pebbly sandstones	Cross-bedding	Moderate	Less common	High energy channel
Medium sandstones	Cross-bedding	Moderate	common	Channel
Medium-fine sandstones	Massive to parallel laminated	Moderate	Less common	Splays
Fine sandstones	Rippled	Low	Absent	levees
Shales	Decimetre-scale bedding	Moderate	Absent	floodplain

Mars analogue concretions & exhumed channels, Utah

Table 6

Comparison between Brushy Basin Member and Cedar Mountain Formation

exhumed and inverted channels.

Property	Cedar Mountain[1]	Brushy Basin[2]
Exposed channel length (maximum)	6.7 km	3.2 km
Width	17-89 m	20-100 m
Thickness	~5 m	2-15 m
Lithology	Conglomerates	Medium sands to conglomerates
Cement	Carbonate	Carbonate and silica
Facies	Migrating meandering channels	Fixed anastomosing channels
Age	Early Cretaceous	Late Jurassic

Sources: 1 Harris (1980), Williams *et al.* (2009). 2 This paper.

Table 7

Comparisons between different Mars analogue inverted and exhumed channel sites.

Terrestrial example	Bullengarook[1]	Mirackina[2]	Oman[3]	Robe River[4]	Green River[5]	Hanksville Brushy Basin Member[6]
Morphology	Single fixed channel	Single fixed channel	Distributary meandering channels Distributary braided channels	Single meandering channel	Multiple migrating meandering channels	Multiple fixed anastomosing channels
Channel length	>20 km	~110 km	~25 km ~45 km	~130 km	6.7 km	3.2 km
Width	1.5-2 km	50-90 m	49-108 m 733-1525 m	500-2000 m	17-89 m	20-100 m
Thickness	4 m	30-40 m	3-6 m 3.6 m	80 m	~5 m	2-15 m
Lithology	Basalt over conglomerate	Sandstone	Cobble conglomerate, pebbly sandstone	Pisolitic ironstone	Conglomerate	Fine sandstone to conglomerate
Induration	Basalt infill, silica	Silica	Carbonate	Haematite	Carbonate	Carbonate
Mars example	Juventae Chasma[7]	Miyamoto[8]	Eberswalde[9] and Aeolis[10] fans	Arabia[11]	Eberswalde fan[9]	Aeolis channels[10]

Sources: 1 Ollier and Pain (1995), Pain *et al.* (2007). 2 McNally and Wilson (1995), Pain *et al.* (2007). 3 Miazels 1987, Burr *et al.* (2009). 4

Morris and Ramanaidou (2007) Heim *et al.* (2006). 5 Harris (1980), Williams *et al.* (2009). 6 This paper. 7 Lucchita (2005). 8 Newsome *et al.*

(2010). 9 (Bhattacharya *et al.* 2005). 10 (Burr *et al.* 2009). 11 Pain *et al.* (2007).

Table 8

Comparisons between different Mars analogue concretion sites.

Property	Meridiani[1]	Navajo Sandstone Concretions[2]	WA concretions[3]	Mauna Kea concretions[4]	Hanksville Dakota Concretions[5]	Hanksville Brushy Basin Concretions[6]
Host texture	Sand	Sand	Sand	Breccia	Sand	Sand
Host mineralogy	Altered basalt, sulphates	Quartz	Quartz, sulphates	Altered basalt	Quartz	Quartz
Host facies	Saline lakes & associated dunes	Dune sands	Saline lakes	Cinder cone	Marginal marine sands	Fluvial channels
Concretion mineralogy	Haematite	Haematite	Haematite	Haematite	Goethite	Calcite
Concretion sphericity	Moderate-high	Low to high	Low-moderate	High	Moderate	Moderate-high
Concretion dimensions	1-8 mm (most 2-5)	1-100 mm	100 microns-10 mm	30-40 microns	5-10 mm	3-10 (most 5)
Concretion fabric	Homogeneous to concentric	Homogeneous to concentric	Homogeneous to concentric	Homogeneous-rimmed	Poikilotopic	Poikilotopic
Weathering properties	Weather out	Weather out	Do not weather out	Do not weather out	Do not weather out	Weather out
Extent	10s of km	Km	Km	<1 km	10s of km?	10s of km?
Greatest analogue value		Mineralogy, fabric, host facies, surface expression	Mineralogy, host lithology, host facies	Mineralogy, host lithology	Extent	Extent, sphericity, surface expression

Sources 1 Klingelhofer *et al.* (2004) and McLennan *et al.* (2005). 2 Chan *et al.* (2004). 3 Benison & Bowen (2006) and Benison *et al.* (2007). 4

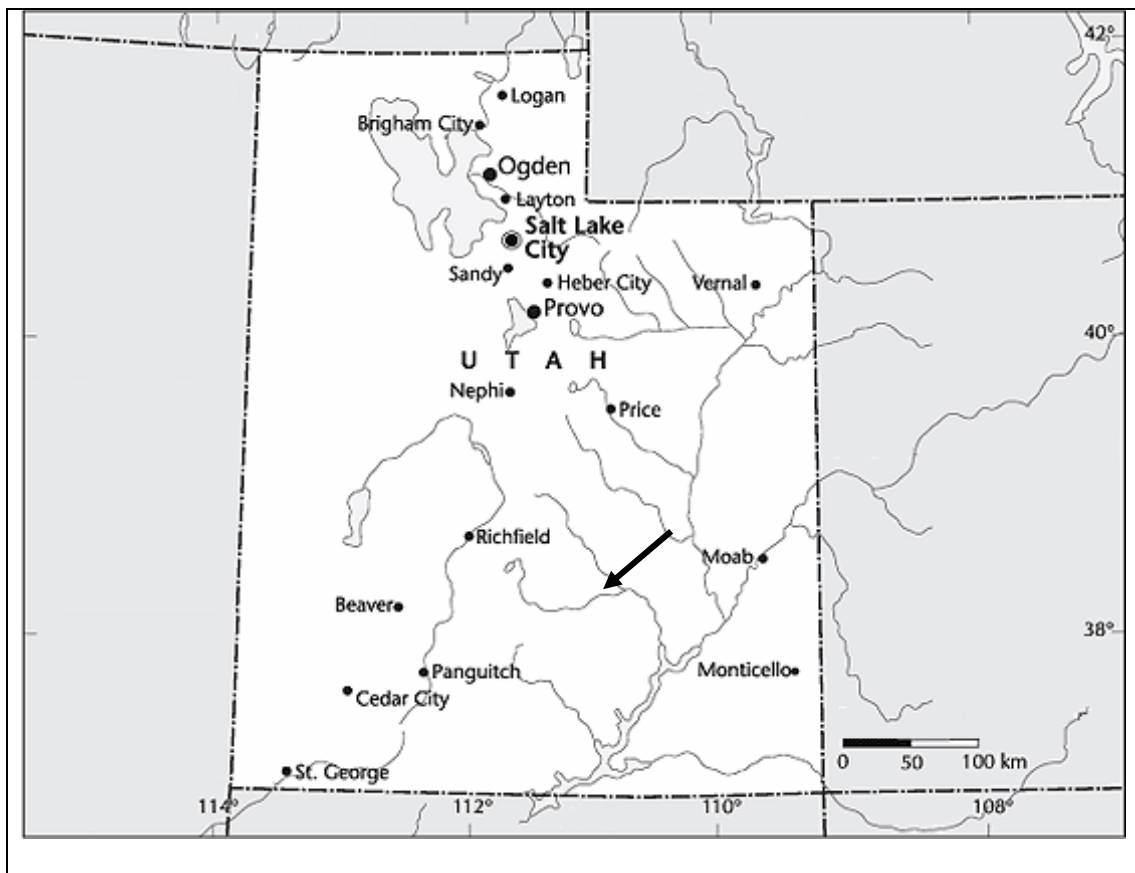Morris *et al.* (2005). 5 Battler *et al.* (2006). 6 This paper.

Figures

Figure 1. Map showing location of study area in Utah (arrowed).
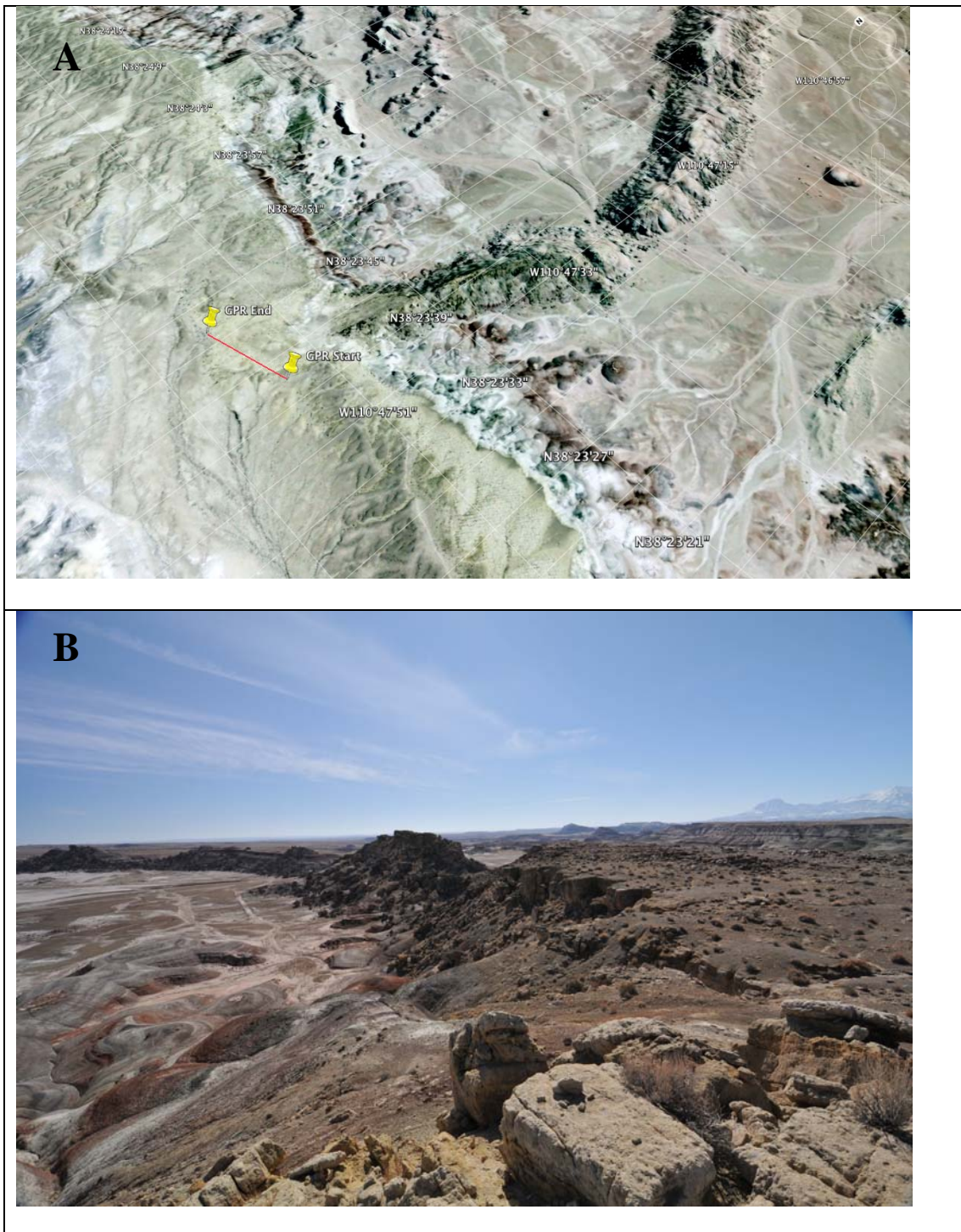
Figure 2. A) Oblique Google earth imaging showing western end of "Kissing Camel Ridge" formed by exhumation of a fluvial channel within the Brushy Basin member of the Morrison Formation and the position of GPR traverses along interpolated un-exhumed extension of the channel. B) View east along Kissing Camel Ridge from the western end.
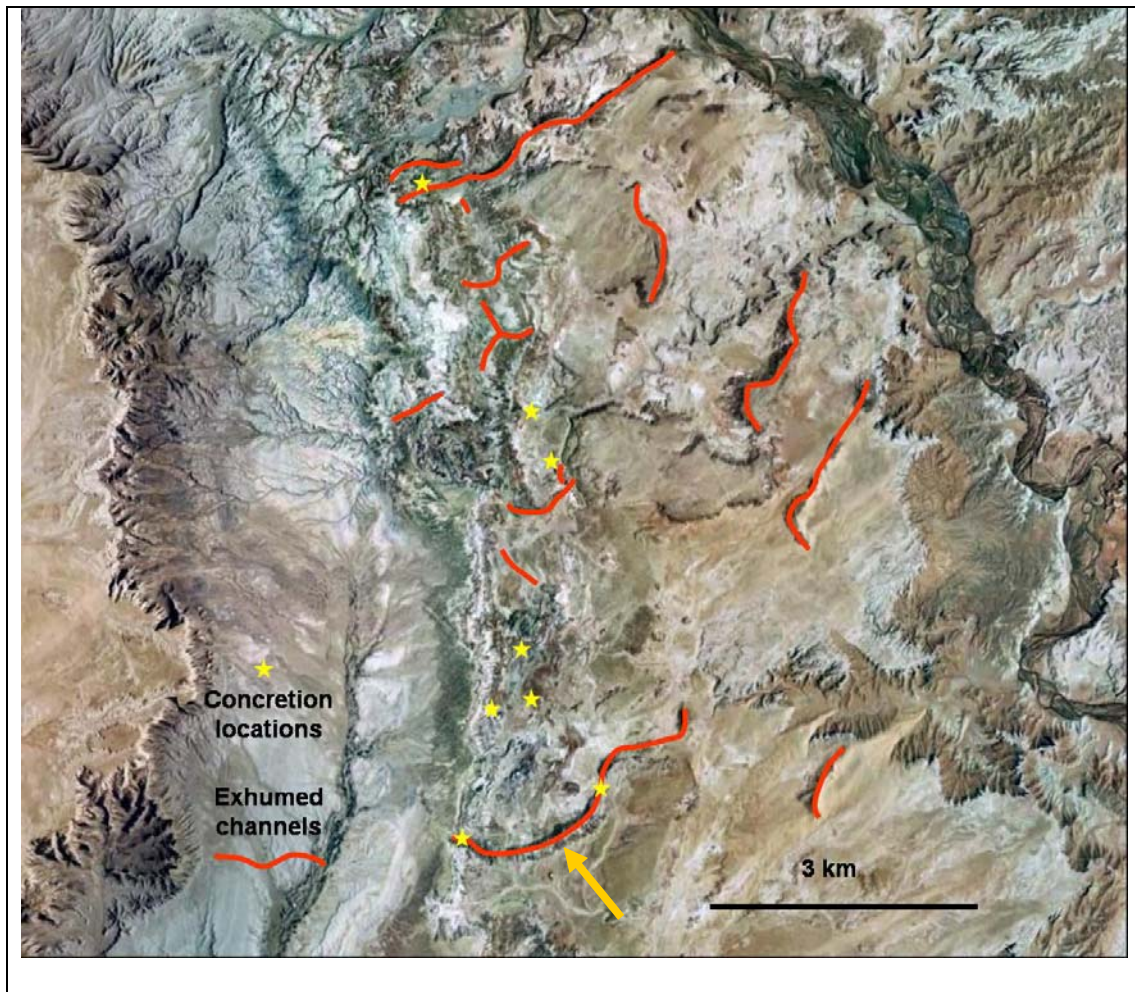
Figure 3. North-east flowing exhumed and inverted anastomosed palaeochannels in the study area with sample concretion locations marked. Flow direction is to the northeast. KCR arrowed.
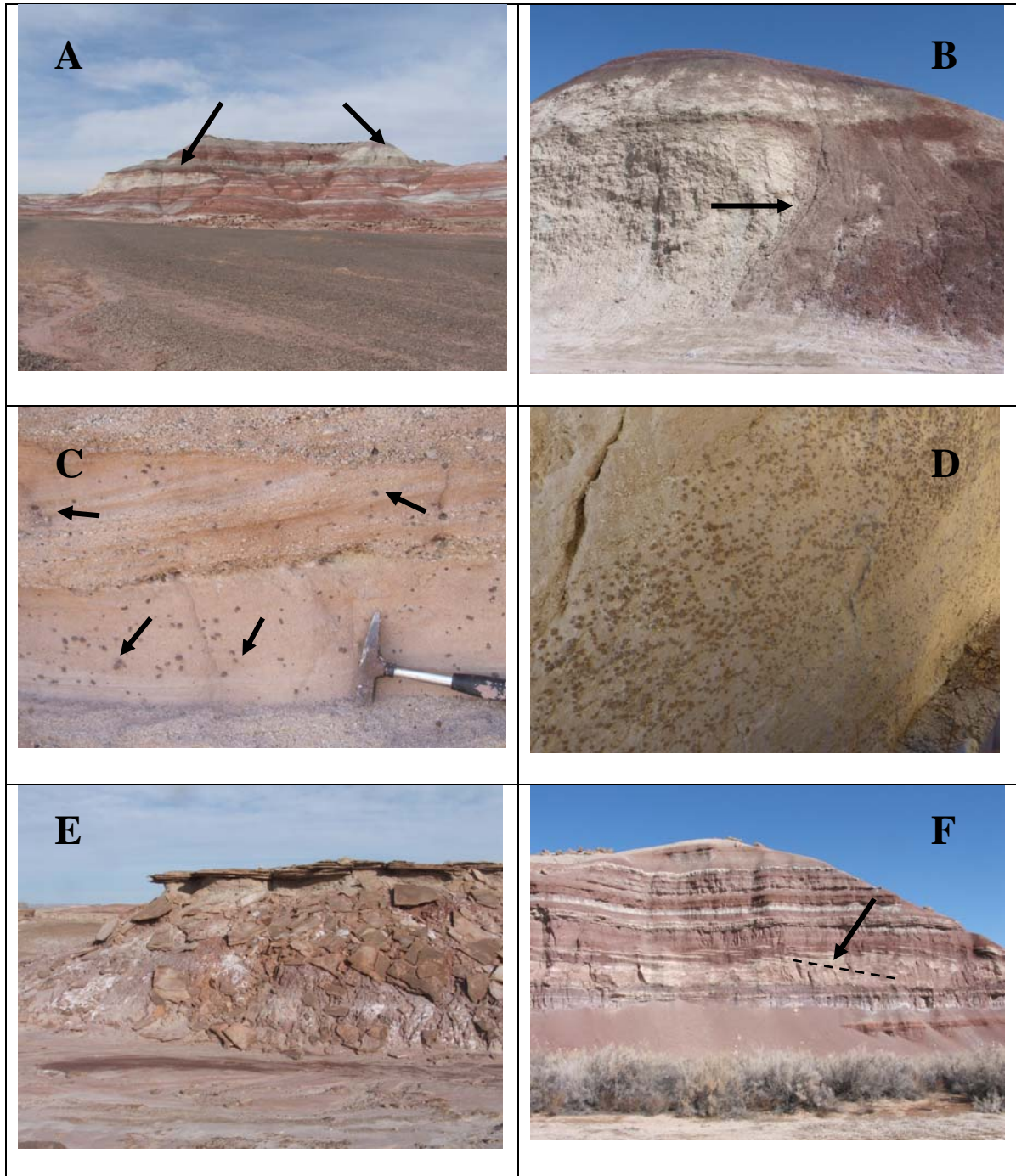
Figure 4. A Two channels (arrowed), part of anastomosing channel complexchannels

~100 m wide. B Edge of channel unit ~5 m thick (arrowed) exposed on side of rise. C

Concretions (some arrowed) in pebbly sandstone. D Cluster of brown-weathered in

channel sandstone. E Thinly bedded laminated sandstone of crevasse splay facies. F

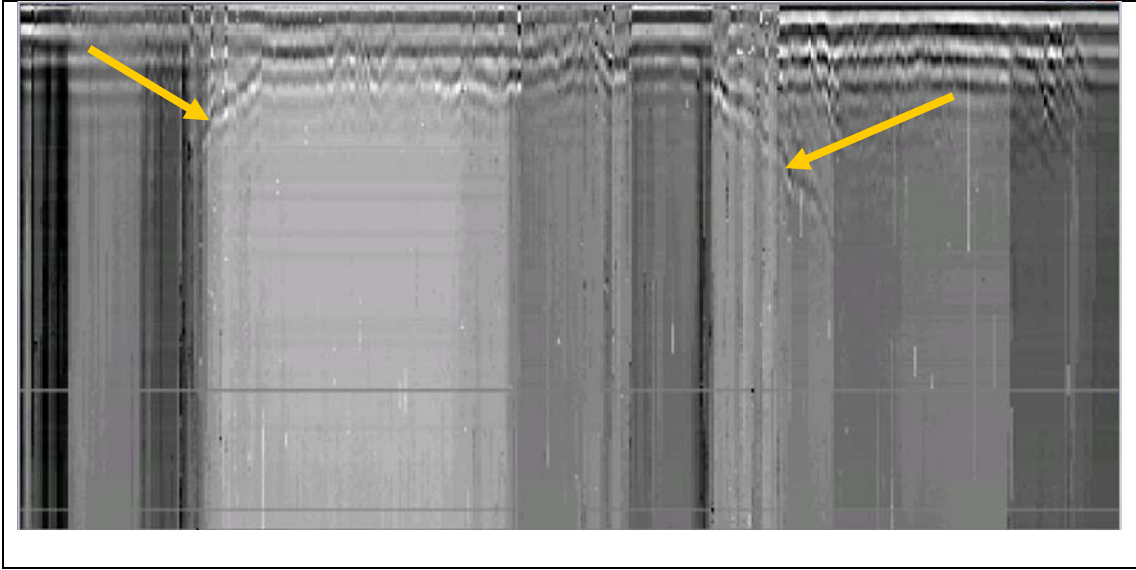Lateral accretion surfaces of meandering channel facies (arrowed and outlined).

Mars analogue concretions & exhumed channels, Utah

Figure 5. A GPR traverse to west of KCR with edges of channel arrowed.

Mars analogue concretions & exhumed channels, Utah

Figure 6. A 5-10 mm concretions weathering out of fine sandstone. B Slope mantled by loose concretions. C. brown weathering concretions and vein-fill of the same material. D vertical fracture (dashed line) acting as permeability barrier to concretion forming fluids present on right but not left.
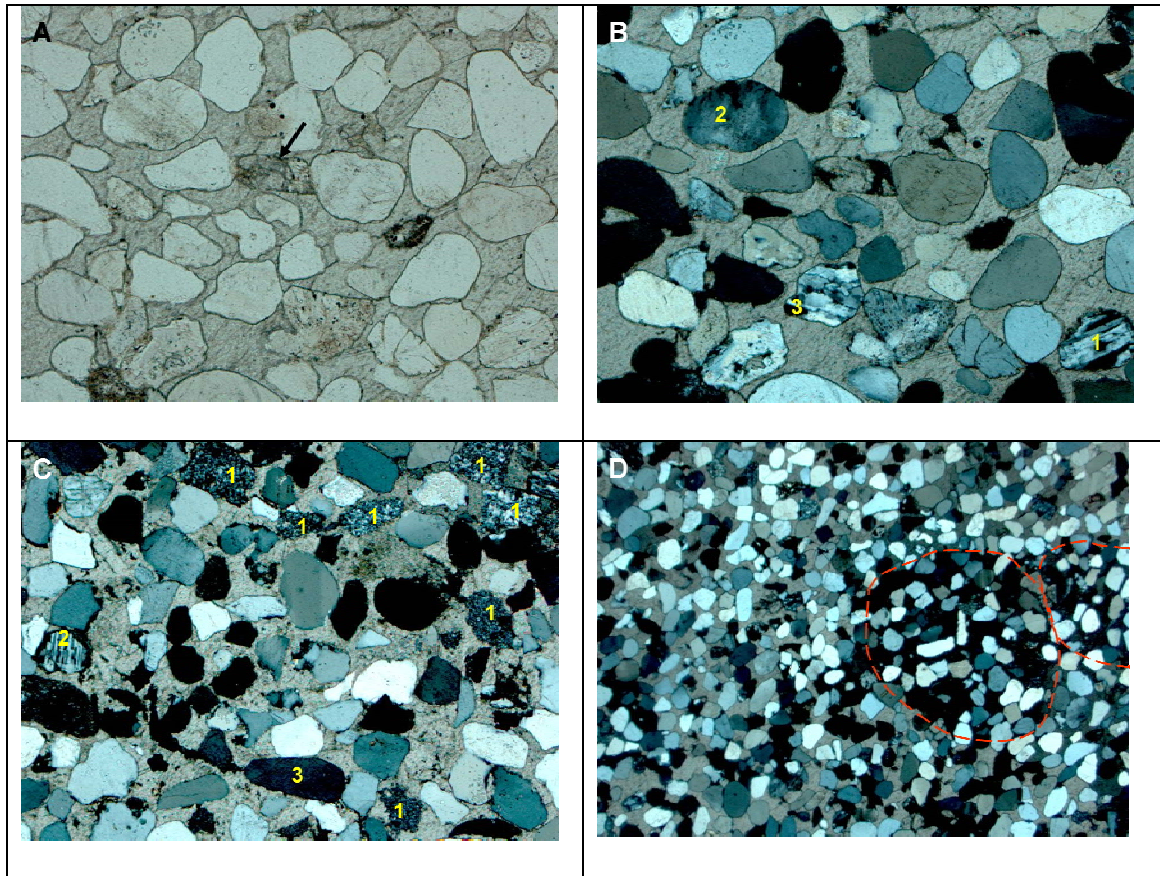
Mars analogue concretions & exhumed channels, Utah

Figure 7. Photomicrographs of concretionary sandstones. **A** – sample 215, plane light, field of view 1.25 mm. Well-rounded sand grains in calcite cement. Calcite-replaced amphibole arrowed. **B** - sample 215, cross-polarised light, field of view 1.25 mm. Grain 1 is plagioclase, grain 2, metamorphic quartz, grain 3 polycrystalline quartz. Other grains, apart from calcite-replaced amphibole in centre, are vein quartz. Poikilotopic calcite cement encloses the grains. **C** - sample 463, cross-polarised light, field of view 1.25 mm. Grains marked 1 are chert, grain 2, plagioclase, grain 4 potassium feldspar (orthoclase). Other grains are vein quartz. Poikilotopic calcite cement encloses the grains. **D** - sample 215, cross-polarised light light, field of view 7.8 mm. Circled area areas of poikilotopic calcite cement undergoing simultaneous extinction. On weathering and surface erosion these domains will form spheroidal concretions.
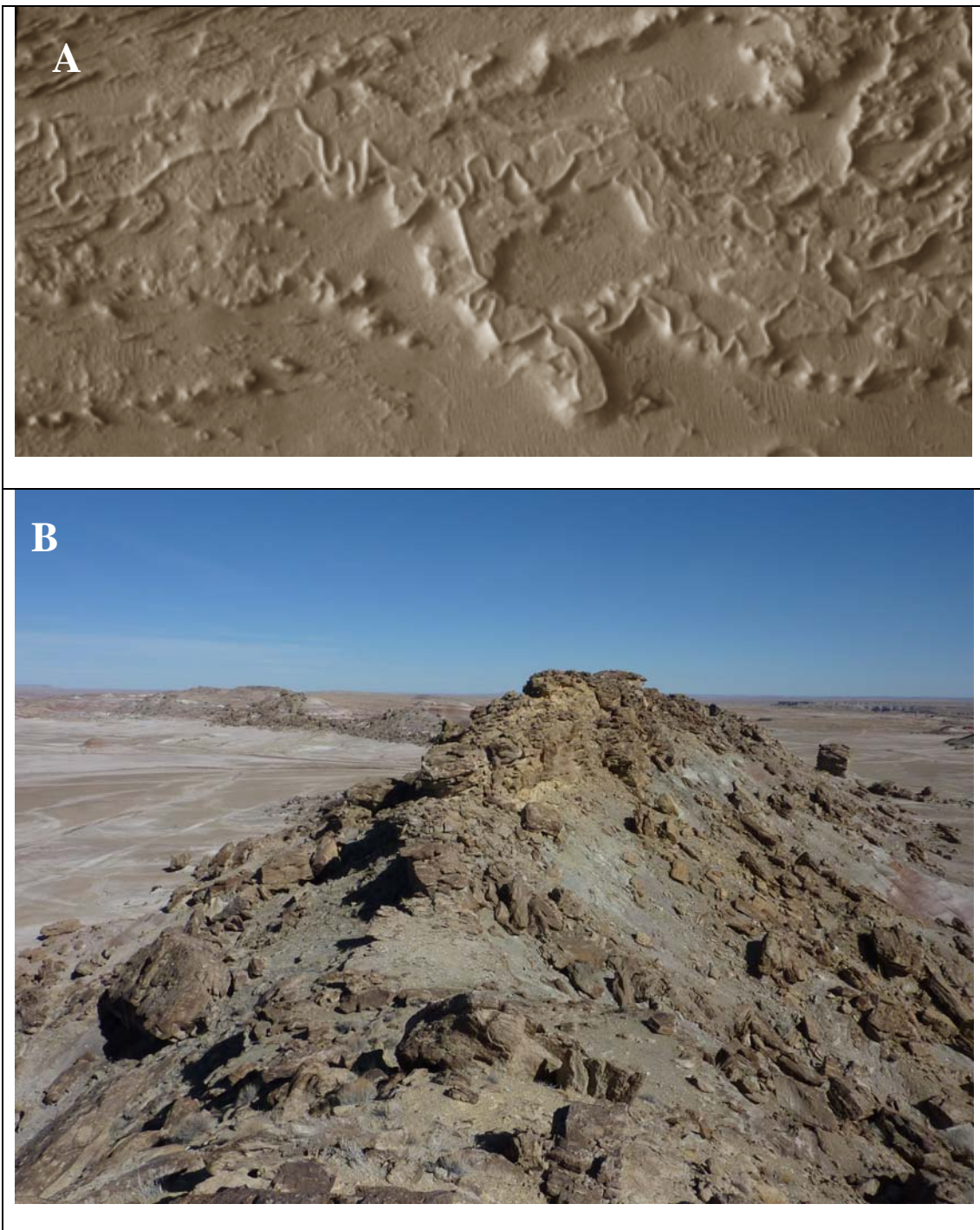
Mars analogue concretions & exhumed channels, Utah

Figure 7. Comparison of terrestrial and martian channels. A: Inferred anastomosing fixed channels in Aeolis, from Themis Image V05875001. B Fifty-metre high silicifed fixed anastomosing channel of KCR, MDRS site.
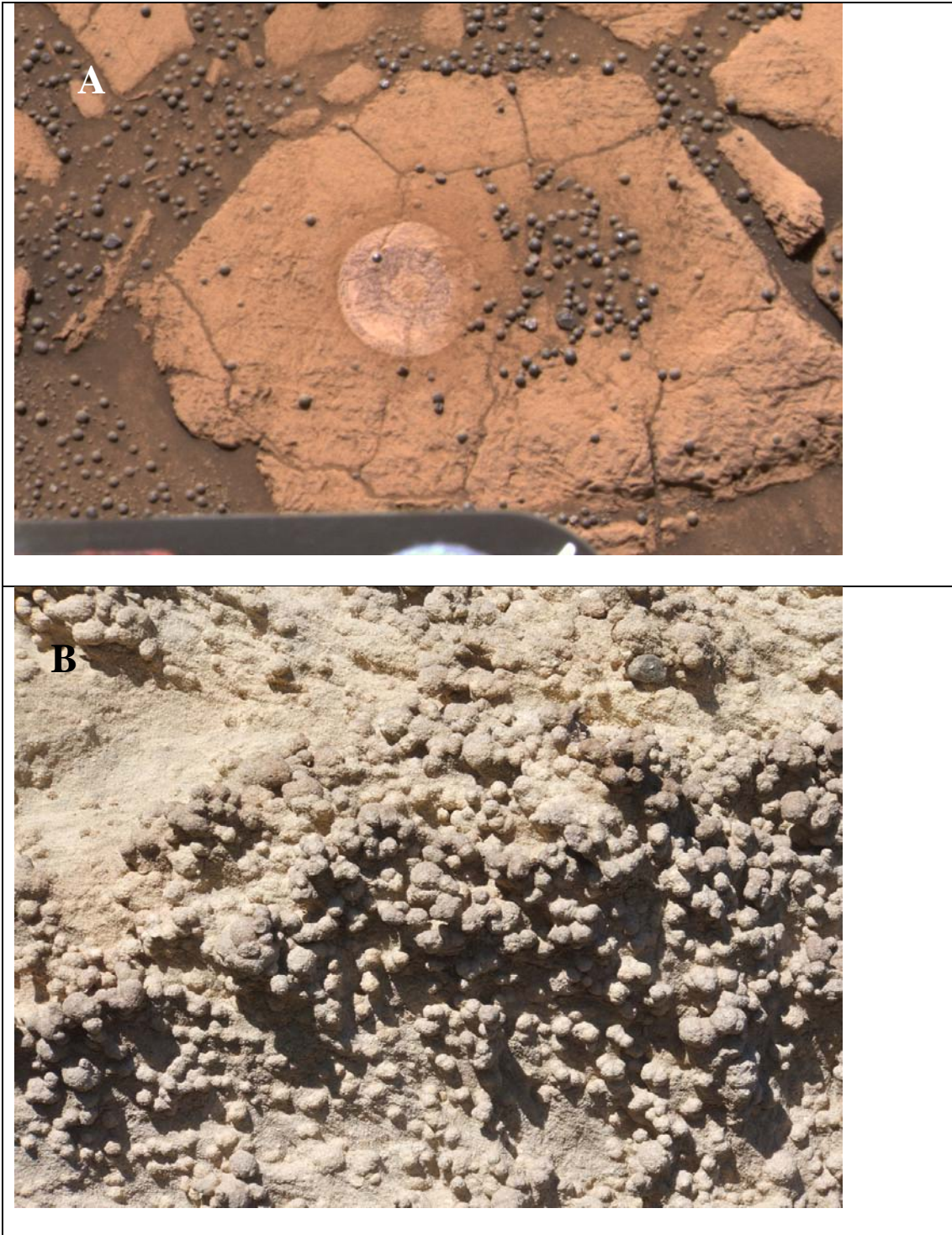
Figure 8. A *In situ* and remobilised concretions at "Berry bowl" location (Eagle Crater), Meridiani Planum (NASA image). B *In situ* concretions on side of KCR, diameter 5-10 mm.

Mars analogue concretions & exhumed channels, Utah

Figure 10. Typical difficult terrain making up inverted and exhumed channels. Photo courtesy Line Drube.