Bulk hydrogen content of high-silica rocks in Gale Crater, Mars with the active Dynamic Albedo of Neutrons experiment

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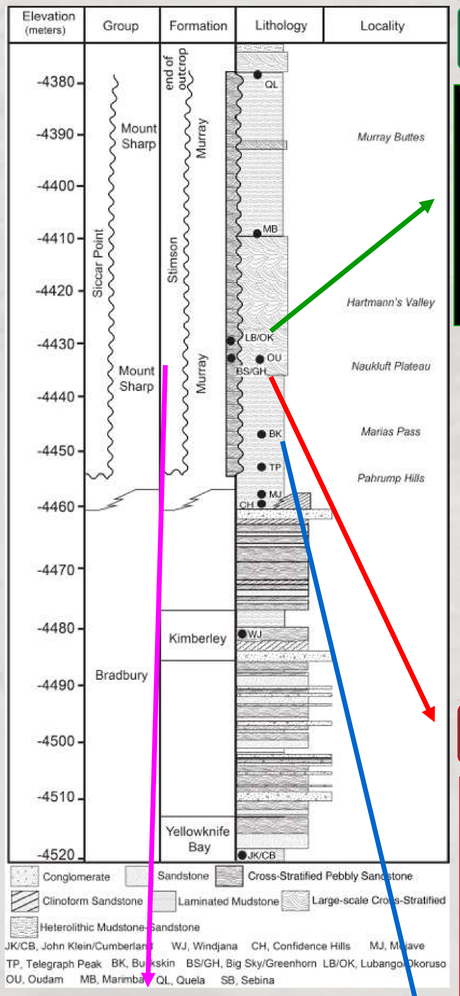
Background

The Dynamic Albedo of Neutrons (DAN) instrument is a neutron spectrometer on the Mars Science Laboratory (MSL) Curiosity rover. DAN is sensitive to thermal and epithermal neutrons that have undergone atomic scattering in the soil. In active mode DAN produces neutrons using a Pulse Neutron Generator which allows counts to be binned by their arrival time at the detectors. Neutron absorbers (Cl, Fe, Ni, Mn, etc.) and scatterers (primarily H) in the soil change the neutron response measured by DAN detectors. We acquire data at every rover stop in addition to dedicated campaigns, providing a wealth of information at locations where fewer targeted observations are made. The field-of-view extends ~3 meters in diameter on the surface at the rear of the rover and ~50 cm in the subsurface, uniquely probing both geochemistry and stratigraphy at depth.

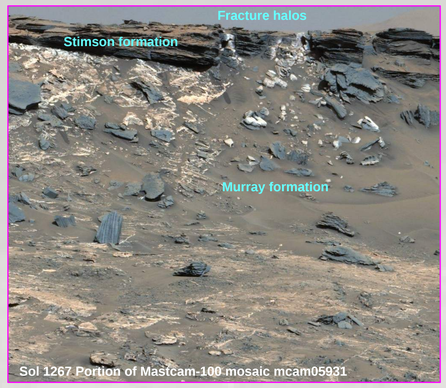
High-silica rocks were observed in the Murray and Stimson formation, which have a discernable effect on DAN data. Murray is composed of finely laminated mudstone which suggest the sediments were deposited in a subaqueous lacustrine environment. The Stimson formation is a draping strata of cross-bedded aeolian sandstones that uncomformably overlies the older Murray. Light-toned rock was first observed in Murray, which had high abundances of silica and depletion of Fe, Mn, Zn, Cl, and Ni suggesting leaching via a low-ph fluid environment. Tridymite, a high temperature polymorph of silica, was also observed in high-Si Murray which suggests a volcanic detrital origin. Throughout the Stimson, high-Si rock was observed in the form of halos surrounding lineaments of fractures. Alteration halos may connect down to high-silica rock in the Murray which would indicate a cogenetic origin.

We aim to estimate the hydration state of high-silica material and their stratigraphic distribution to help uncover the timing and extent of recent fluid-processing events in Gale Crater, Mars.



Murray-Stimson Outcrops

- At the Murray-Stimson contact, alteration halos may be seen to reach down to the Murray below, suggesting a cogenetic relationship [2].



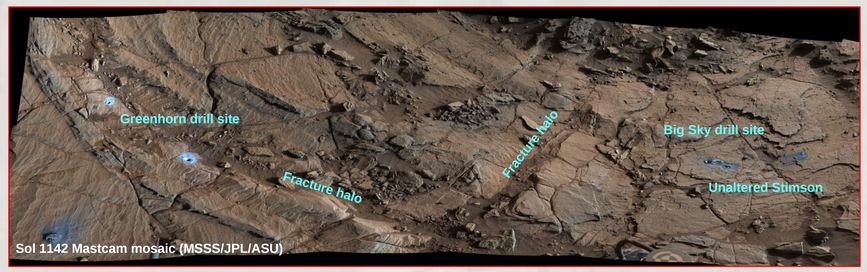
Sol 1267 Portion of Mastcam-100 mosaic mcam05931

Sol 1316-1329 – Naukluft Plateau (Stimson formation) Fracture halo at Lubango/Okoruso drill sites

Mastcam mosaic acquired on Sol 1316 (MSSS/JPL/ASU)

- A recent alteration halo investigation occurred at the drill sites of "Lubango" (halo rock) and "Okoruso" (off-halo rock). Okoruso is not pictured above.
- These light-toned features follow fracture lineaments surrounded by more intact rock.
  - They extend up to tens of meters laterally and vary in width from a few to several decimeters, sometimes cross-cutting one another.
- The Alpha Particle X-ray Spectrometer (APXS) on Curiosity rover shows halos to be enriched in Silica, and depleted in metals *e.g.* Fe, Mn, Ni, and Cr [1,2].
  - The Lubango halo showed that this altered Stimson rock had a significant amorphous component, 73wt% as compared to 35wt% in Okoruso [2].
  - Chemcam finds that the amorphous component has a significant abundance of opal-a with ~5-7wt% H_2O, which is a relatively high value with respect to the bulk hydrogen estimates in DAN active measurements thus far [3,4].

Sol 1127-1143 – Naukluft Plateau (Stimson formation) Fracture halo at Greenhorn/Big Sky drill sites

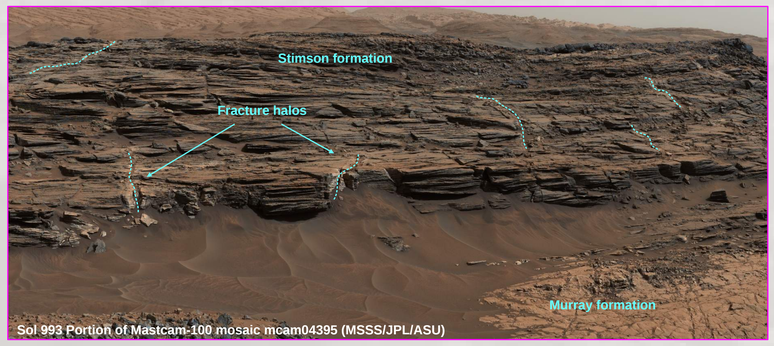


Sol 1142 Mastcam mosaic (MSSS/JPL/ASU)

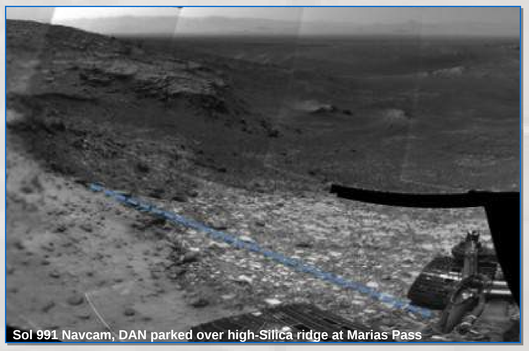
- Earlier in the mission, high-Si fracture halos at the "Greenhorn" (halo rock) and "Big Sky" (off-halo rock) drill sites were studied.
  - Greenhorn was less depleted of metals than Lubango and had a smaller amorphous component (65 wt%) suggesting the alteration process was less extensive here.

Sol 987-997 Marias Pass – high-Si near Buckskin drill site

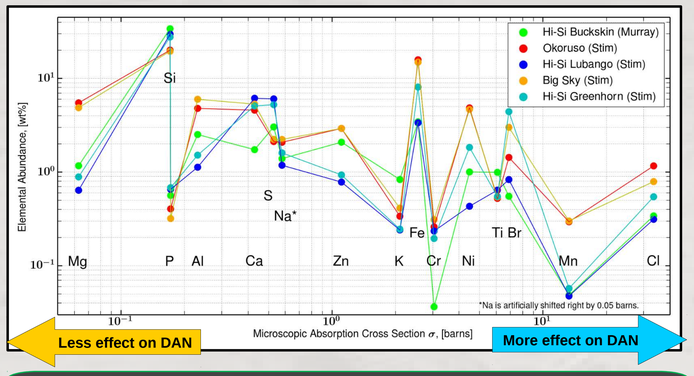
- High-Si rock was first discovered at Marias pass in large areas of light-toned bedrock (Buckskin drill site) and later seen in fracture-associated halos in the Murray.
- The Buckskin drill site contained an X-ray amorphous component of ~60wt%.
  - The amorphous component is ~39 wt% opal-A (or high SiO_2 glass) and opal-CT [5].
  - Opal could form via low-ph, leaching environment or as a precipitate from the diagenesis of high SiO_2 glass [5].
- Chemin analysis of Buckskin shows the existence of Tridymite a high-temperature (>870˚ C) polymorph of SiO_2 that is generated efficiently by silicic volcanism [5].
- Separate mechanisms may be required to explain the high-Si fracture halos in the Murray and the zones of altered bedrock that contain Tridymite. [2,5]



Sol 993 Portion of Mastcam-100 mosaic mcam04395 (MSSS/JPL/ASU)

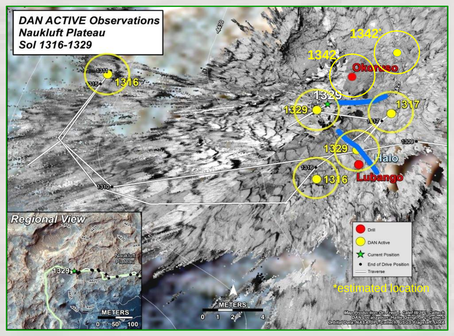

Sol 991 Navcam, DAN parked over high-Silica ridge at Marias Pass

Geochemical abundances vs neutron absorption cross section

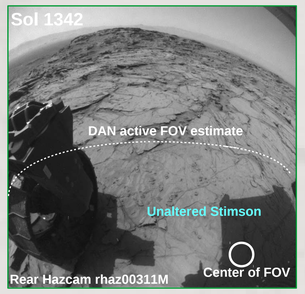


- A neutron's energy is reduced (moderated) when scattering on a nucleus (most efficiently on Hydrogen).
- DAN detectors are sensitive to thermal and epithermal (low energy) neutrons that have been moderated by the soil.
- High-Si rocks are depleted in neutron absorbers, which allows them to be distinguished by DAN.
- Alteration halo measurements show a significant **increase** in the neutron flux. This could be due to a lack of neutron absorbers and/or elevated hydrogen.

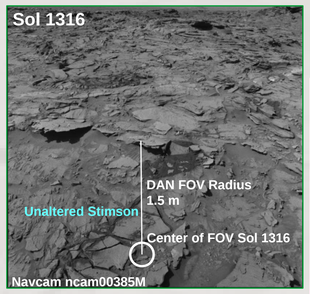
DAN active campaign at Lubango/Okoruso



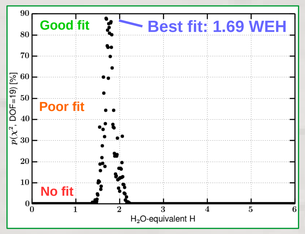
- On sol 1316 and 1342 we obtained DAN active measurements over unaltered Stimson adjacent to alteration halos.
  - On sol 1329 we obtained a dedicated DAN active measurement over an alteration halo (Lubango drill site).
- Hazcam and Navcam images (below) show a portion of the DAN FOV.
  - On sol 1316 and 1342 unaltered Stimson encompassed the FOV.
- Using the Monte-Carlo N-Particle eXtended (MCNPX) code, we model the underlying geochemistry and the DAN instrument.
  - Unlike models that assume a bulk-Mars geochemistry, we use APXS-derived geochemical abundances from nearby drill sites to make more precise hydrogen abundance estimates.

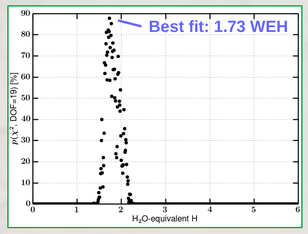


Rear Hazcam rhaz00311M

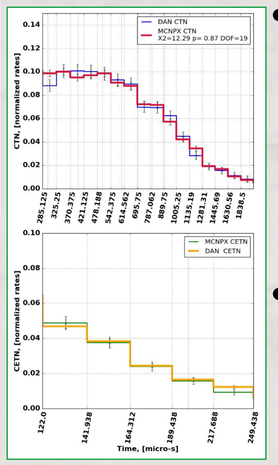


Navcam ncam00385M



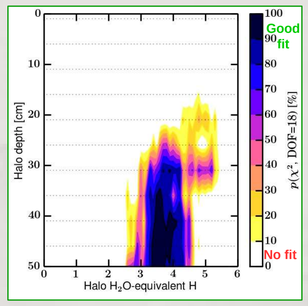


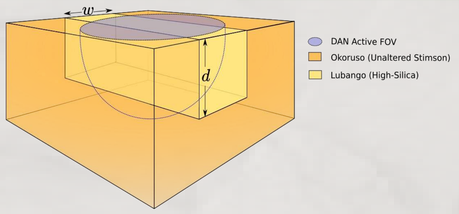
Sol 1316 DAN active data vs best-fit model



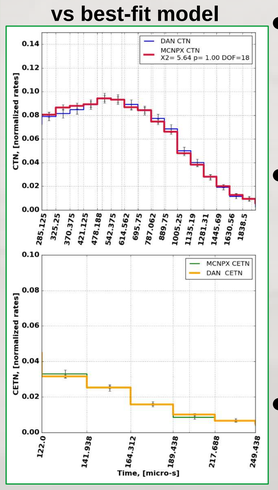
- We vary hydrogen abundance by 0.01 water-equivalent hydrogen (WEH) and hold all else constant, generating 1000's of simulation results.
  - On sol 1316 and 1342, the geochemistry of the nearby Okoruso drill site is used in MCNPX.
- Both areas show a similar hydrogen content, despite being on opposite sides of the fracture.
  - This suggests we have a good hydrogen estimate of unaltered Stimson in the vicinity of the halos.

Rear Hazcam rhaz00305M





Sol 1329 DAN active data vs best-fit model



- On sol 1329, altered material encompasses a fraction of the DAN FOV.
  - This fraction is proportional to the width of the halo.
- We model an idealized, 2-layer geometry where the top is a mixed abundance of Okoruso and Lubango, that overlies unaltered Stimson (Okoruso).
  - Unaltered Stimson is held at a constant 1.73 WEH.
- Modeling heterogeneities, ***where appropriate***, yields appreciably different results from homogeneous models.

Preliminary Results, Gabriel et al. *In prep.*

- We find the **Lubango alteration halo is hydrogen rich (3.4 - 4.3 WEH)** with respect to the surrounding unaltered Stimson **(1.66 - 1.82 WEH)**. *These values may change slightly in further modeling.*
  - This is consistent with a genesis by fluid alteration and with the measurements of opal abundances by Chemcam and Chemin [2,3].
- We find the **Lubango halo is not surficial. It extends at *least* ~30cm deep, down to our FOV depth limit (~50 cm).**
  - This is *consistent* with the halos extending deep, potentially to the Murray.
- We **developed a refined data processing method** based on [3] and demonstrated how **DAN active can be used to uncover stratigraphic information**, provided the rocks have a sufficiently varied abundance of neutron moderators.
- **Future study: Do fracture-associated halos extend to the underlying Murray? Is the underlying Murray altered? Do less-altered halos show correspondingly lower hydration?**
  - More measurement localizations and modeling required!

References: [1] Frydenvang *et al.* (2017) *In prep.* [2] Yen, A.S. *et al.*, (2017) *Submitted*. [3] Rapin, W. *et al.*, (2017), *LPSC*. [4] Litvak, *et al.* (2016) *JGR:P*, 151, 5, 836-845. [5] Morris, R.V., (2016) *PNAS*, 113, 7071.

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