Karst Phenomena in the Northern Black Hills Area, South Dakota and Wyoming / USA

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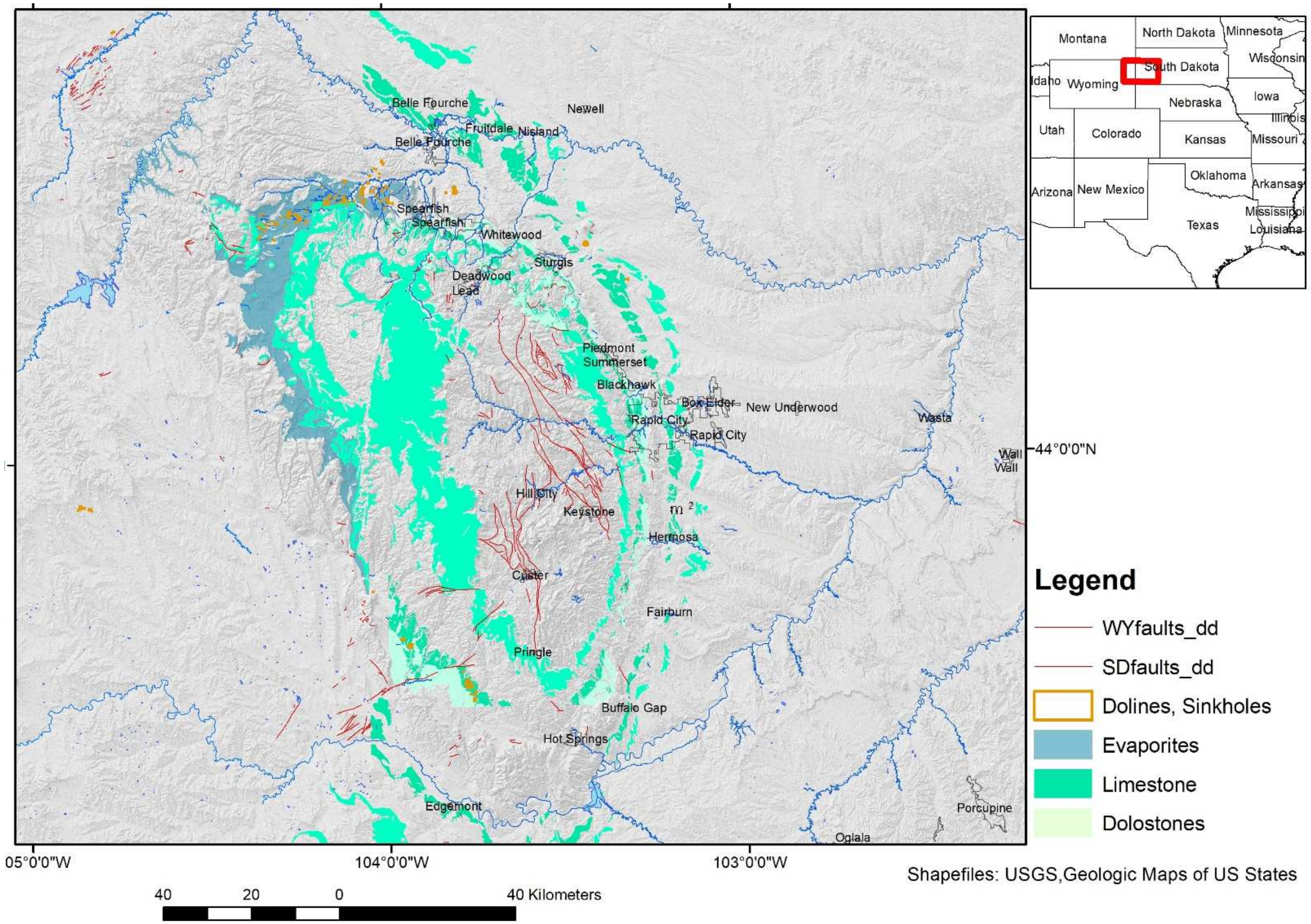
03.04.2018

Karst Phenomena in the Black Hills and Adjacent Areas

Rock Units prone to Karstification – Shapefiles provided by USGS

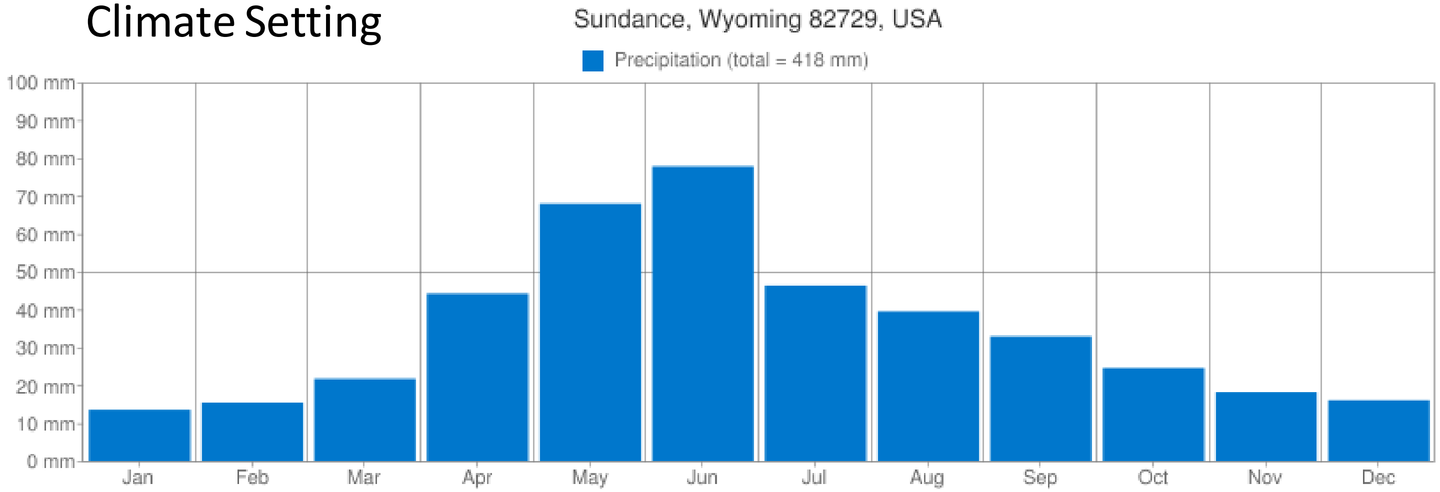


Class caves, sinking streams, and other karst features are found in limestones, gypsum and dolomites. Dissolution of gypsum and anhydrite in four stratigraphic units in the Black Hills, South Dakota and Wyoming, has resulted in development of sinkholes. Subsidence has caused damage to houses and water and sewage retention sites. Evaporite karst has developed extensively in the anhydrite and gypsum in the Minnelusa, Spearfish, and Gypsum Spring Formations (Epstein and Putnam, 2005).

The water table and the amount of water availability influence the karst development which will be affected, thus, by climate change.

Martin, J. E., Swyer, J. F., Fahrenbach, M. D., Tomhave, D. W., and Schulz, L. D., 2004, Geologic Map of South Dakota: South Dakota Geological Survey

Climate Setting



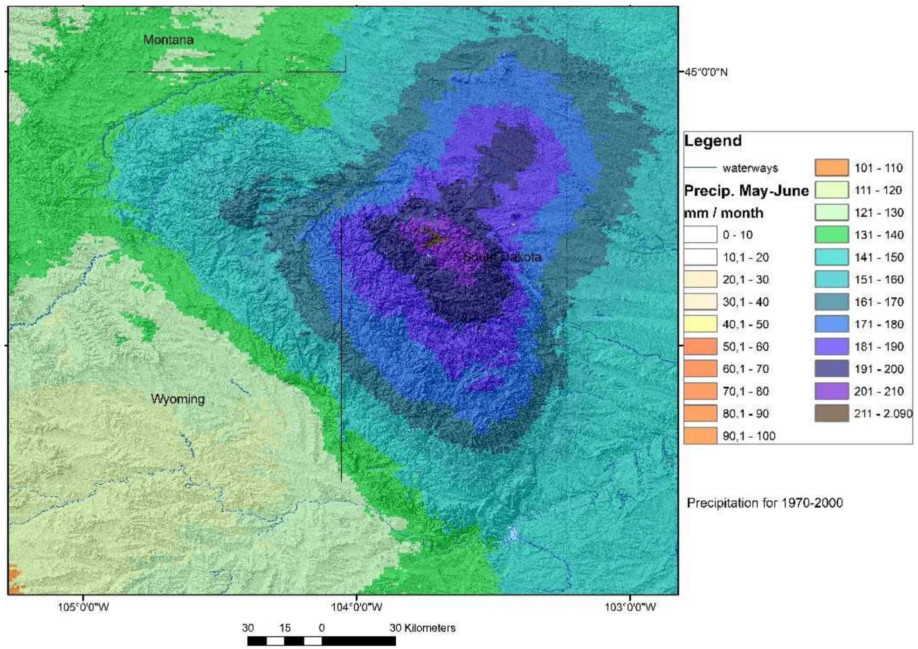
Month	Rainfall (mm)
January	14
February	15
March	22
April	44
May	68
June	78
July	46
August	40
September	33
October	25
November	18
December	16
Year	**418**

SamSamWater Climate Tool

Name of location (approximately): Sundance, Wyoming 82729, USA
Latitude: 44.39899 (decimal degrees)
Longitude: -104.36739 (decimal degrees)
Altitude: (m above mean sea level)

Average precipitation (in mm or liter per m²) for this location is listed in the table on the left..

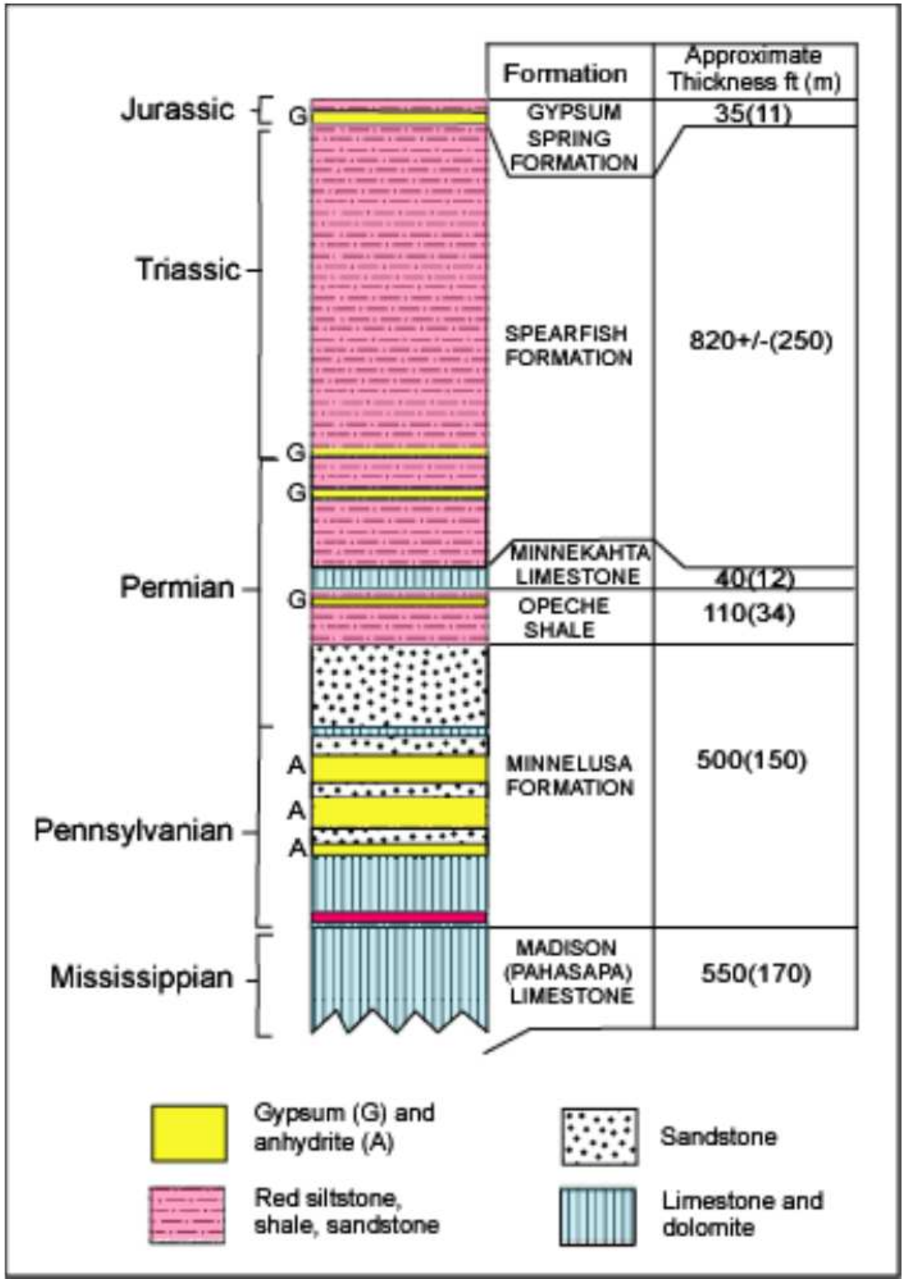
https://www.samsamwater.com/climate/climatedata.php?lat=44.39899&lng=-104.36739&loc=Sundance%2C+Wyoming+82729%2C+USA



Precipitations in May – June for 1970-2000, http://worldclim.org/version2

Source of data: CRU CL 2.0 which is described in New, M., Lister, D., Hulme, M. and Makin, I., 2002: A high-resolution data set of surface climate over global land areas. Climate Research 21:1-25 and Aquastat.

Stratigraphic Column showing Distribution of Gypsum and Anhydrite in the Northern Black Hills



The dissolution process of the subsurface materials causes collapse of the overburden materials resulting in the formation of sinkhole depressions and caves. These dissolution processes depend on surface water input that will be affected by climate change. Flash floods, less snow cover and more humid winters will have an impact on karstification processes and, thus, on sinkhole-, solution fissures- and on cave-development.

A sinkholes inventory map is one of the main steps in sinkhole susceptibility analysis, hazard evaluation, and risk management. Different types of distinguishing surface features can be used in recognizing the karst landforms using field research as well as high resolution remote sensing data such as ArcGISEarth and Google Earth. The investigations are focused on the detection of ring / circular and oval features and depressions or sinkhole clusters.

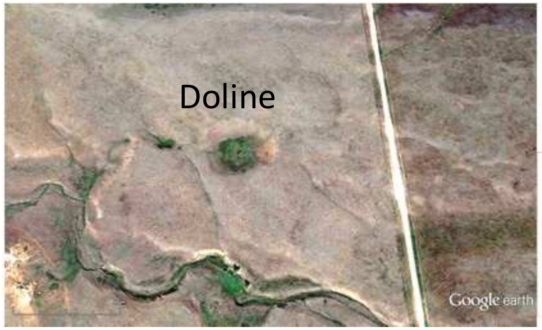
Jack B. Epstein, Daniel H. Doctor (2013): Evaporite Karst in the Black Hills, South Dakota and Wyoming, and the Oil Play in the Williston Basin, North Dakota and Montana. 13th Sinkhole Conference, NCKRI SYMPOSIUM 2,161-176, http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1124&context=sinkhole_2013

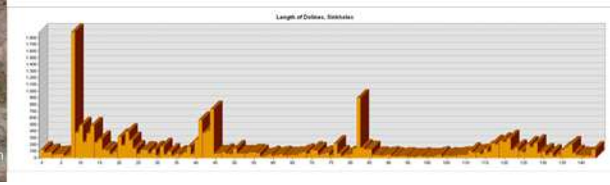
Inventory of Karst Features → **Spatial Analysis** → **Sediment Fill Analysis**

Inventory of Karst Features
Remote sensing inventory based on different satellite data

Spatial Analysis
GIS integrated spatial and geostatistic analysis, morphometric analysis of dolines (slope angle, depth, contour)

Sediment Fill Analysis
Field research: sedimentologic analysis of sinkhole bottom sediments, morphometric inventory, vegetation research





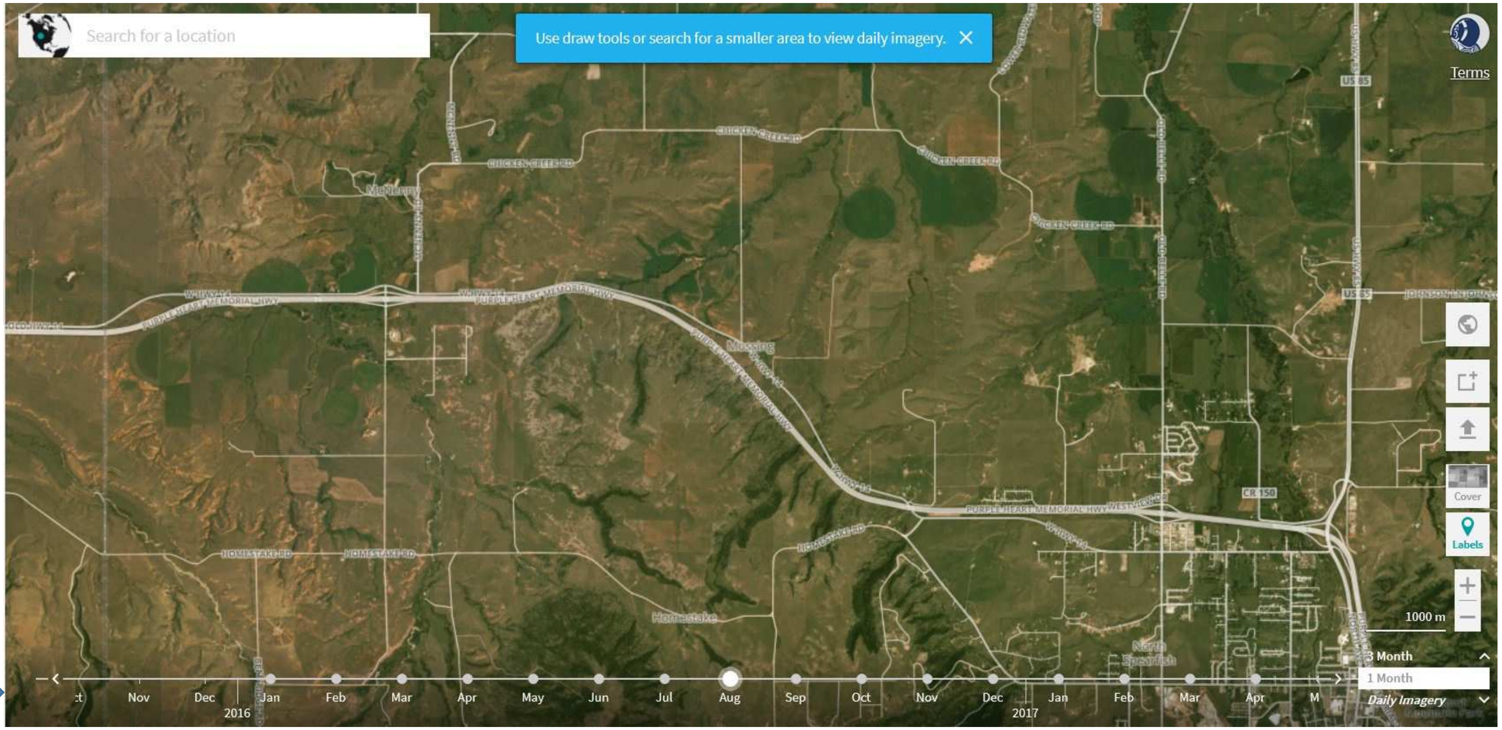
Impact of Climate Change on Karstification Processes

Climate change might affect the following factors influencing karstification:

- Vegetation condition and cover
- Morphometric properties of dolines and depressions due to changing morphodynamic conditions (slope degree, depth, etc.)
- Sediment input into sinkholes as response to heavy rainfall
- Solution processes
- Weathering processes, soil development

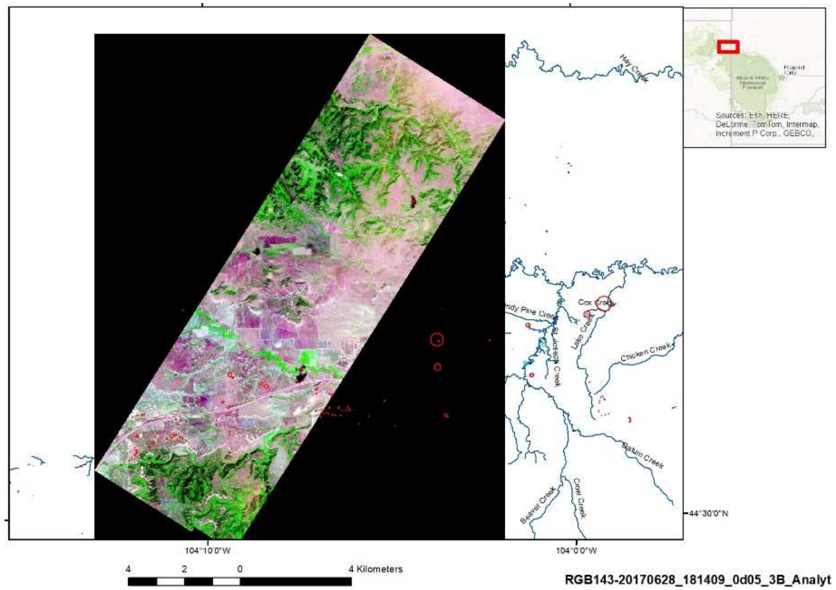
Monitoring seasonal Changes and Changes over Decades

Seasonal changes



https://www.planet.com/explorer/#/center/-103.954,44.539/zoom/13/mosaic/global_monthly_2016_08_mosaic

This research is supported by the Planet Education and Research Program of Planet (Planet Team (2017). Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA. https://api.planet.com by providing RapidEye-scenes and PlanetScope-images of the Northern Black Hills, especially time series for change detection.



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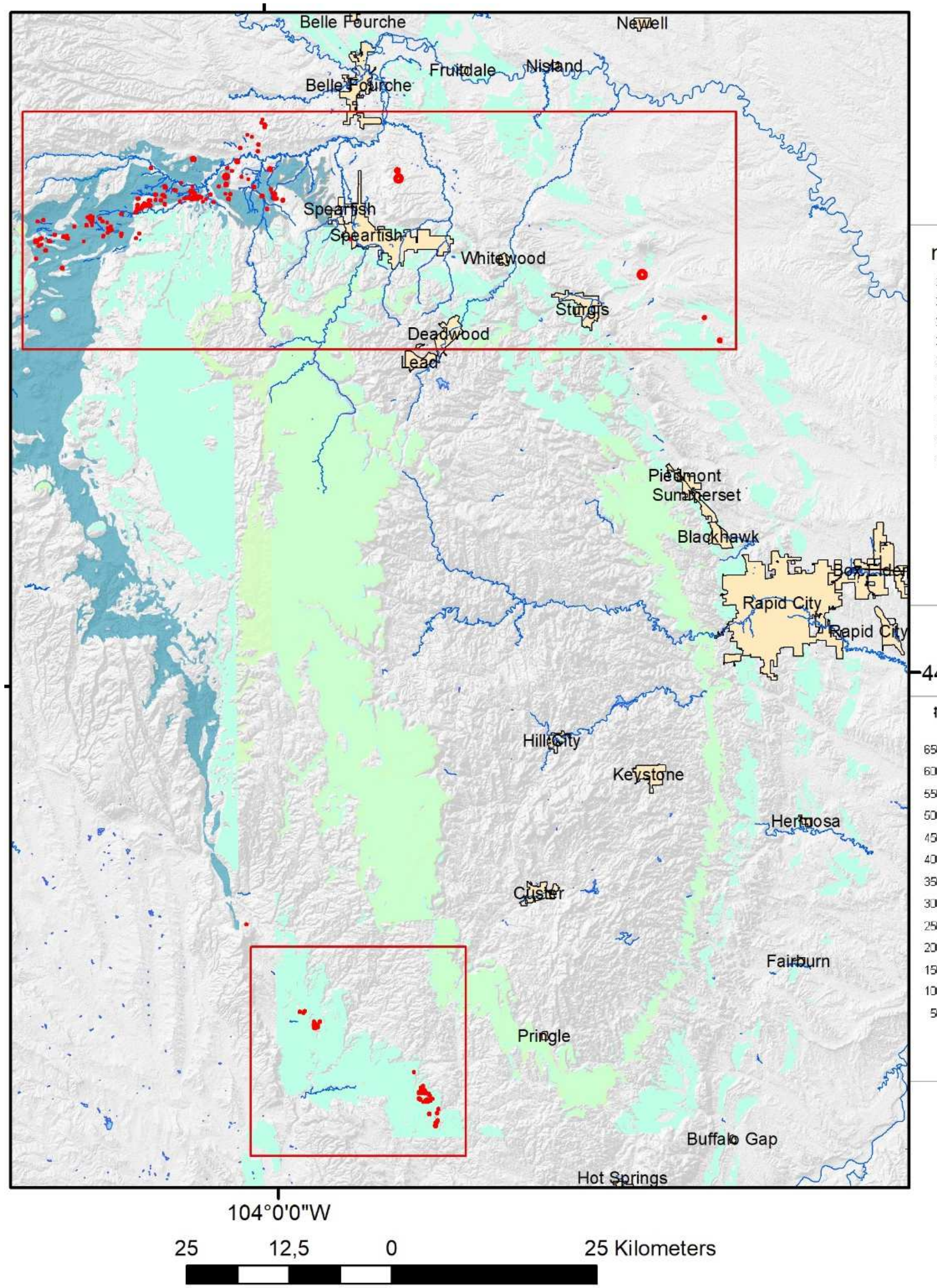
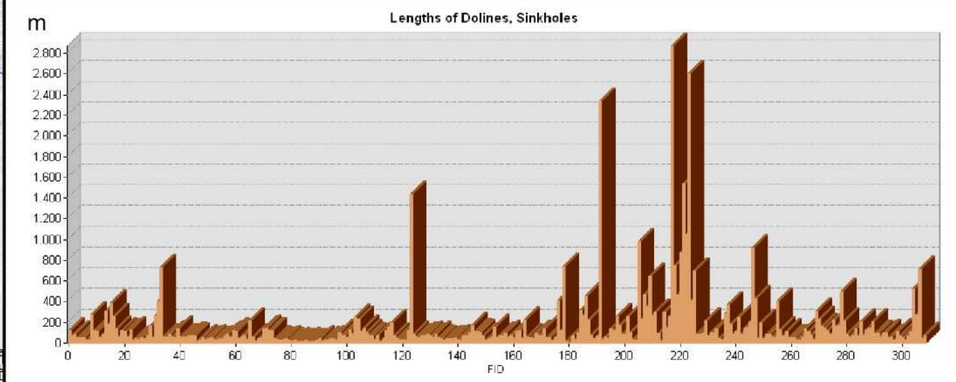
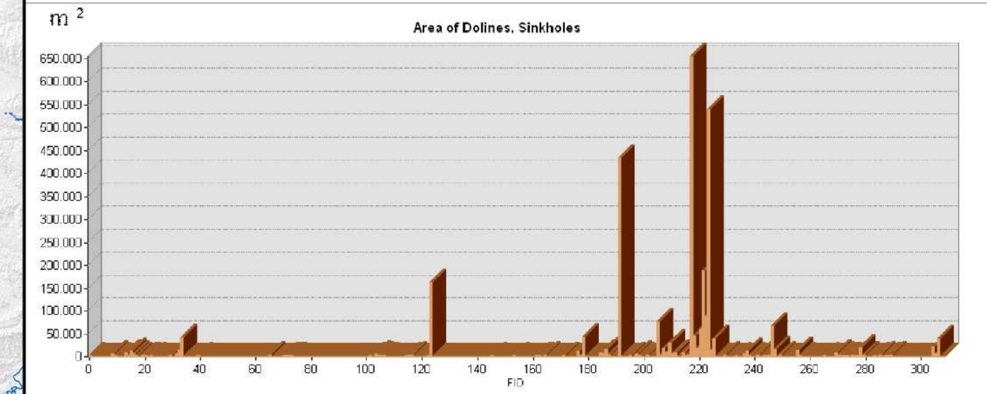
Morphometric Analysis of Circular Features derived from Satellite Images

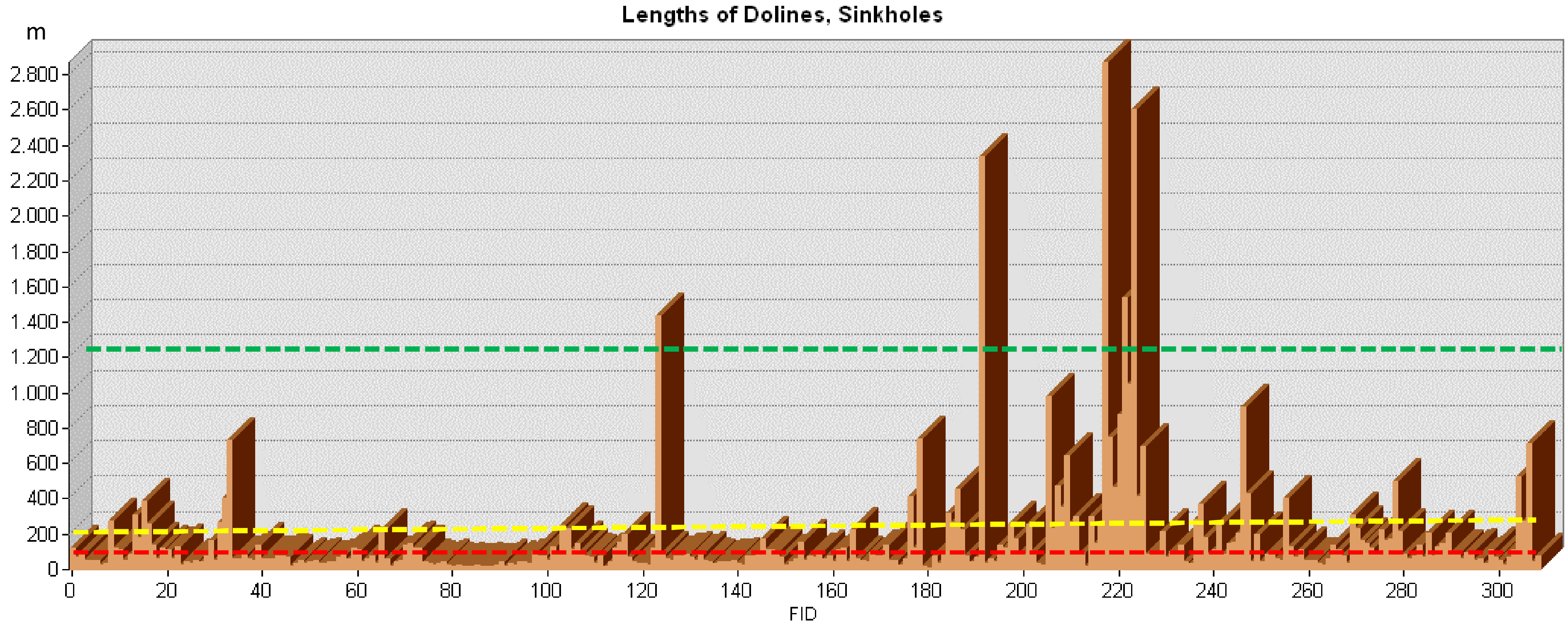


Length and Area of Sinkholes





Sizes of mapped Circular Features assumed to be related to Dolines / Sinkholes and Circular, Enclosed Depressions



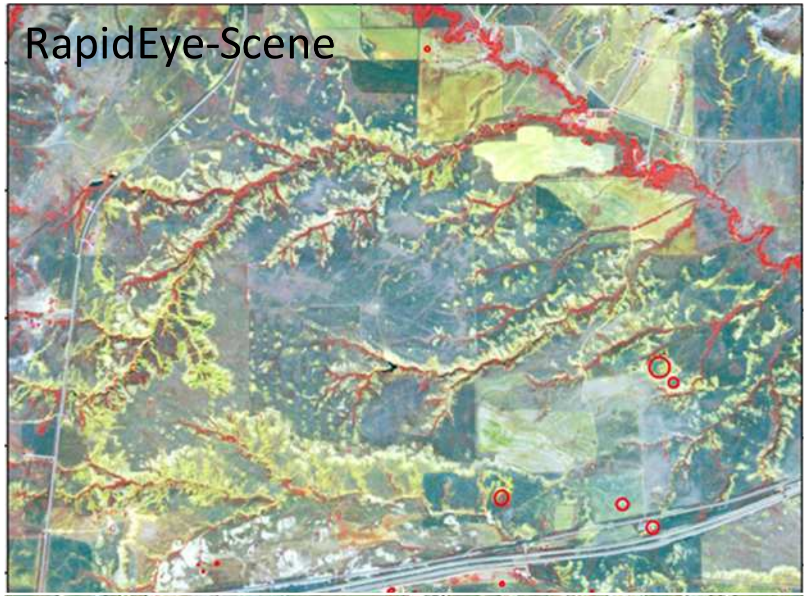
Length of circular features with not verfied origin

Length of enclosed depressions

Length of collapsed dolines

Circular Features visible on Satellite Data

types of circular features related to karst phenomena could be detected:

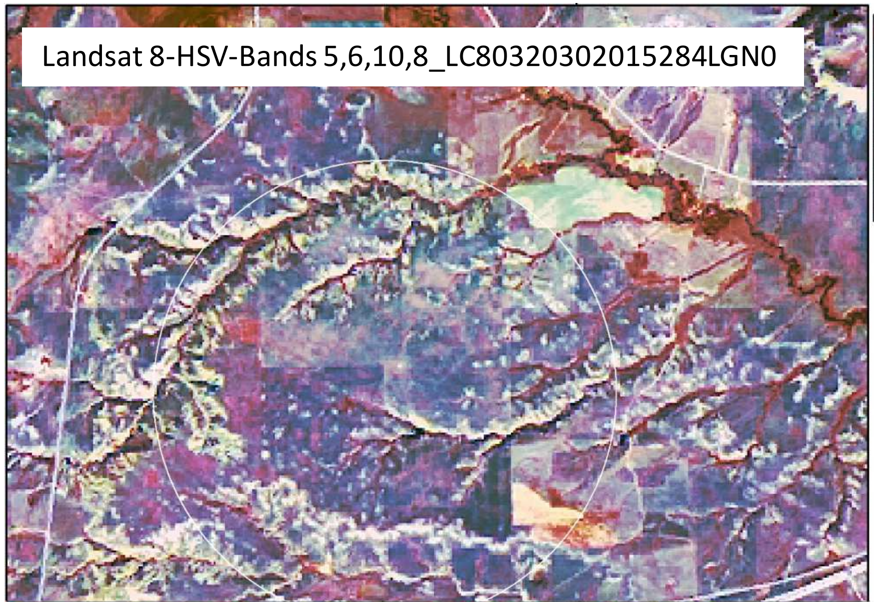


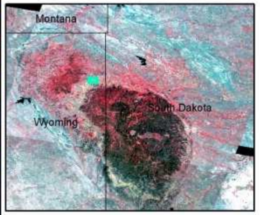
- Larger circular features with several hundred m to 2 km in diameter (origin has to be investigated and verified)

- Enclosed, circular depression caused by solution, sinking and erosion processes, up to several hundred meter in diameter

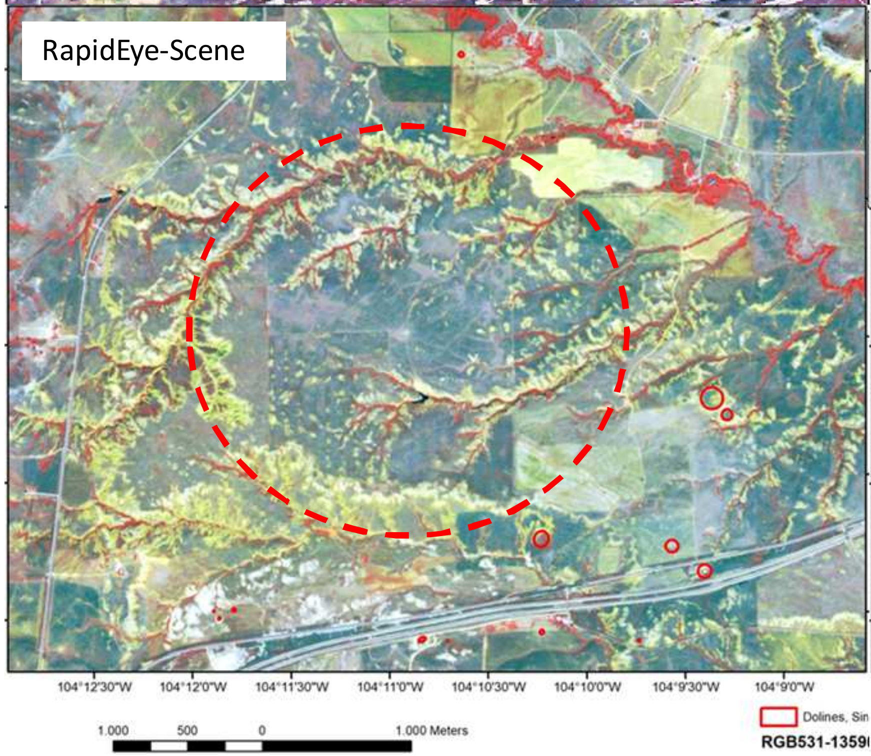
- Bedrock collapse dolines, about 10 -100 m in diameter

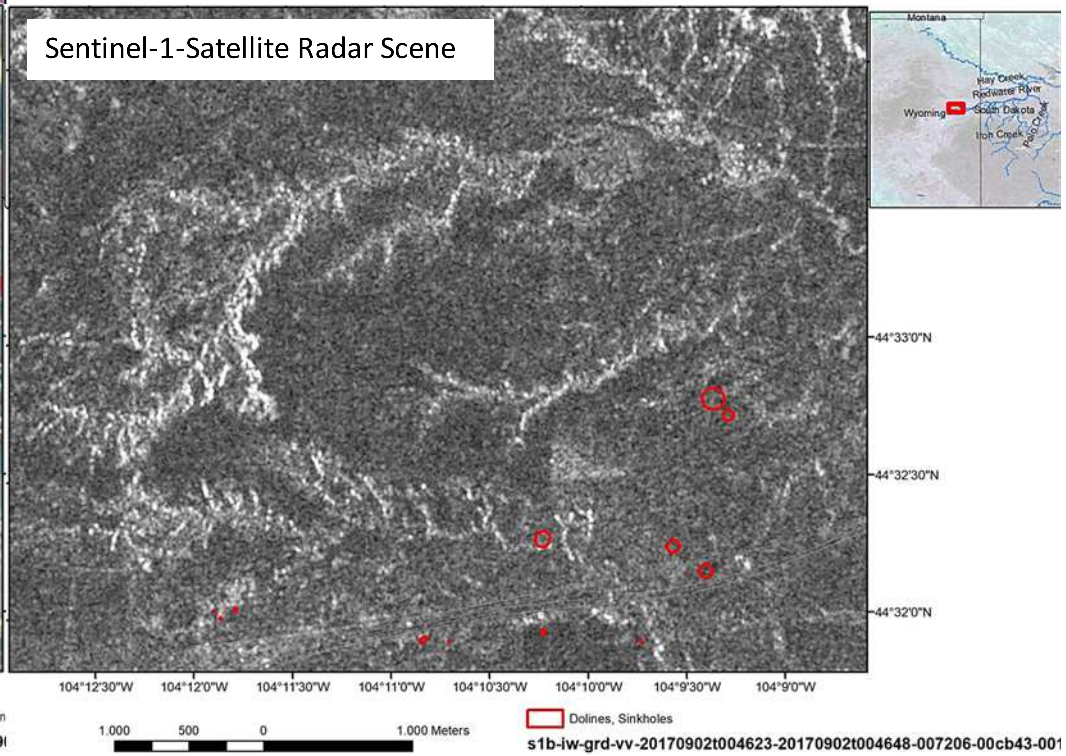
Circular Structure in the Northern Part of the Black Hills



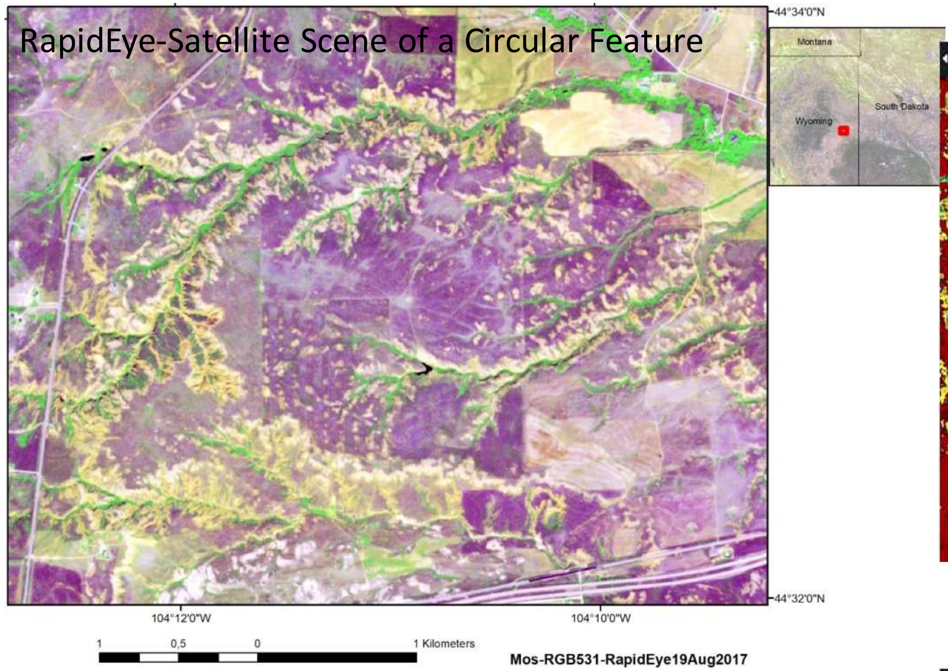


The origin of the circular structure might be related to a larger karst sinkhole (?) or a volcanic intrusion (?).

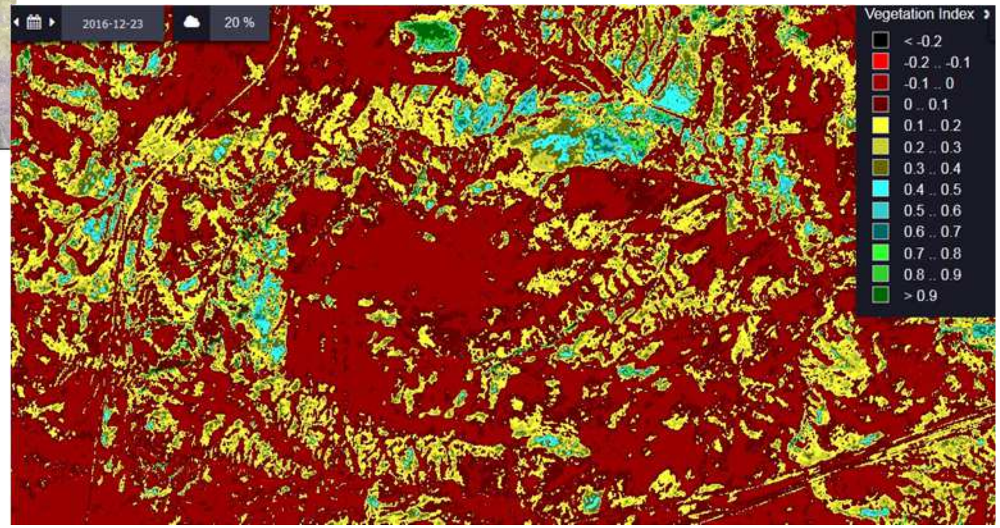




Circular Structure in the Northern Part of the Black Hills

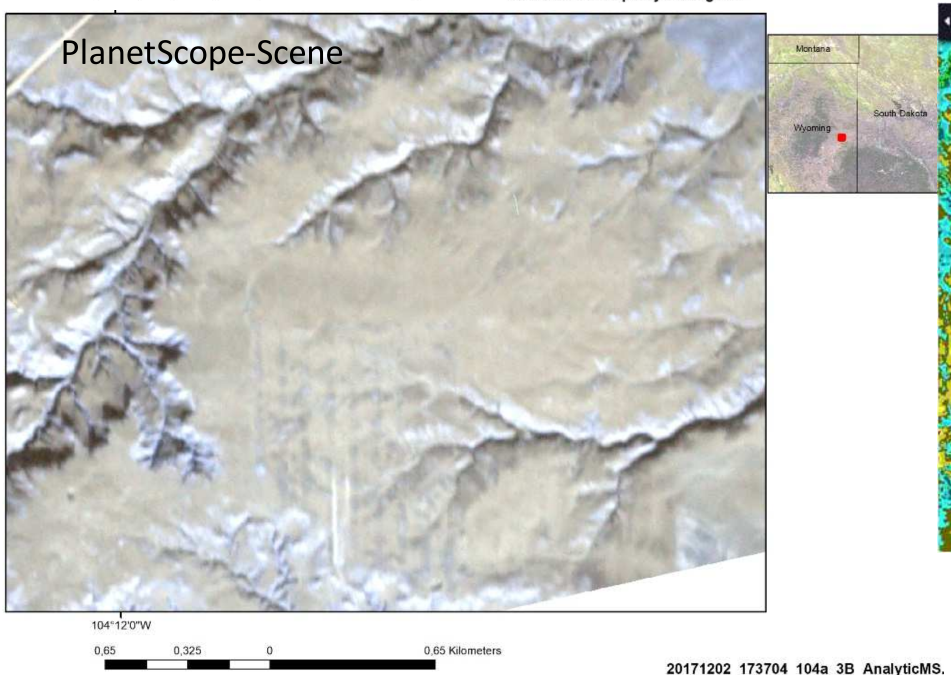


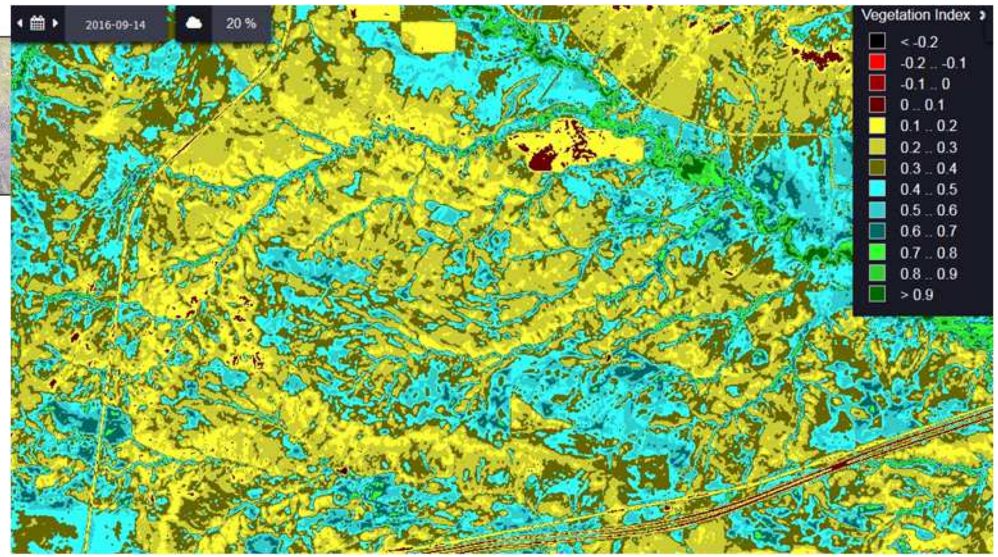
Sentinel-2- Vegetation Index (NDVI) Scene



Sentinel-2- Water Index (NDWI) Scene

23.12.2016

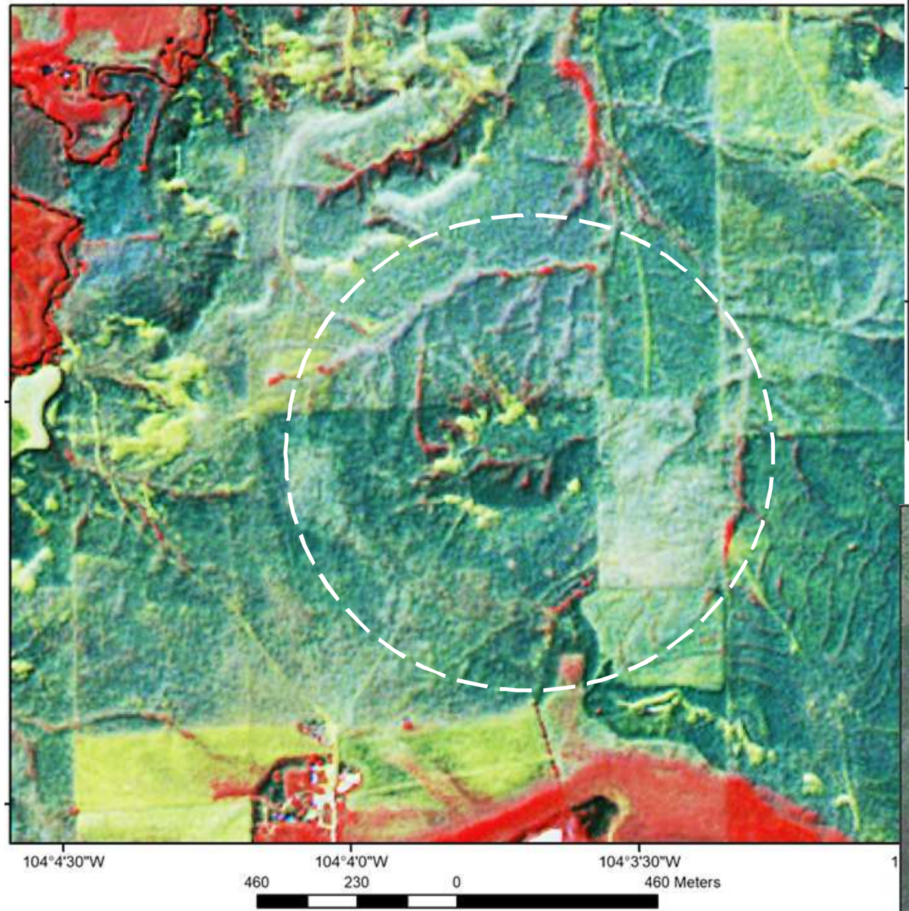




14.09.2016

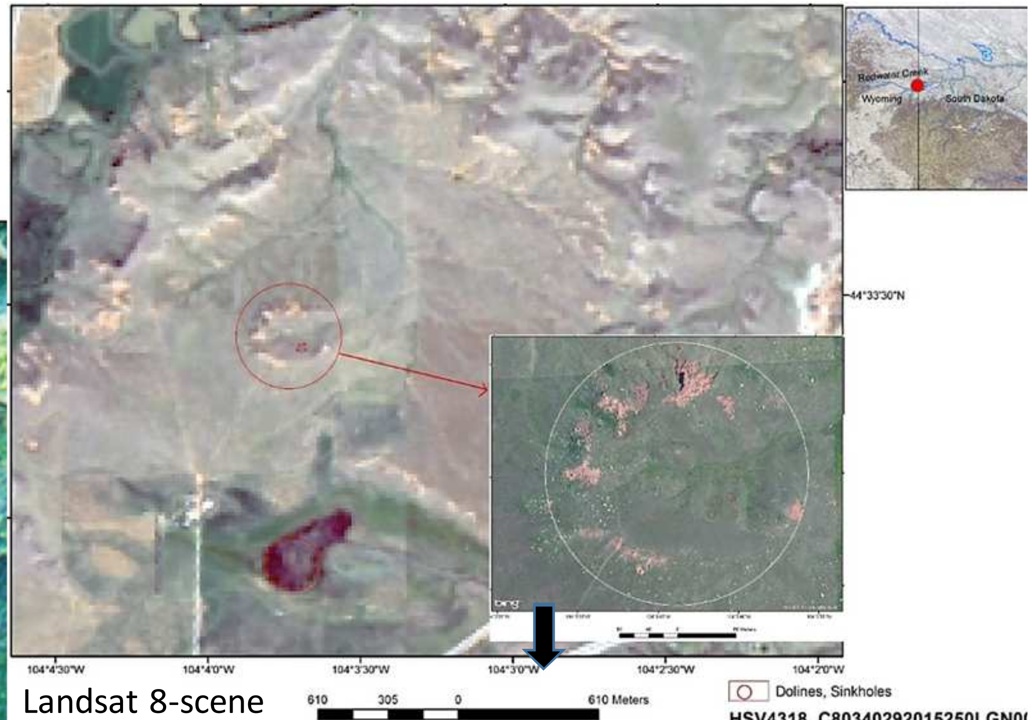
http://apps.sentinel-hub.com/sentinel-playground
http://www.sentinel-hub.com/blog/sentinel-playground

Circular Structures

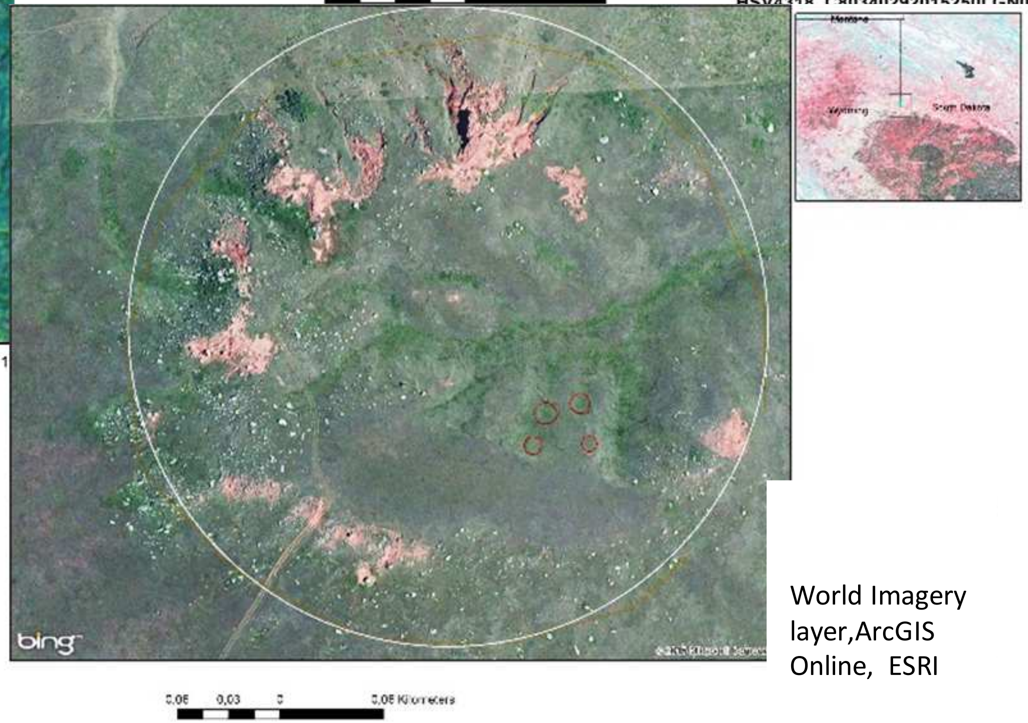


RapidEye-Scene, RGB 5,3,1

Circular structure due to dissolution processes in the subsurface or due to updoming of the strata above intruding igneous rocks underneath ?

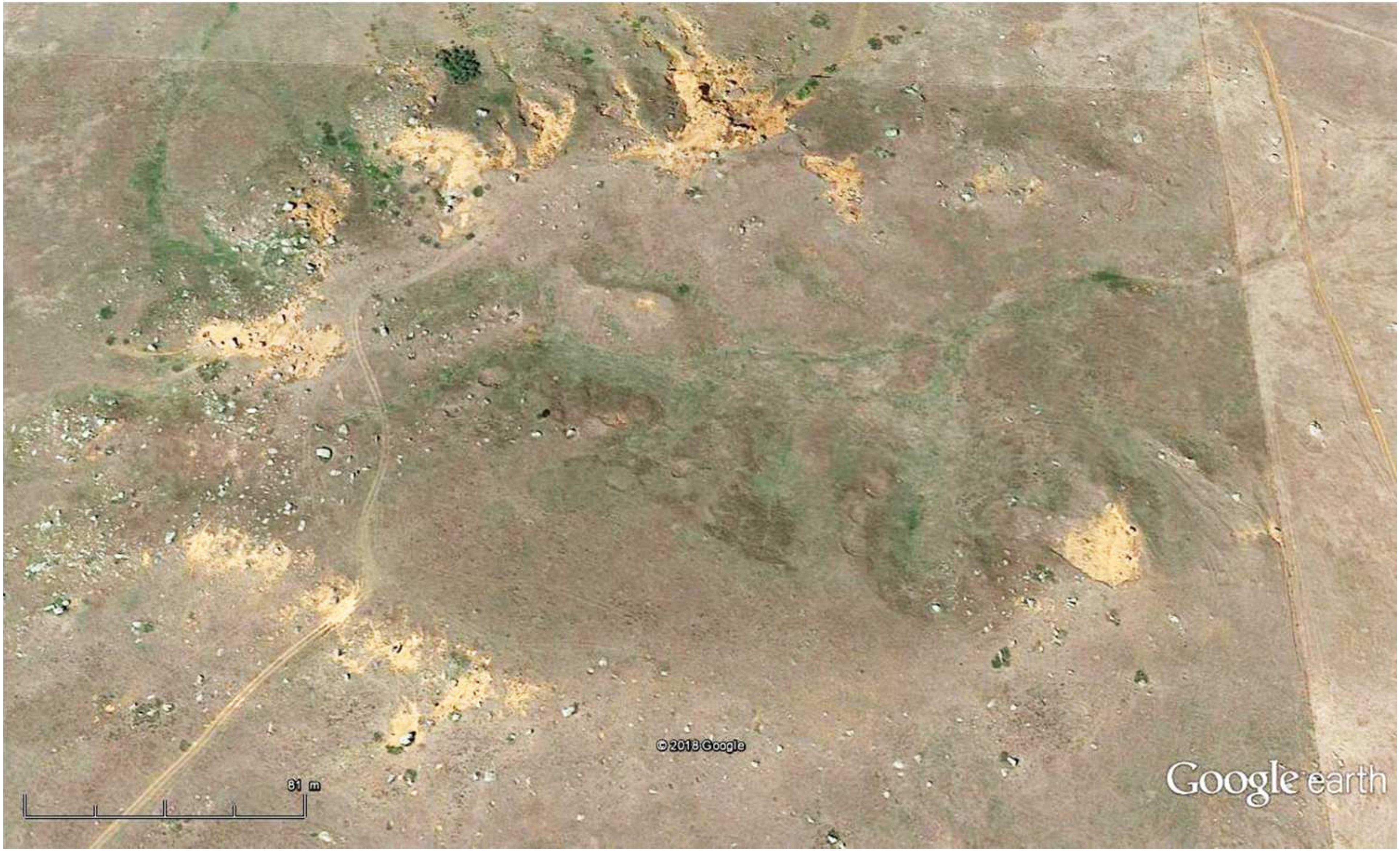


Landsat 8-scene



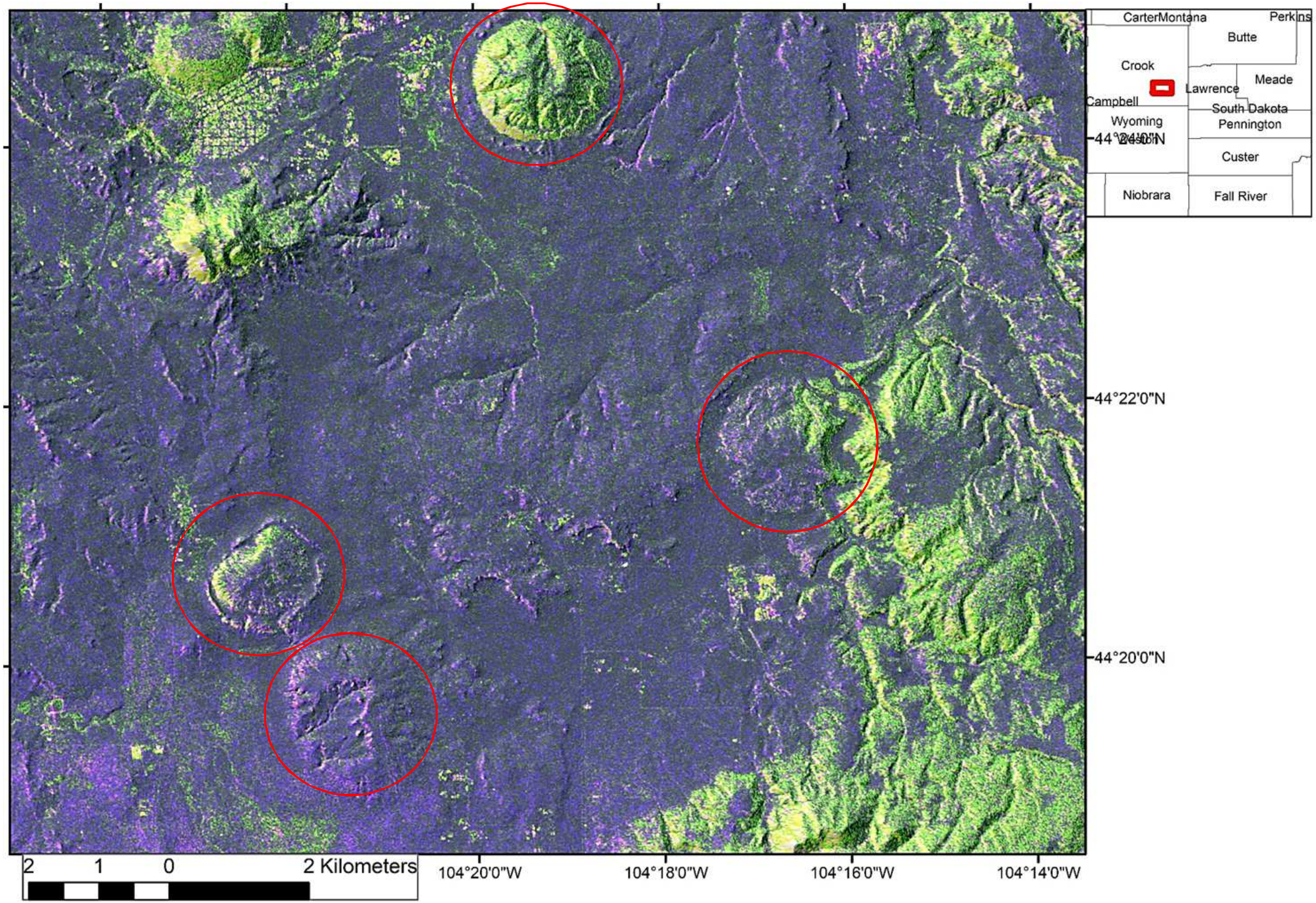
World Imagery layer,ArcGIS Online, ESRI

Circular Structure in the Northern Part of the Black Hills



44°33'24.46" N 104°03'42.61" W

Sentinel-1-Radar-Scene of larger Circular Structures

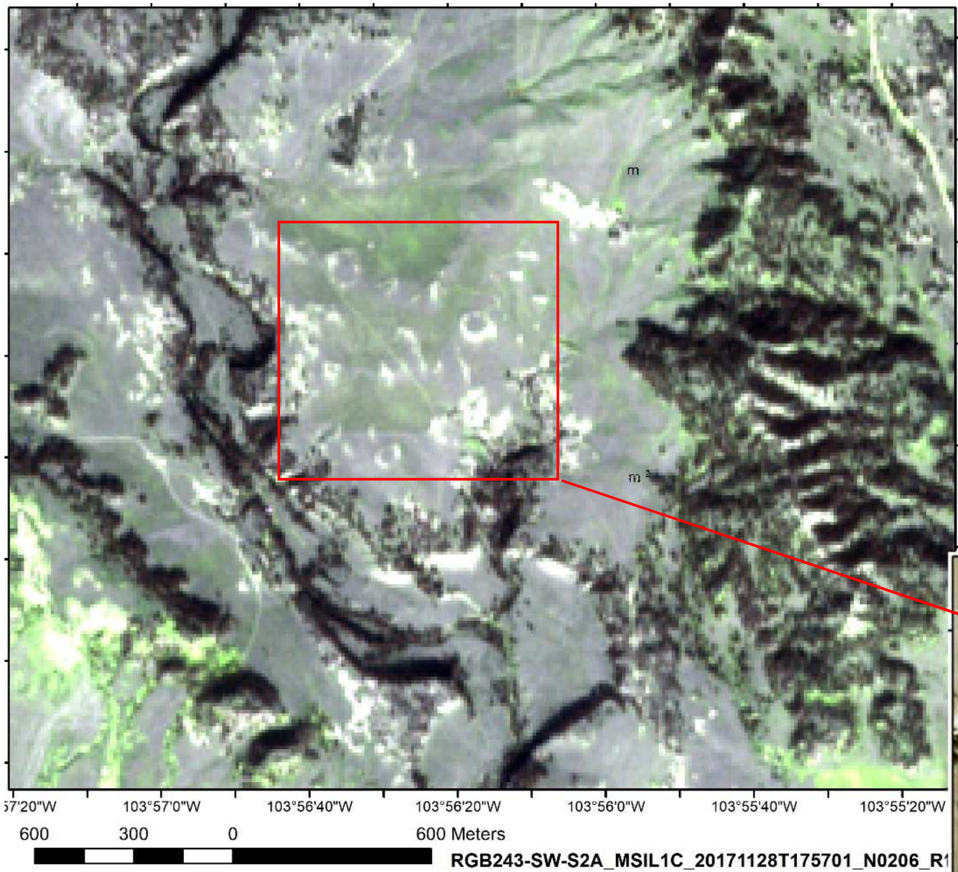


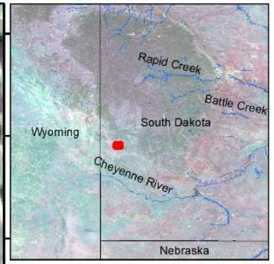
Filter_RGB-subset_0_of_S1B_IW_GRDH_1SDV_20170902T004623_20170902T004648_007206_00CB43_09D9_Cal_TC_

Circular Structure

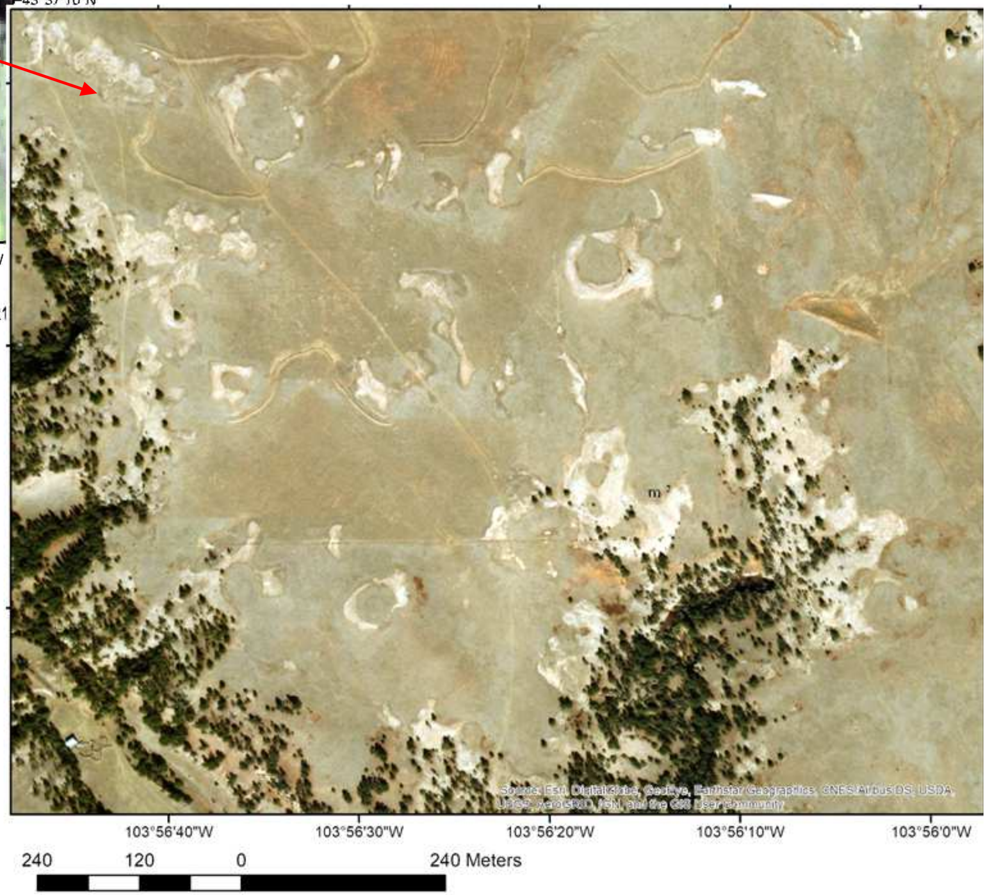
44°20'33.29" N 104°22'08.69" W

Enclosed, circular Depressions



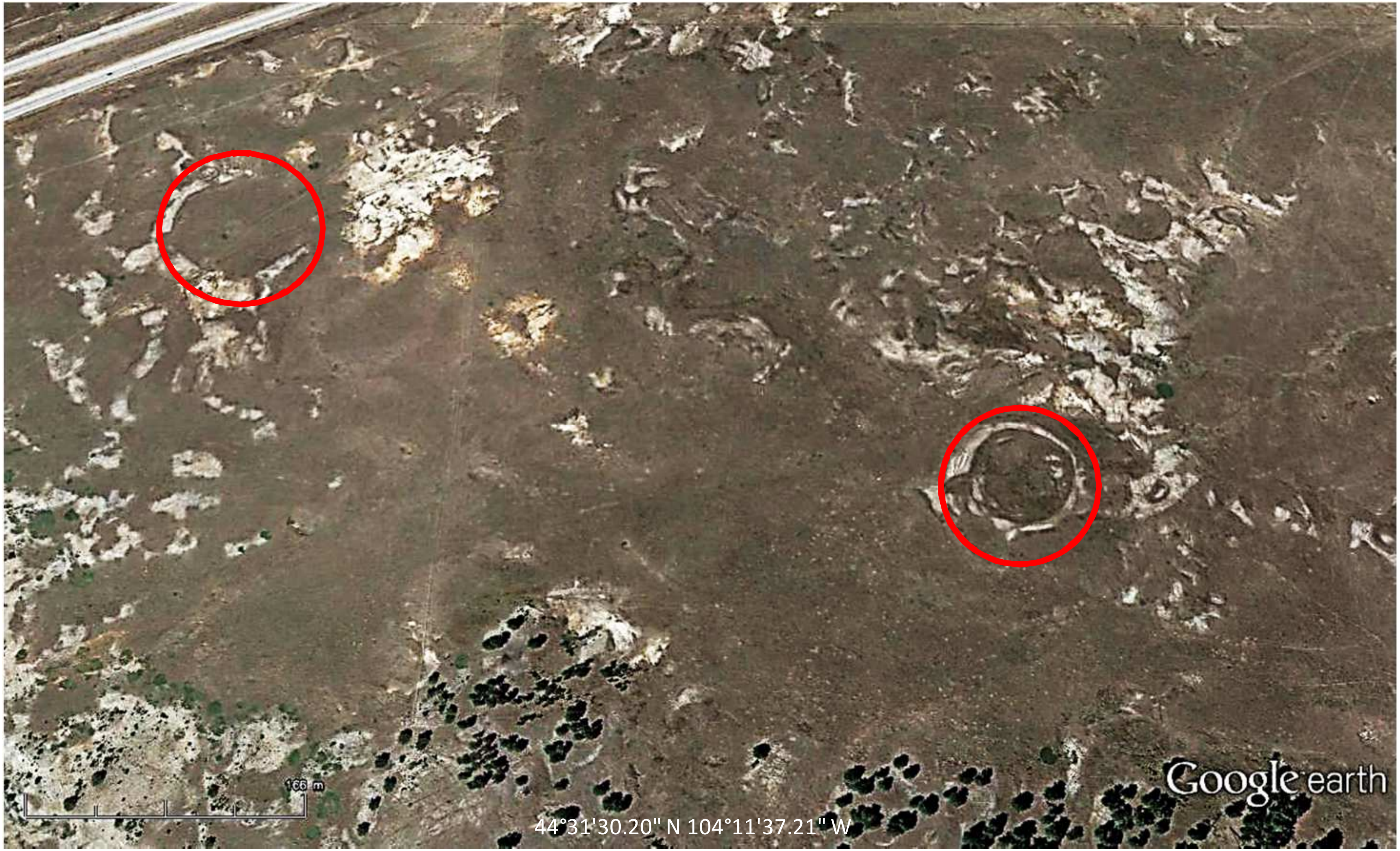


Sentinel-2-scene

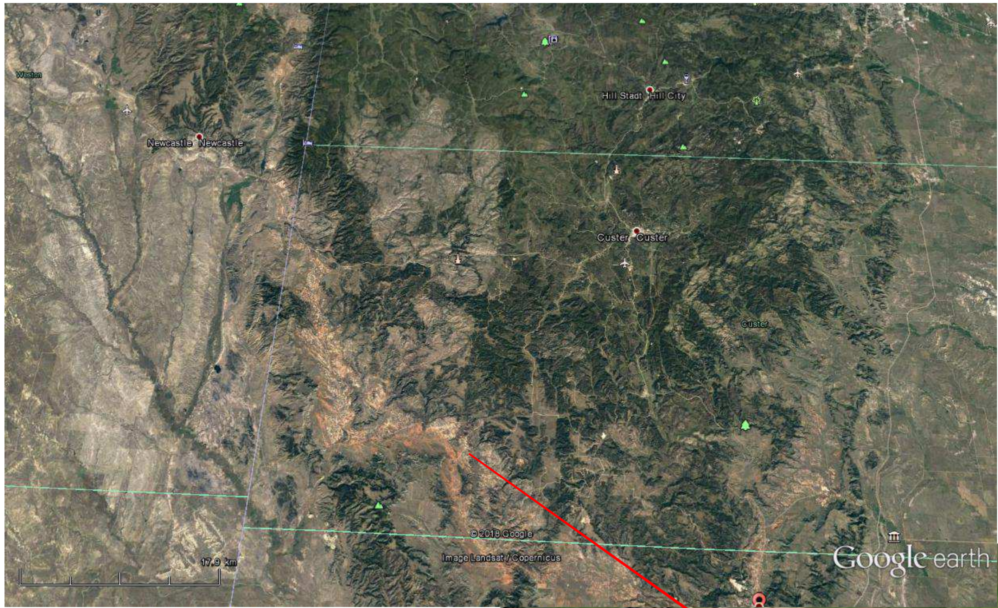


Enclosed Depressions

Circular Features

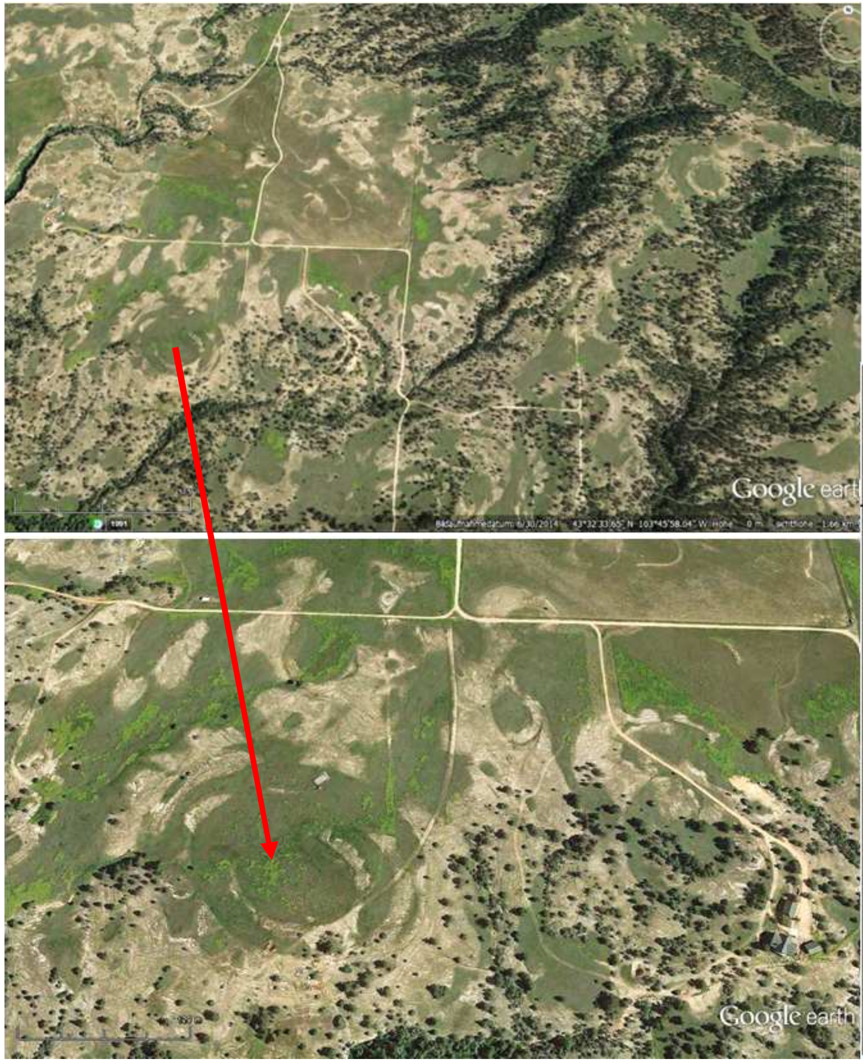


Solution Dolines



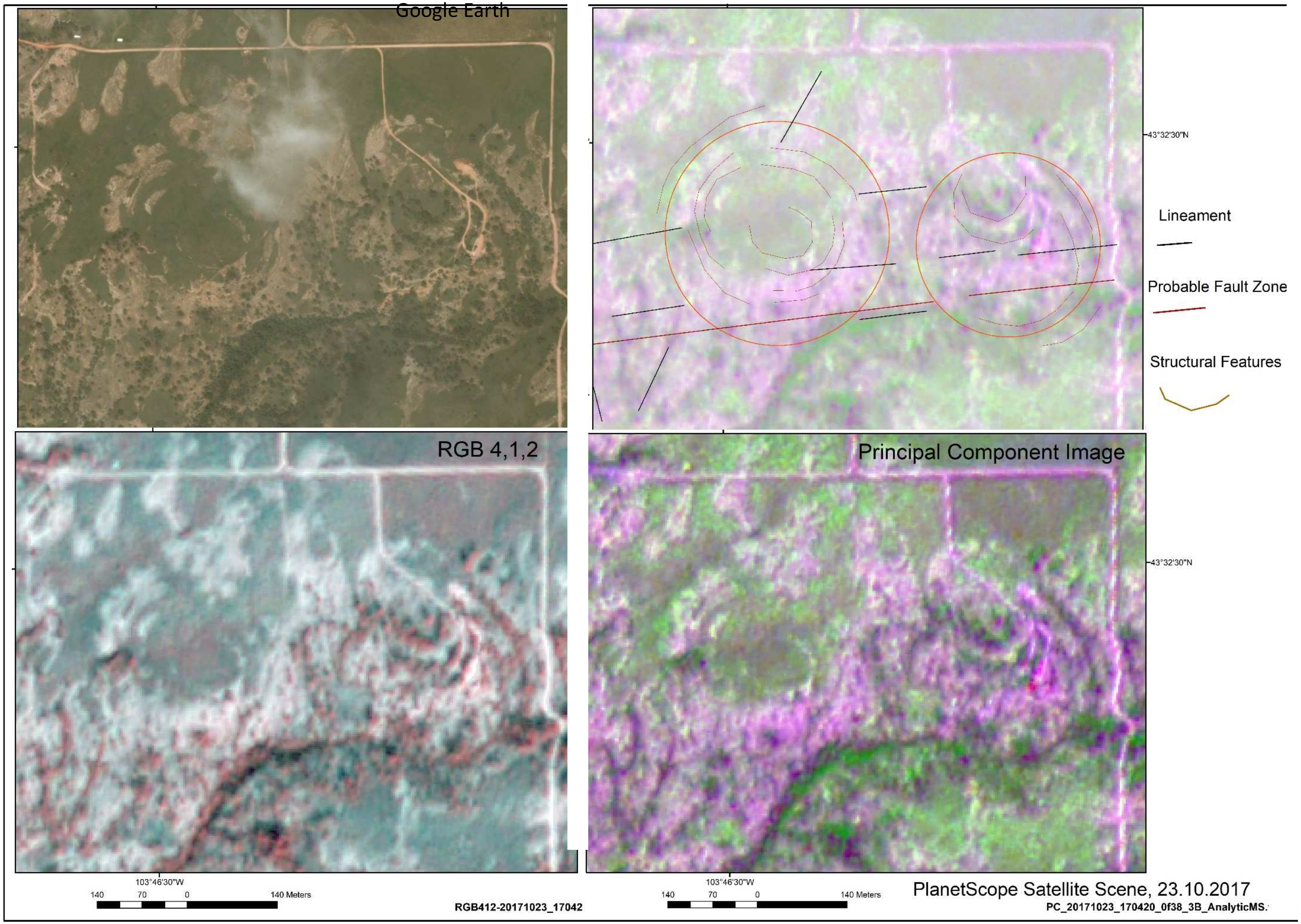
43°37'29.45" N 103°56'26.40" W

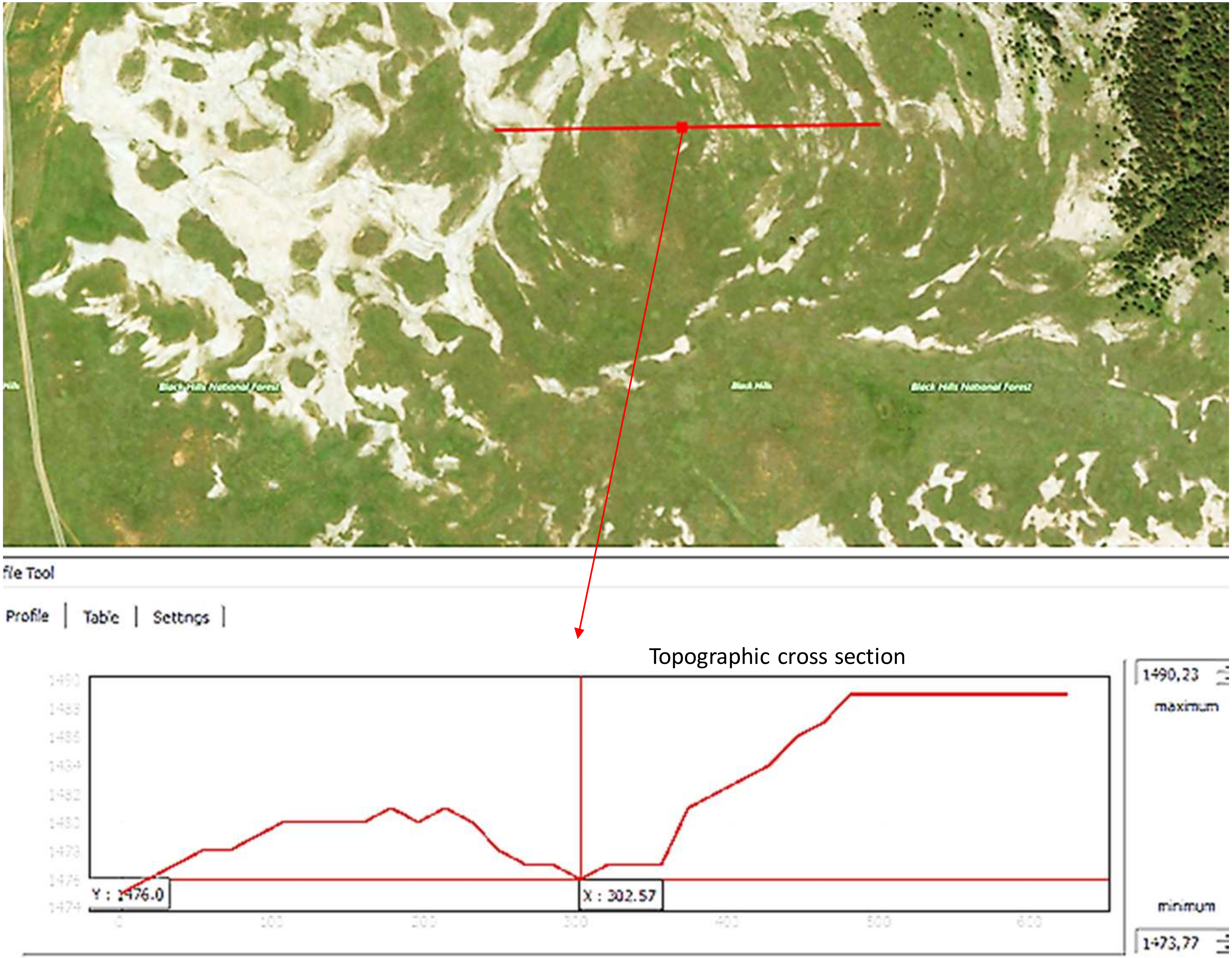
Circular, multi-ringed Structures in the Western Part of the Black Hills



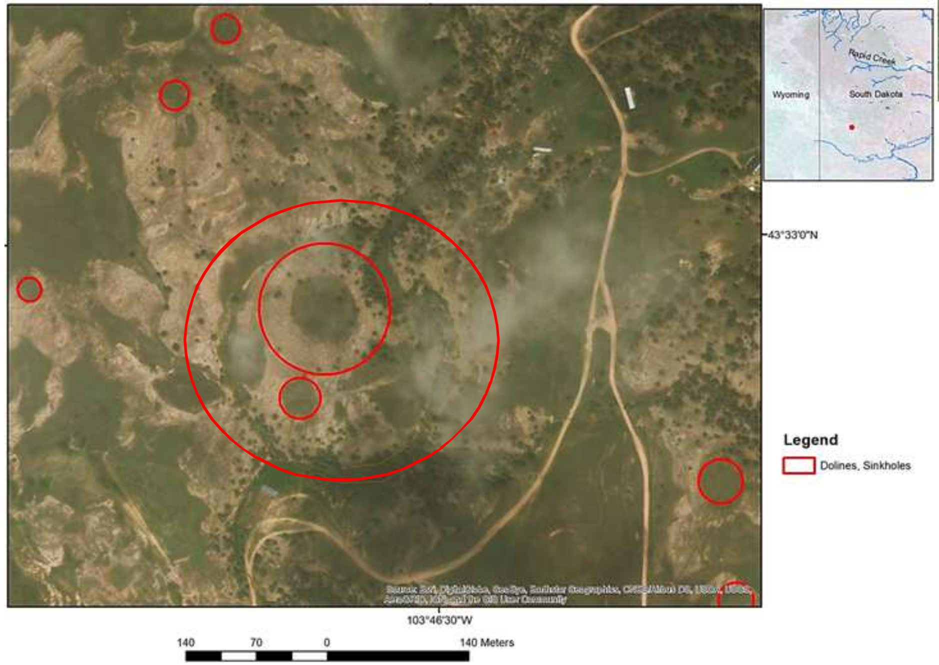
43°32'27.82" N 103°46'21.68" W

Circular, multi-ringed Structures in the Western Part of the Black Hills

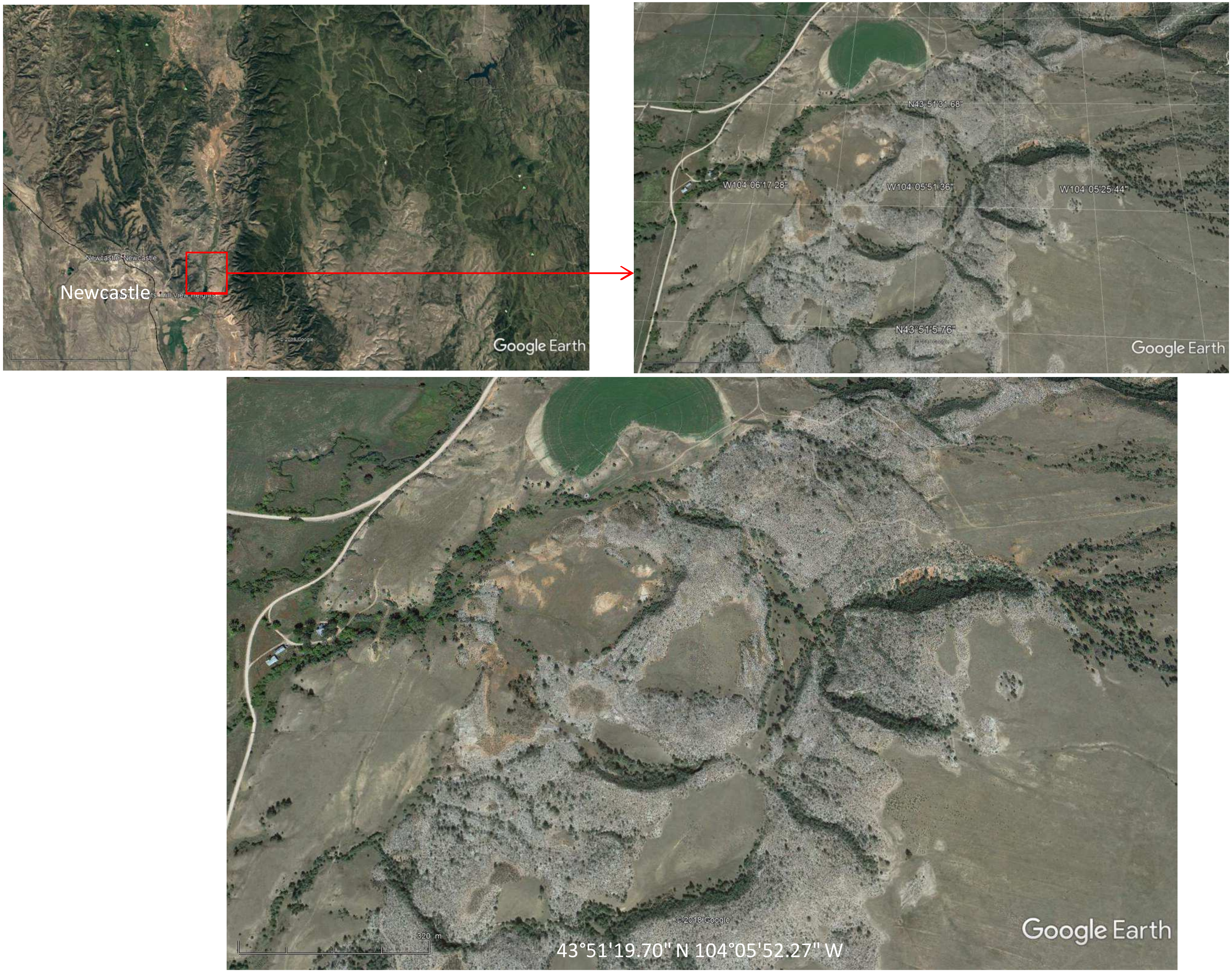



Black Hills National Forest
Black Hills
Black Hills National Forest
file Tool
Profile
Table
Settings
Topographic cross section
1490,23
maximum
minimum
1473,77
Y : 1476.0
X : 302.57
1490
1488
1486
1484
1482
1480
1478
1476
1474
0
100
200
300
400
500
600

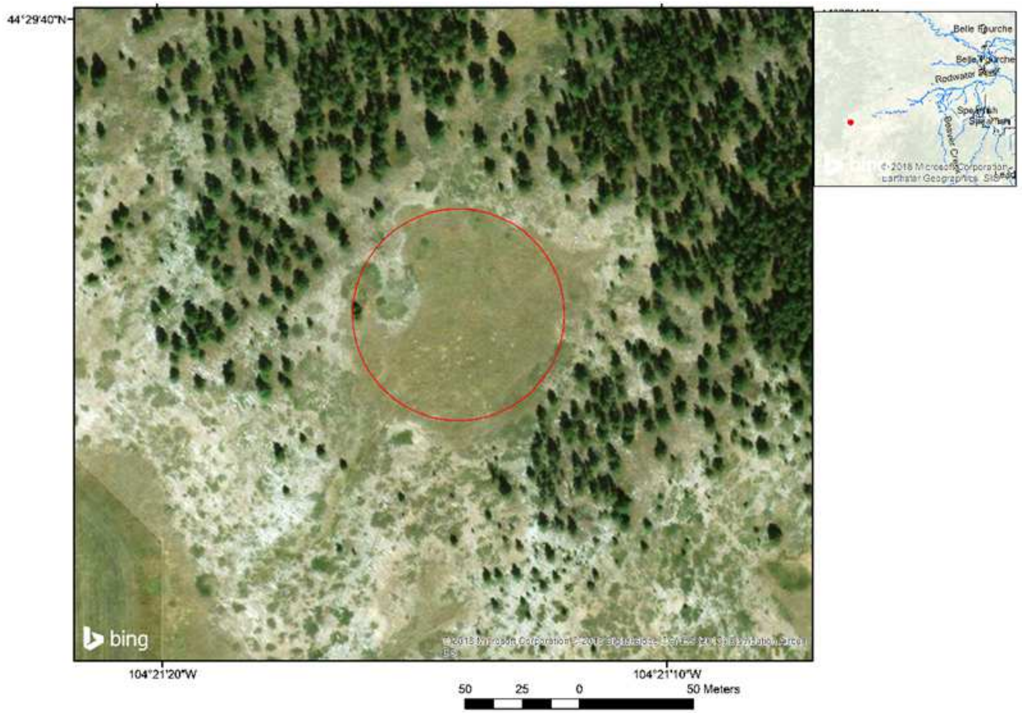
Enclosed Depressions / Solution Dolines ?

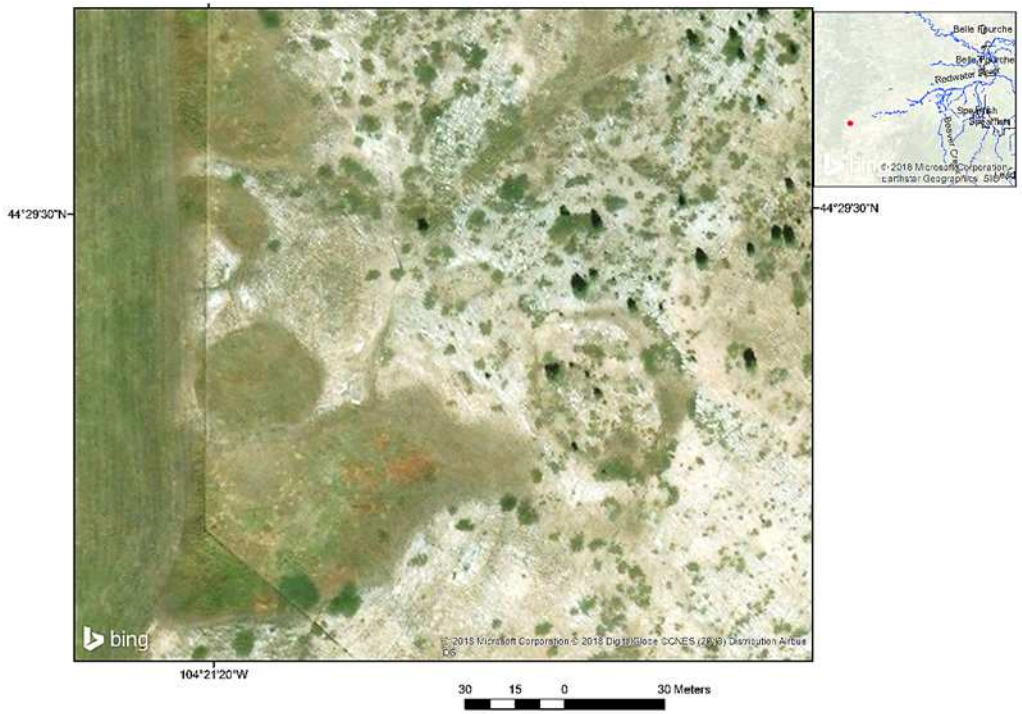


43°32'57.80" N 103°46'36.50" W

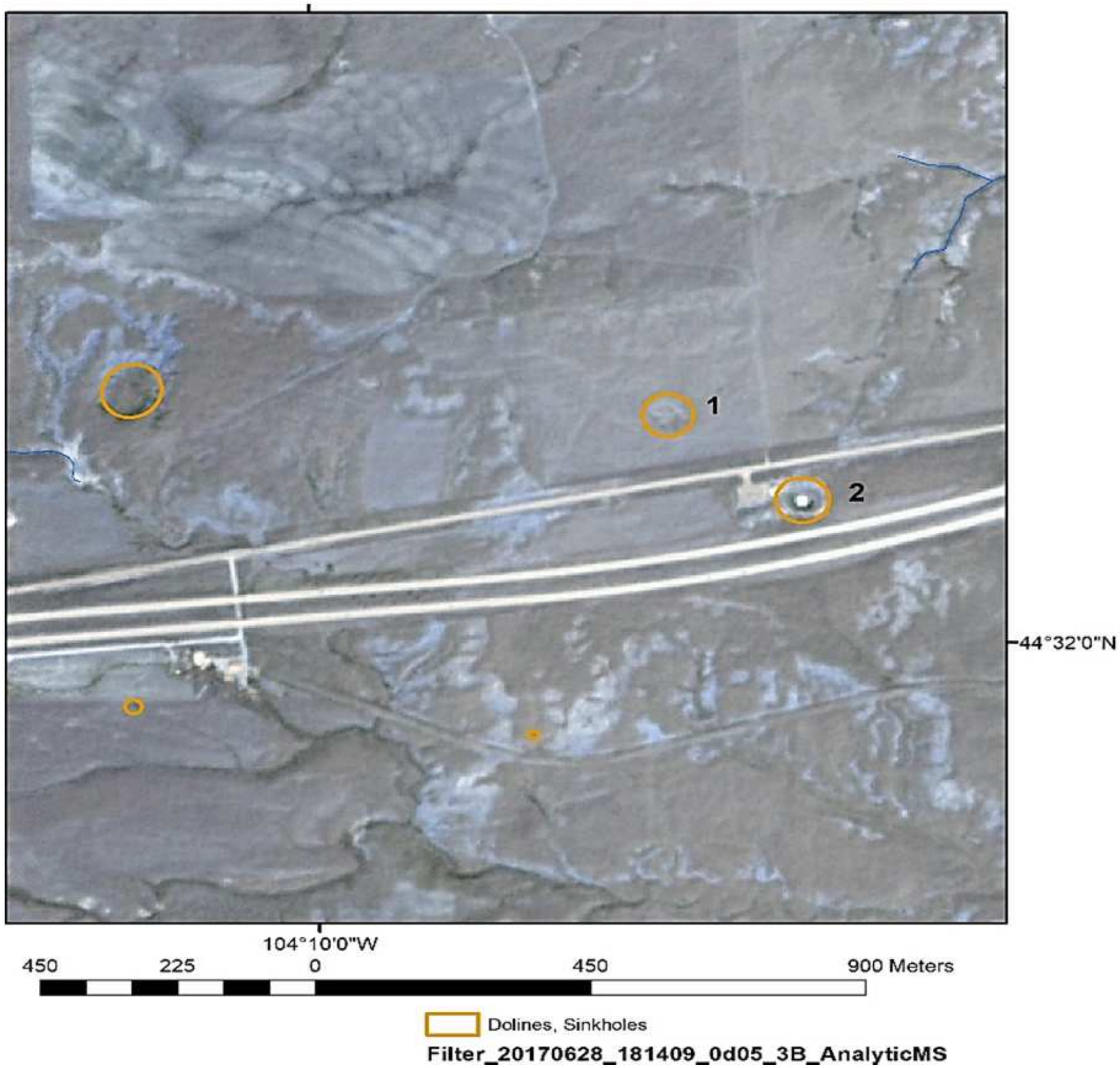

Newcastle
Google Earth
N43°51'31.68"
W104°06'17.28"
W104°05'51.36"
W104°05'25.44"
N43°51'5.76"
Google Earth
320 m
©2018 Google
Google Earth
43°51'19.70" N 104°05'52.27" W

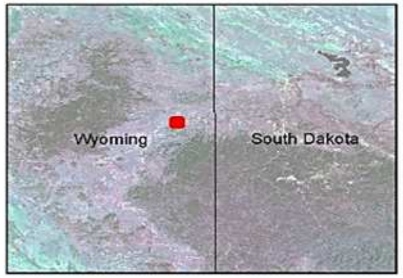
Circular Features – Enclosed Depressions





Collapsed Dolines in the Northern Part of the Black Hills





Theilen-Willige, 27.05.2017

Two sinkholes located 5.6 km (3.5 mi) west of Beulah, Wyoming, and immediately north of Interstate 90. The "Vore Buffalo Jump" is an 18-m (60 ft)-foot deep sinkhole.

Jack B. Epstein, Daniel H. Doctor : EVAPORITE KARST IN THE BLACK HILLS, SOUTH DAKOTA AND WYOMING, AND THE OIL PLAY IN THE WILLISTON BASIN, NORTH DAKOTA AND MONTANA. 13TH SINKHOLE CONFERENCE NCKRI SYMPOSIUM 2, 2013

Karst Phenomena

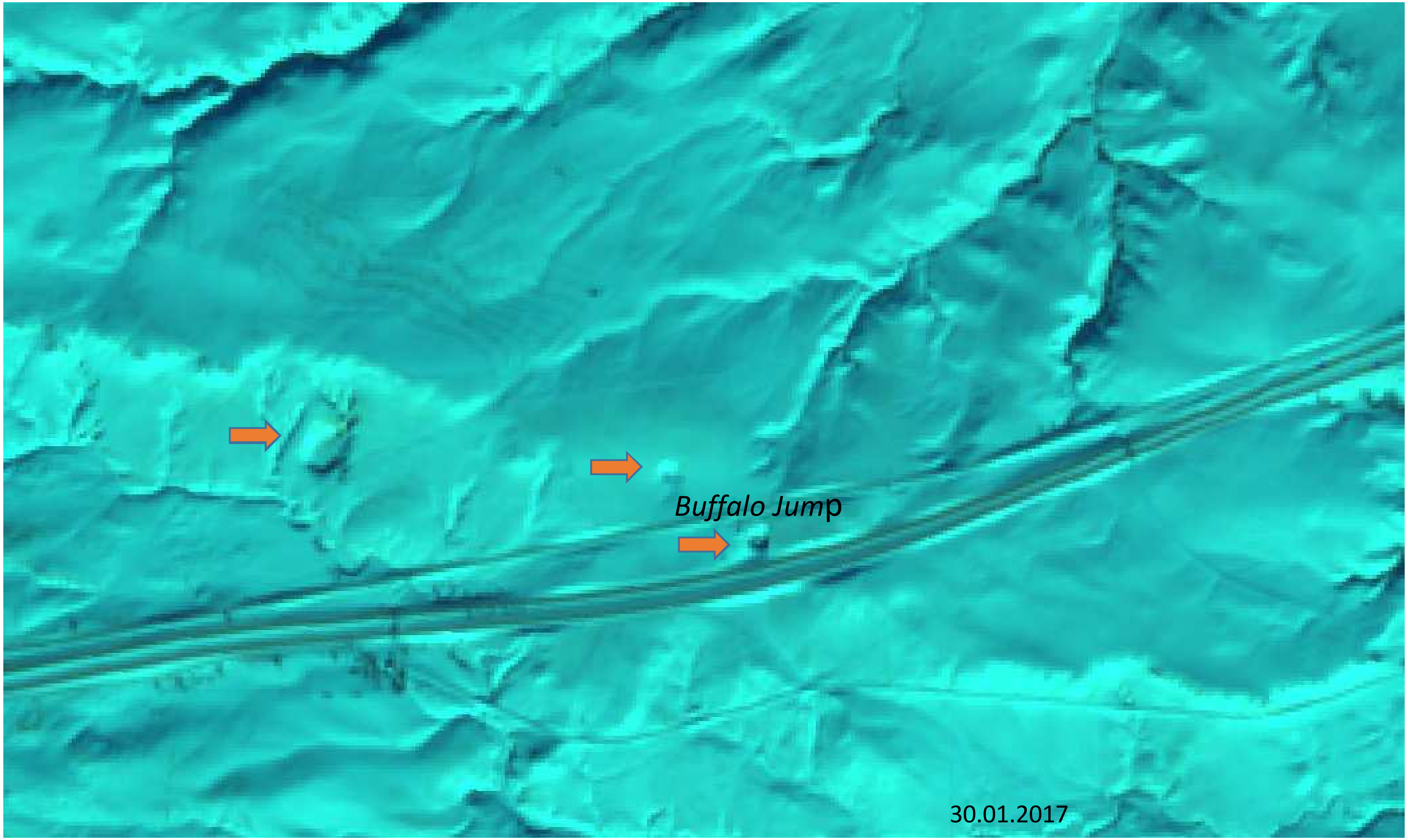
The Vore Buffalo Jump, one of North America's most important and spectacular Plains Indian archeological sites, is a stone's throw from I-90 in northeast Wyoming. See the excavation and learn the history, science and culture of North American Plains Indians. Over 20 layers of artifacts and bone have been discovered, dating back to 1500-1800 AD.

Archaeologists estimate that at least 4,000 bison were killed in this trap.

Vore Buffalo Jump Bone Bed Dig

http://www.blackhillsbadlands.com/business/vore-buffalo-jump

Use of wintertime, Snow covered Sentinel-Image for the Detection of Dolines

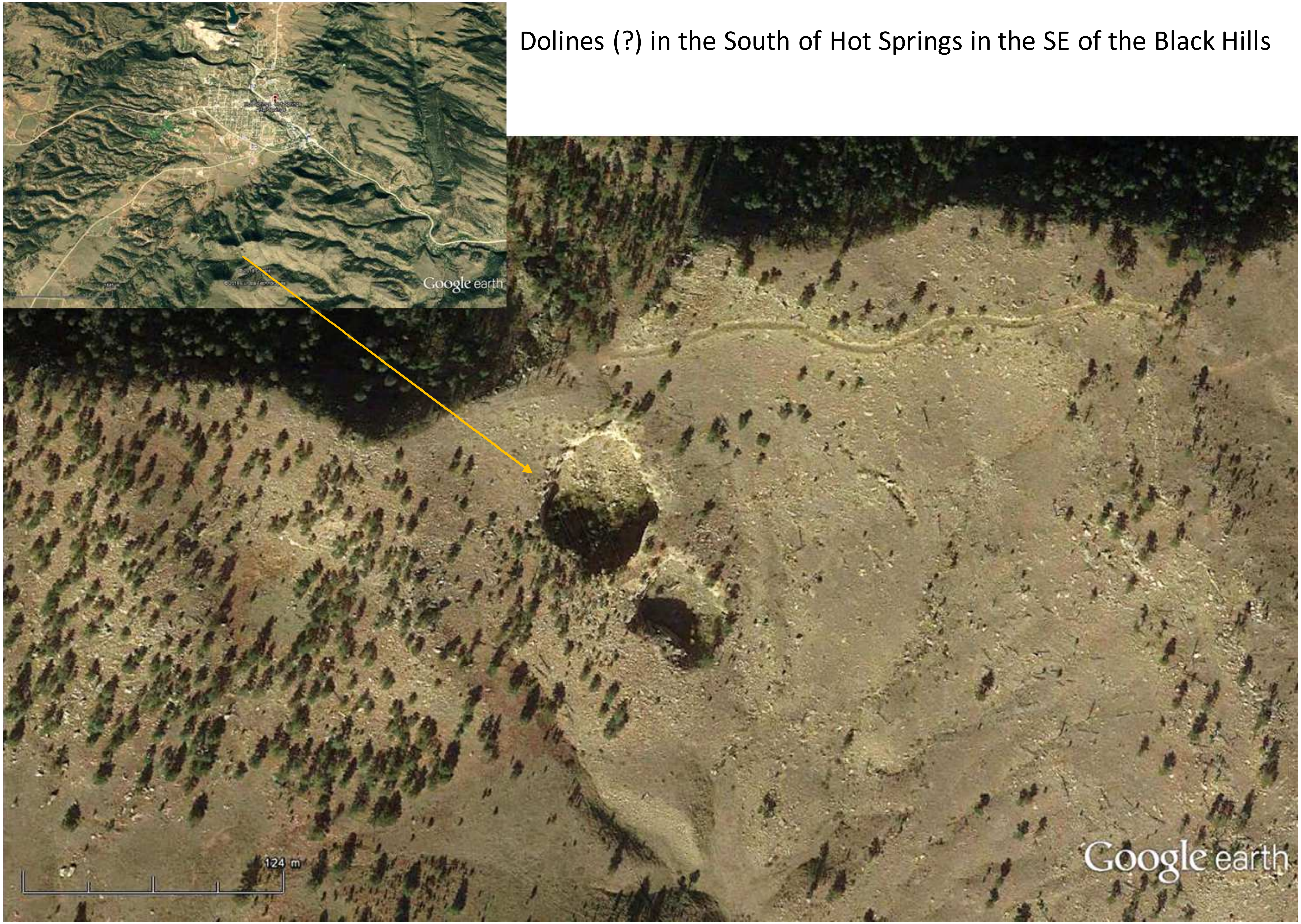


Collapse Doline

44°31'40.48" N 104°09'22.99" W

44°28'40.14" N 104°20'22.42" W

Dolines (?) in the South of Hot Springs in the SE of the Black Hills



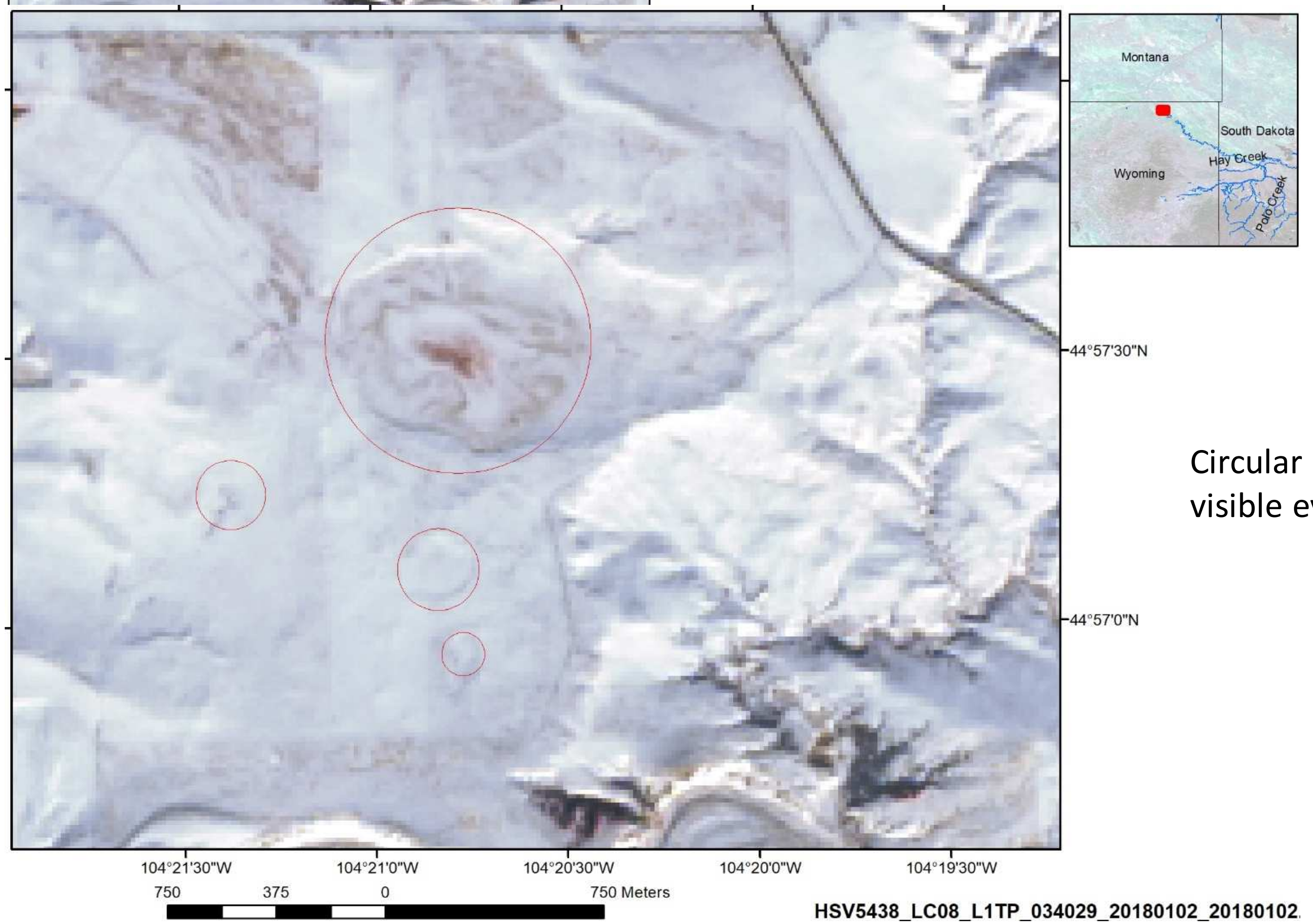
43°23'59.71" N 103°28'51.39" W

43°22'38.89'' N 103°32'49.53'' W

Landsat-8-Scene with Snow Cover

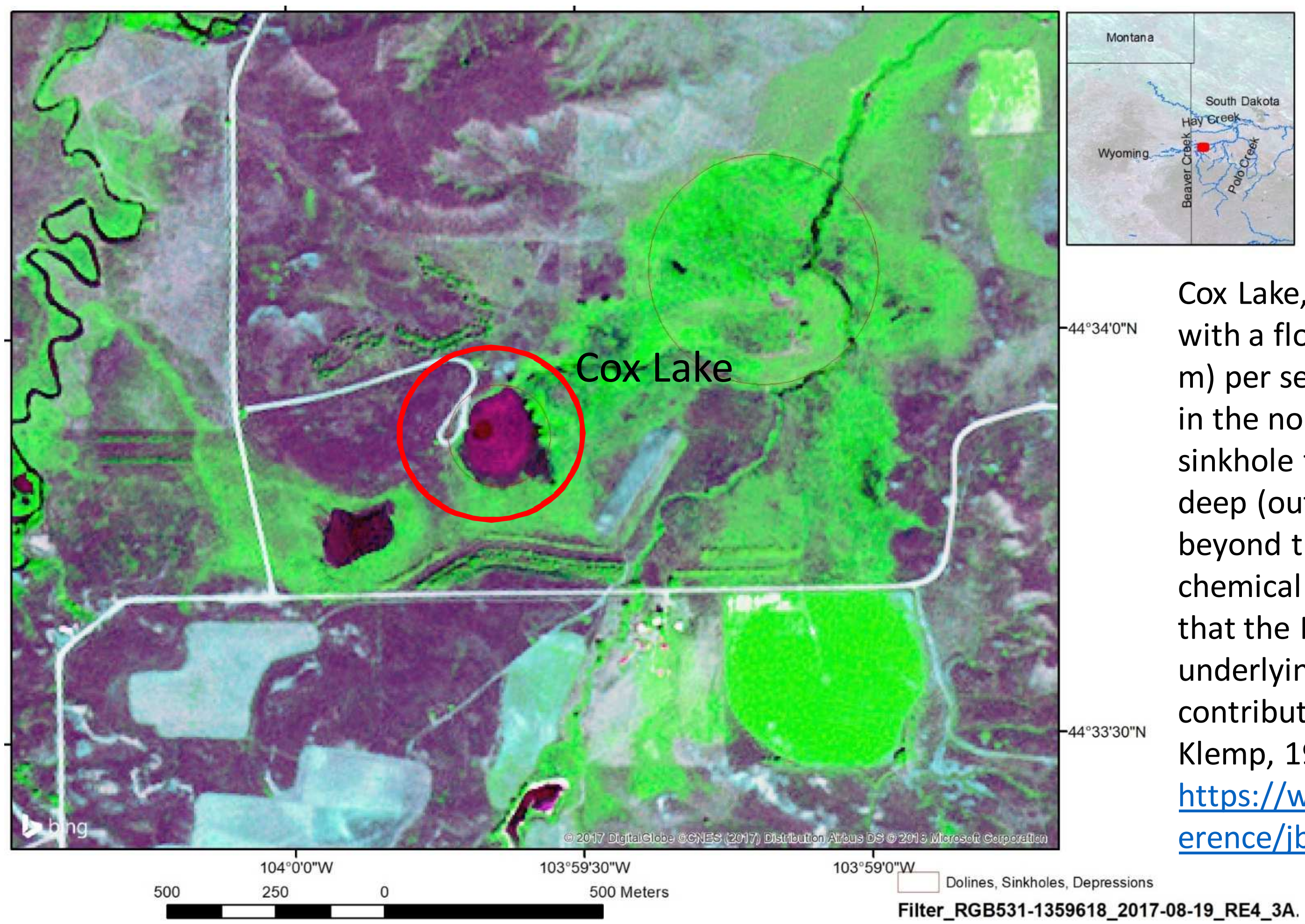
Detection of circular, morphologic depressions with unknown origin that might be related to karst phenomena - a resurgent (artesian) spring?

02.01.2018



Circular morphologic depressions become visible even when covered by snow.

Sinkholes

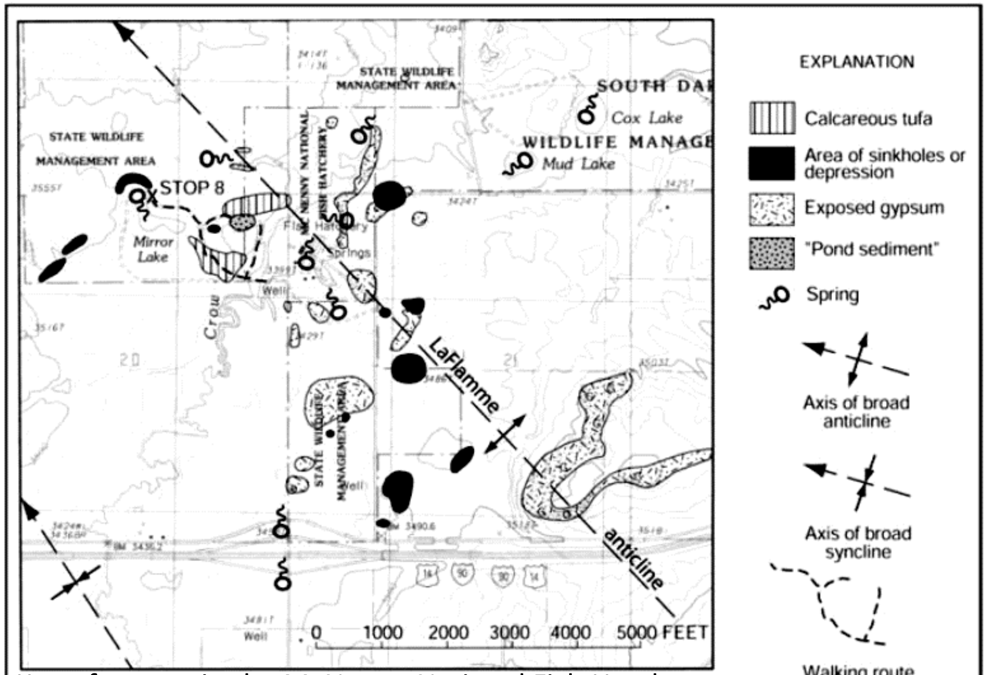


Filter_RGB531-1359618_2017-08-19_RE4_3A.

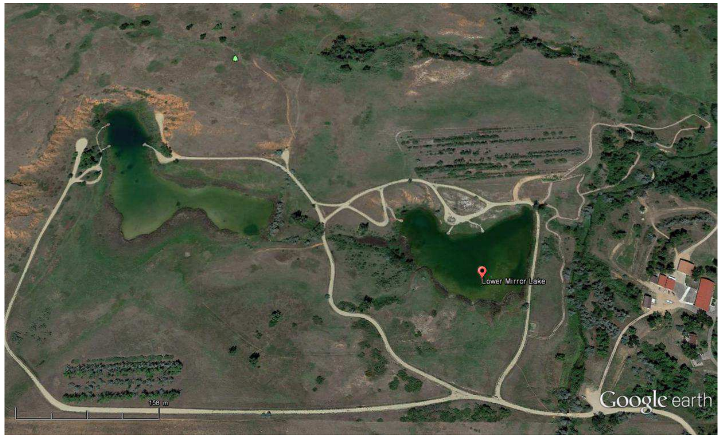
Cox Lake, a resurgent (artesian) spring with a flow of nearly 5 cubic feet (0.5 cu m) per second in the Spearfish Formation in the northern Black Hills. It occupies a sinkhole that is more than 60 ft (18 m) deep (outlined by the darker water just beyond the edge of the dock). The chemical signature of the water indicates that the Minnelusa Formation and underlying Madison Limestone are the contributing aquifers (Epstein,2001, Klemp, 1995).
https://water.usgs.gov/ogw/karst/kigconference/jbe_hydrologyhazards.htm

Cox Lake

44°33'52.84" N 103°59'37.96" W



Karst features in the McNenny National Fish Hatchery

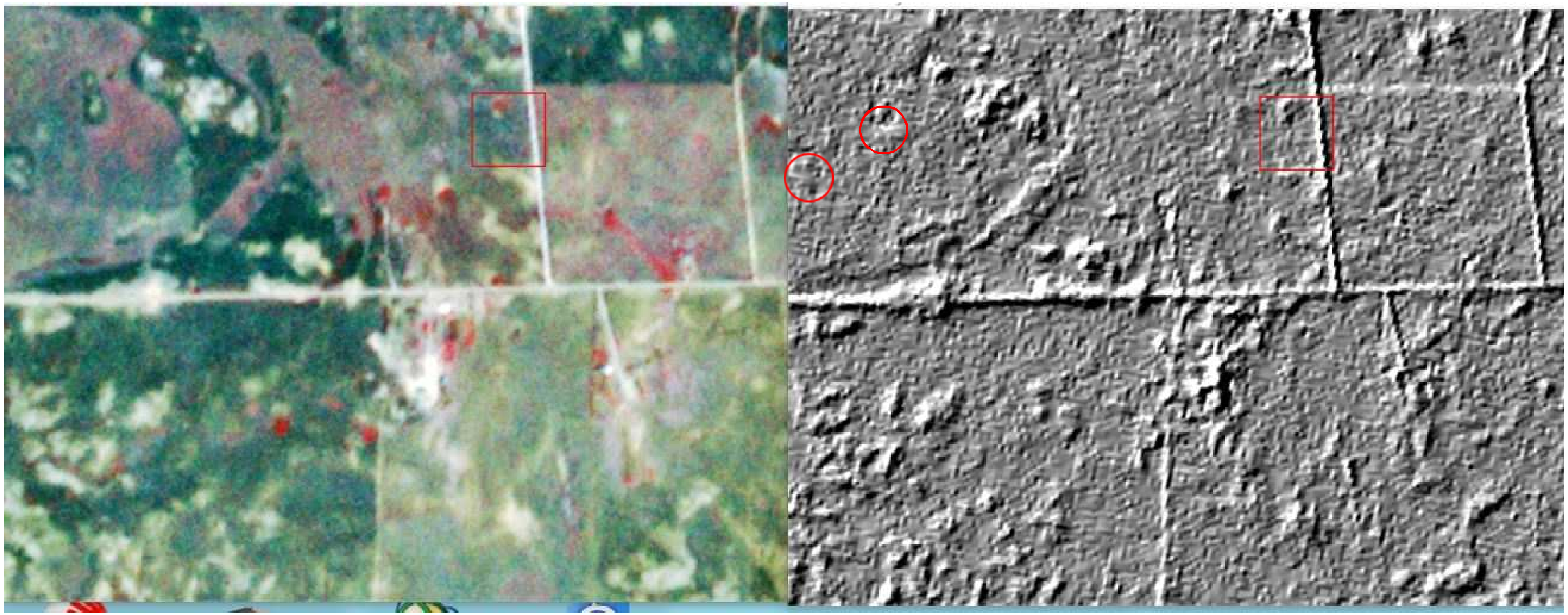


Michael P.Terry, Edward F.Duke and Jacob A. Tielke (Eds.,2010): Geologic Field Trips in the Black Hills Region, South Dakota., Bulletin Series of the South Dakota School of Mines and Technology, Department of Geolgy and Geologic Engineering, Bulletin No.21. Rapid City, South Dakota, USA, p.63

Mirror Lake has a dog-leg shape; the eastward-trending section is partly artificial, formed by a dam at the east end. The northwest-trending, 900-foot-long alcove is cut into a 50-foot-high ridge of the Spearfish Formation. The lake, similar to other lakes in the area (Cox Lake, Mud Lake, and the McNenny springs), occupies a depression formed by dissolution of gypsum at depth. Numerous shallow sinkholes, several feet deep, are found at the north end of the alcove. These presently are active and indicate that the lake is expanding fairly rapidly to the northwest by continued collapse of sediment due to solution of gypsum. Much of the fine sediment derived from the Spearfish Formation is presumably carried away by the emerging spring water. Two deposits of

Merging RGB-PlanetScope-Images with Morphologic Convolution-Directional-Images

Merging the “morphologic” image products derived from “Morphologic Convolution” image processing in ENVI software with RGB imageries, the evaluation feasibilities were improved. Dolines can be better identified.

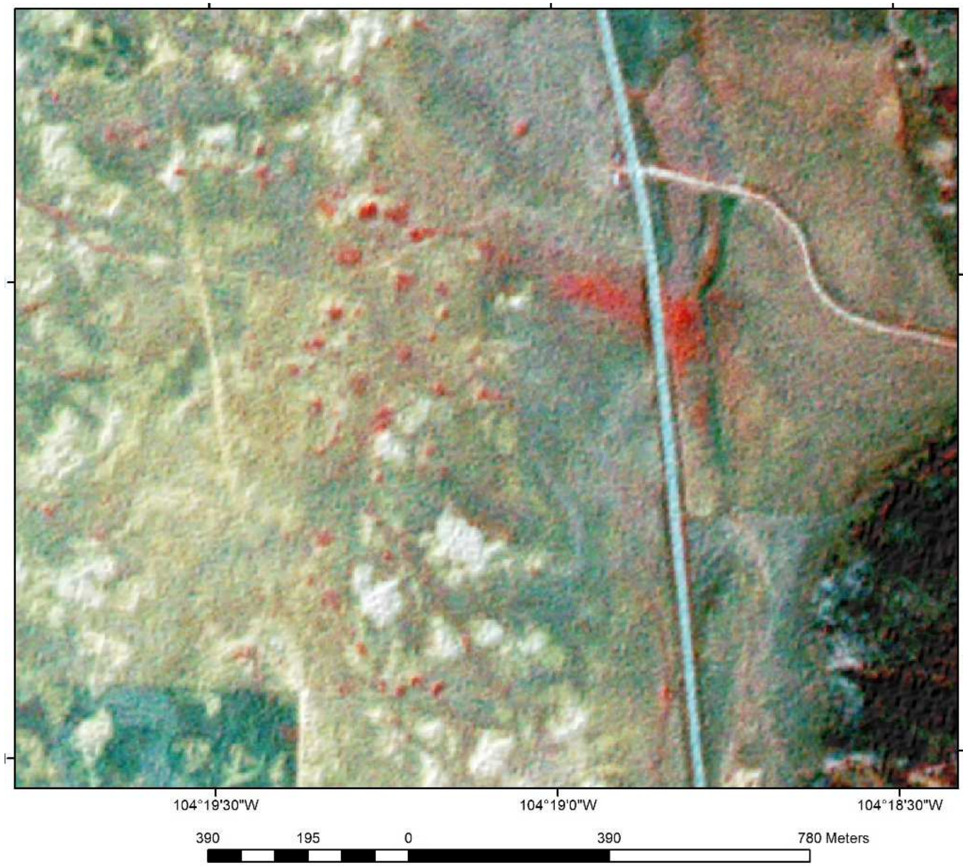


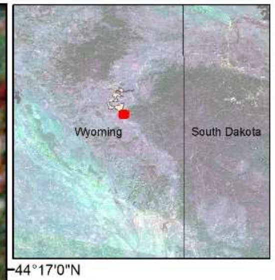
PlanetScope Sensor Resolution:

- At nadir – 3.0-m (International Space Station orbit, ISS); 3.9-m (sun synchronous orbit, SSO)

PlanetScope Spectral Band Wavelength Range: (in nm)
- Blue – 455 to 515
- Green – 500 to 590
- Red – 590 to 670
- NIR – 780 to 860

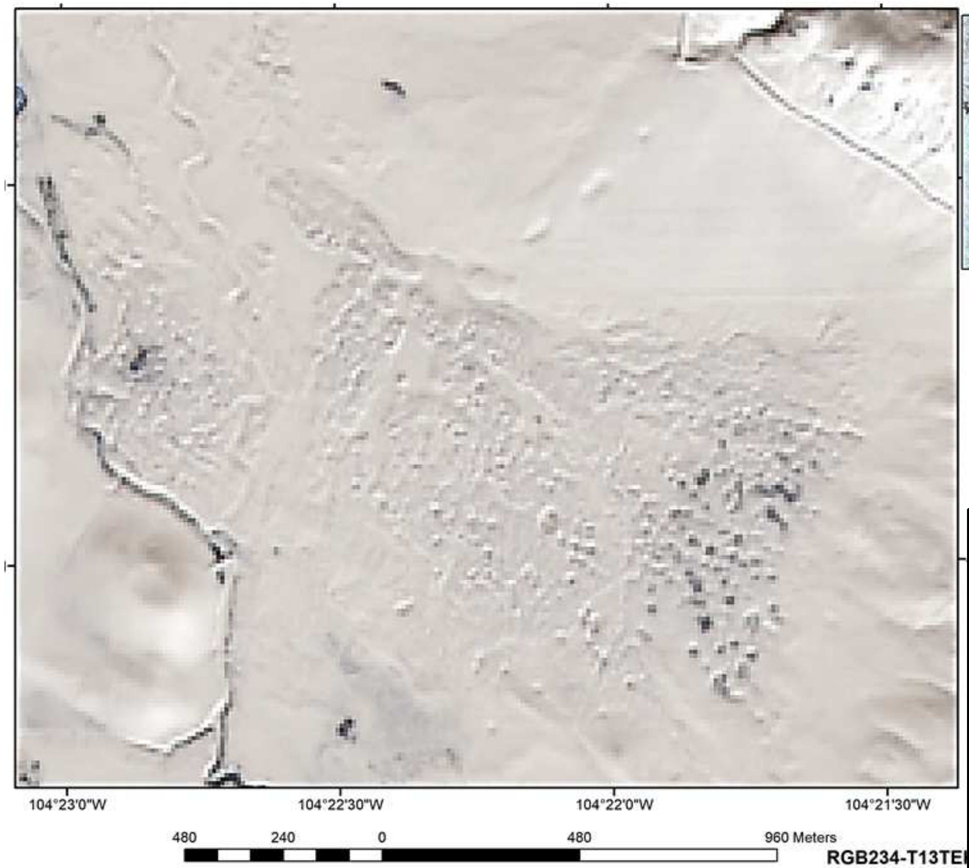
Doline Fields visible on a PlanetScope Image and the corresponding Google Earth Scene





PlanetScope RGB-image merged with the Morphologic Convolution, Directional (40°) image product

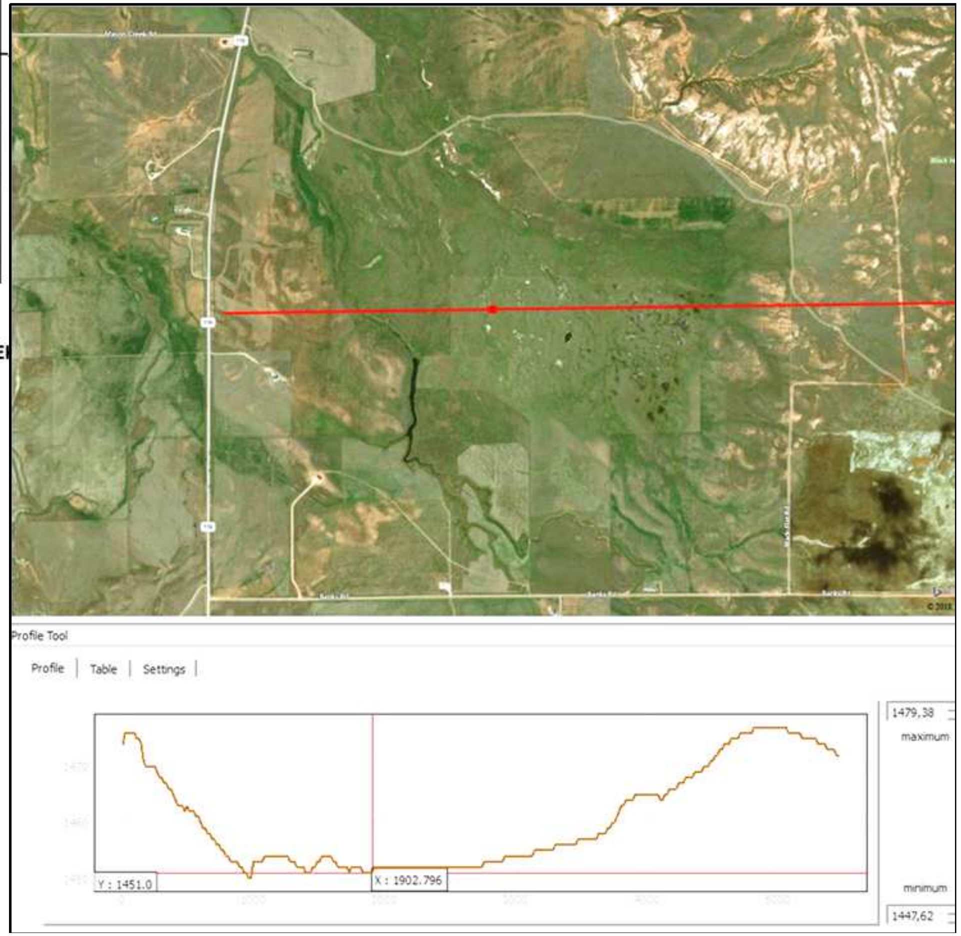
Doline fields showing vegetation with higher photosynthetic vitality (red colors)



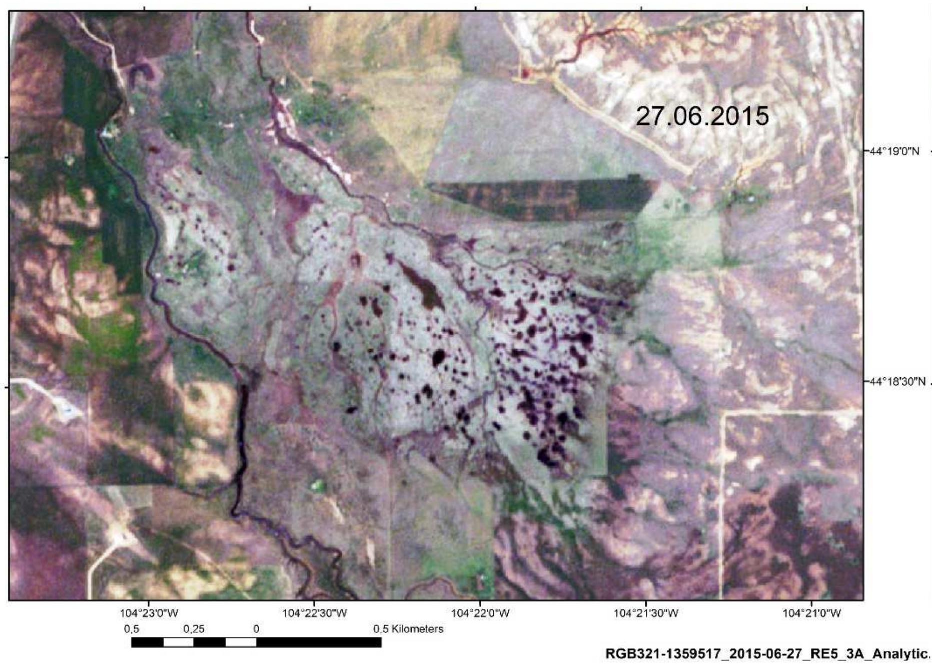
Karst development in evaporitic rocks in the NW of the Black Hills leading to doline fields

Doline Fields in the NW of the Black Hills

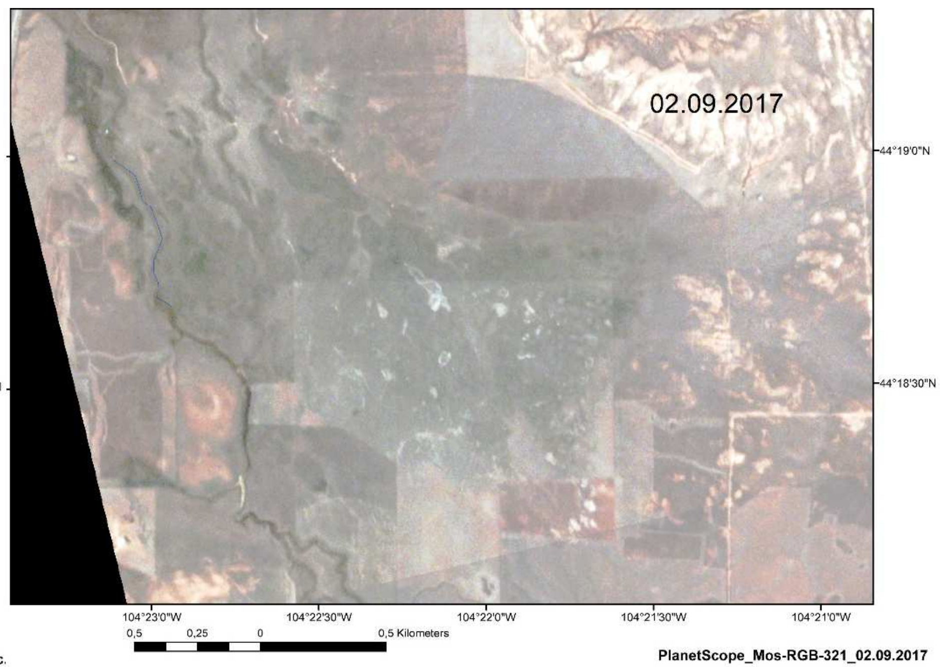
Snow covered Sentinel-2-scene of the karst area in the NW of the Black Hills in comparison with a World Imagery-scene of the same area



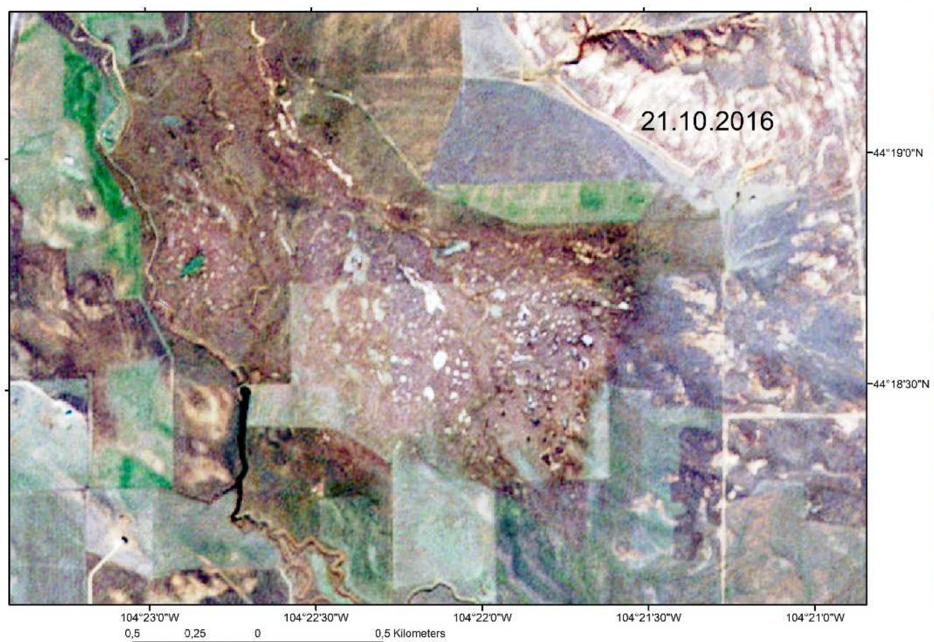
Seasonal Changes documented by RapidEye Satellite Images



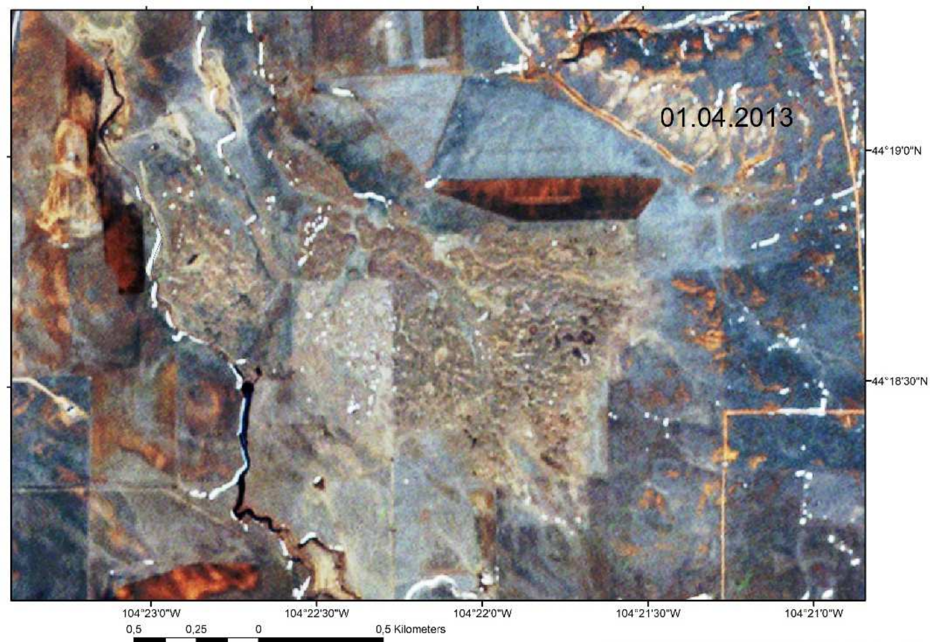
RGB321-1359517_2015-06-27_RE5_3A_Analytic.



PlanetScope_Mos-RGB-321_02.09.2017

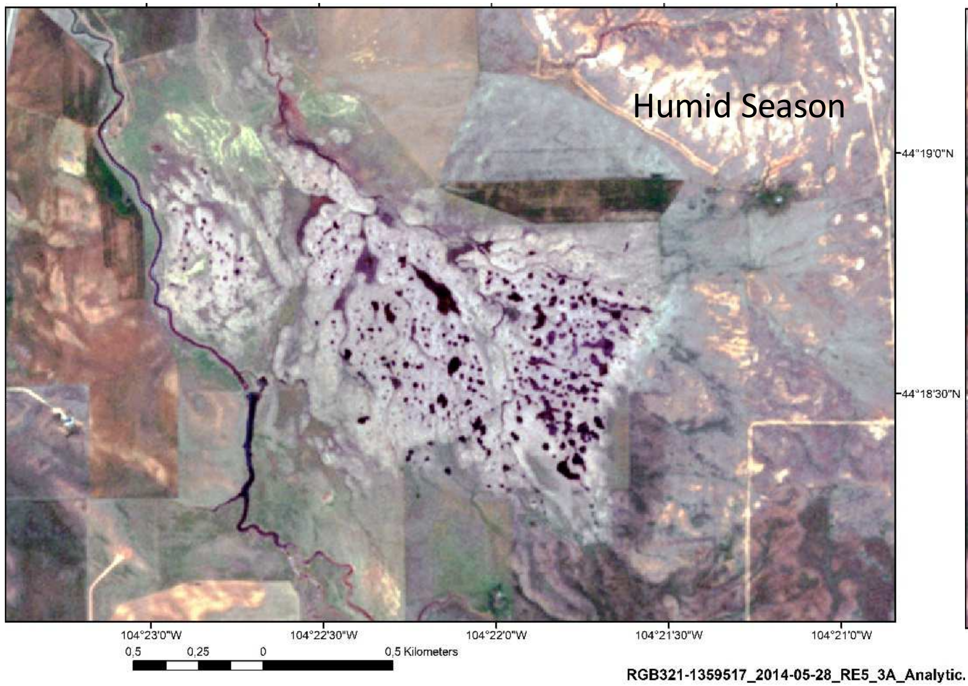


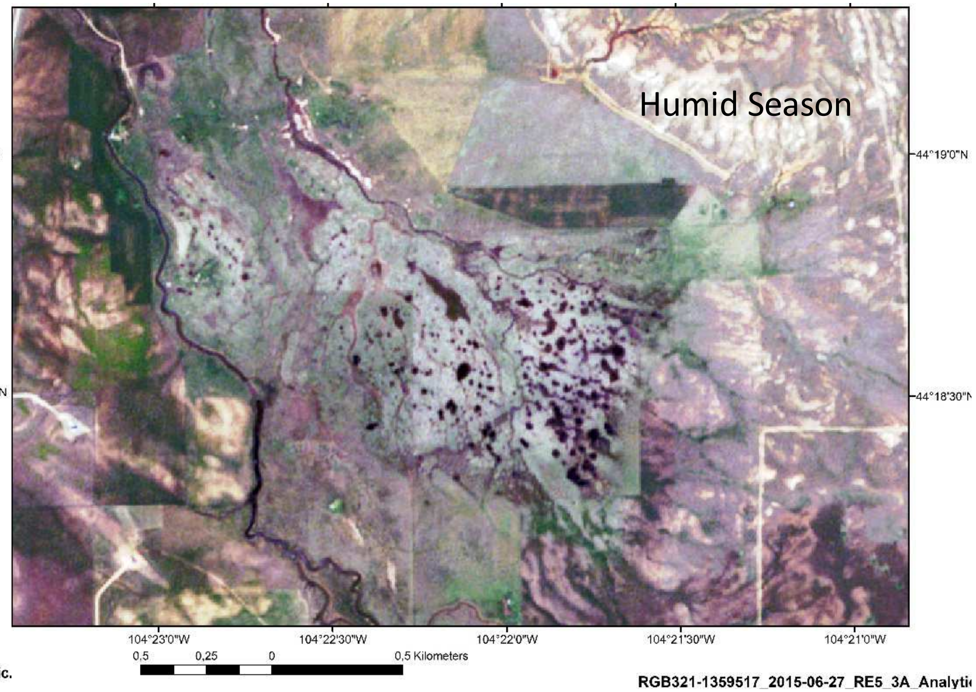
RGB321-1359517_2015-10-21_RE2_3A_Analytic

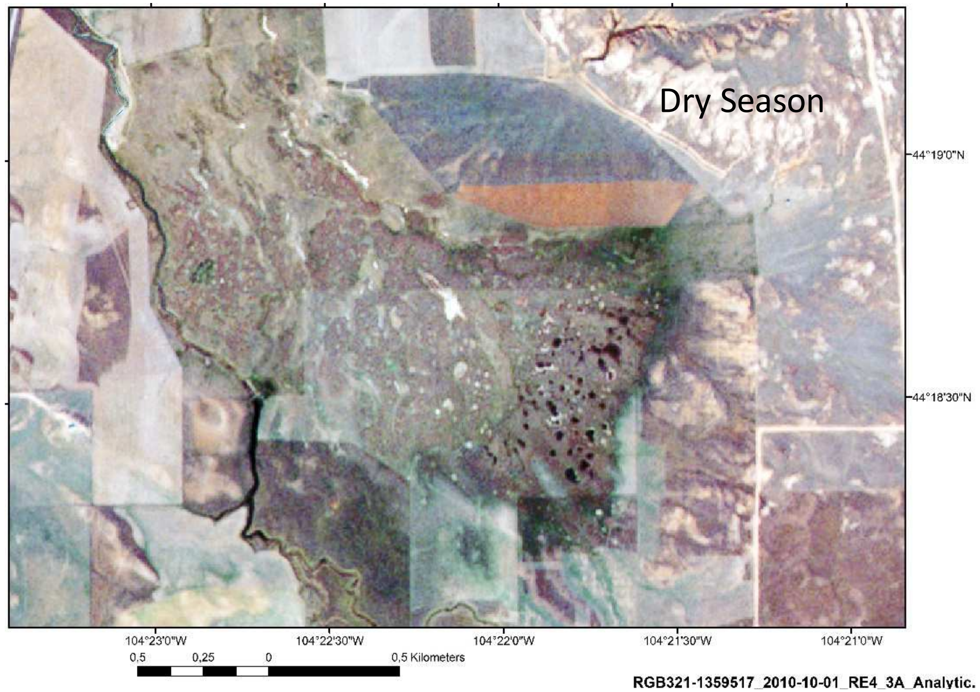


RGB321-1359517_2013-04-01_RE2_3A_Analytic.

Seasonal Changes documented by RapidEye Satellite Images

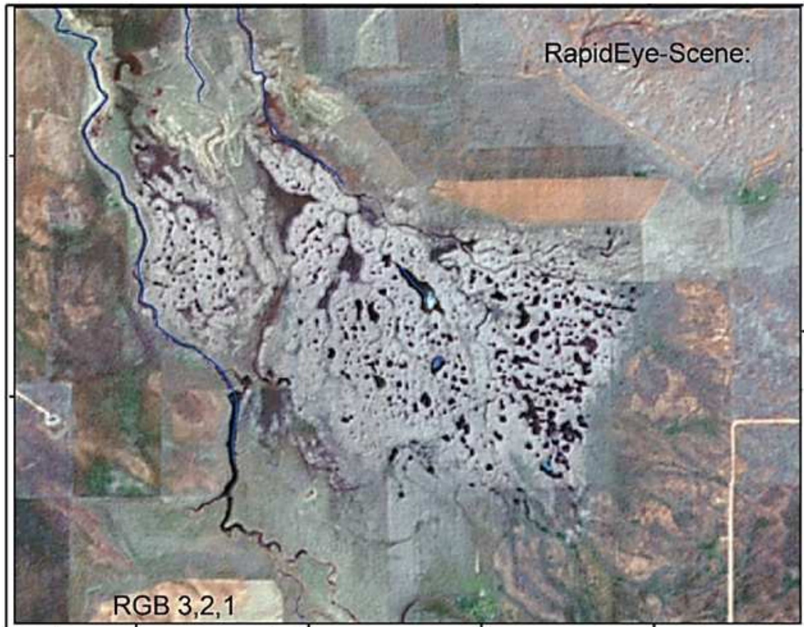


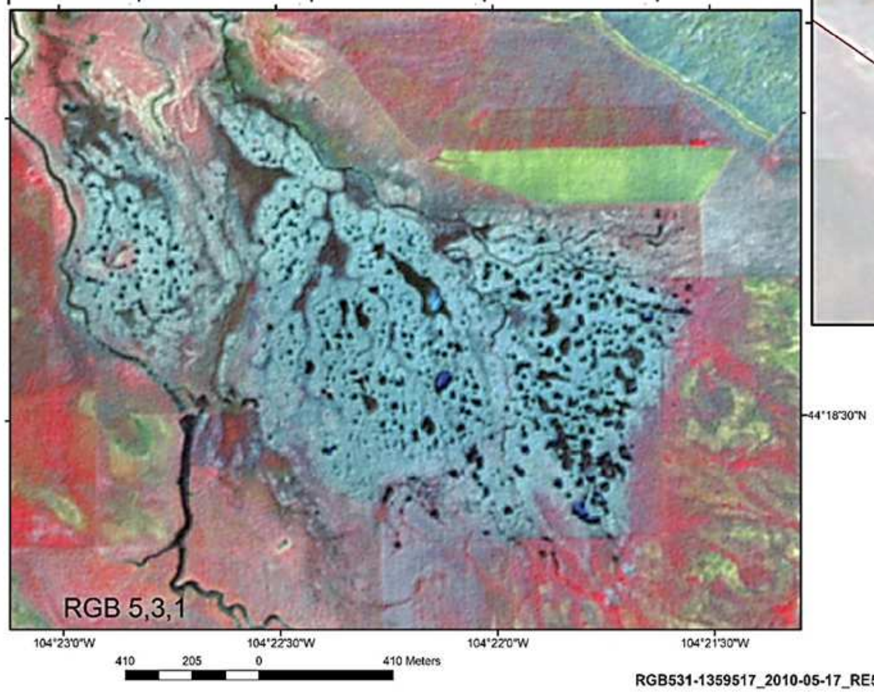




During the dry season there is no more water body visible. Evaluating the RapidEye-scene of May 2010 the linear arrangement of the small ponds becomes obvious leading to the conclusion that subsurface structures have an influence on their distribution . The structural influence on doline development can be partly derived from lineament analysis. The doline clusters occur in areas where SW-NE and SE-NW oriented lineaments are intersecting.

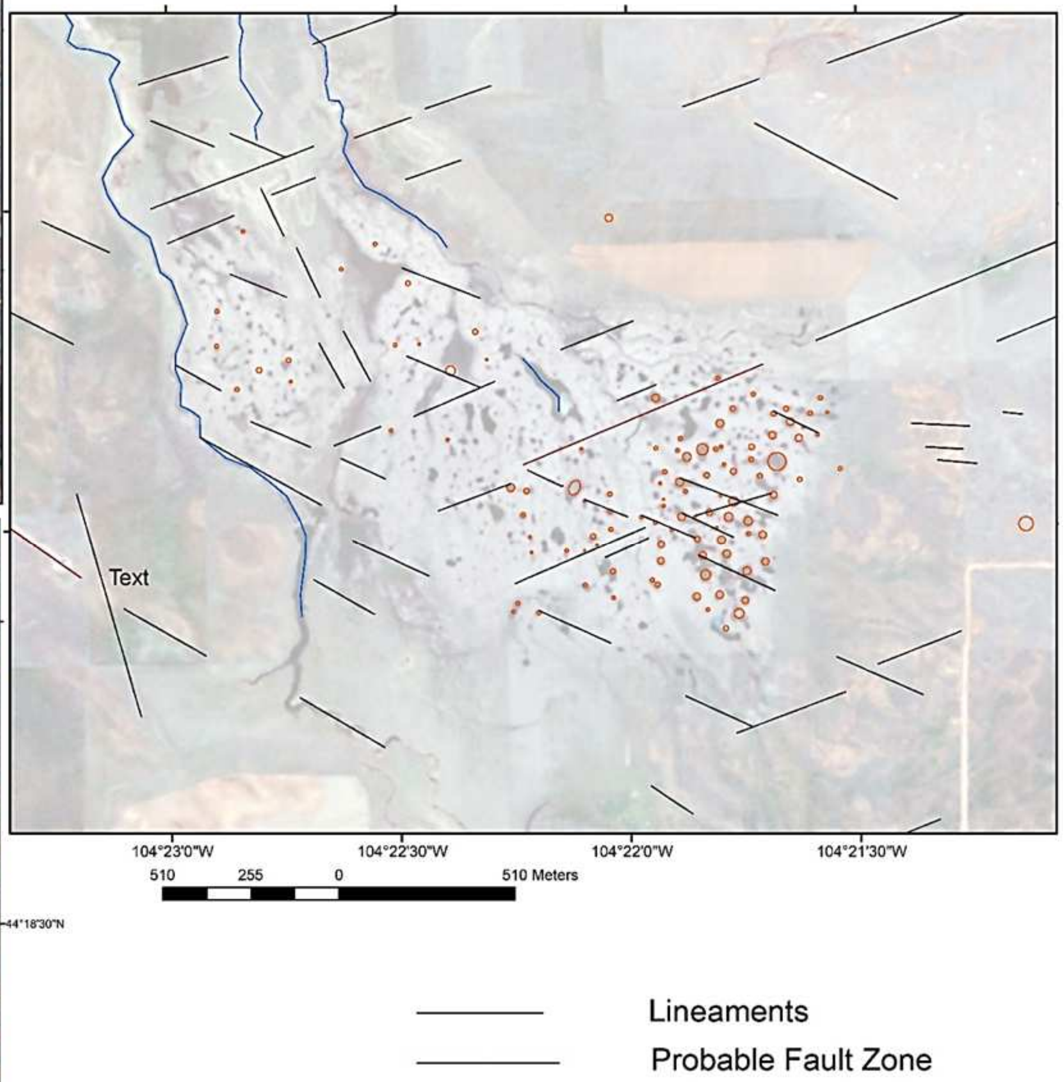
Linear Arrangement of Dolines



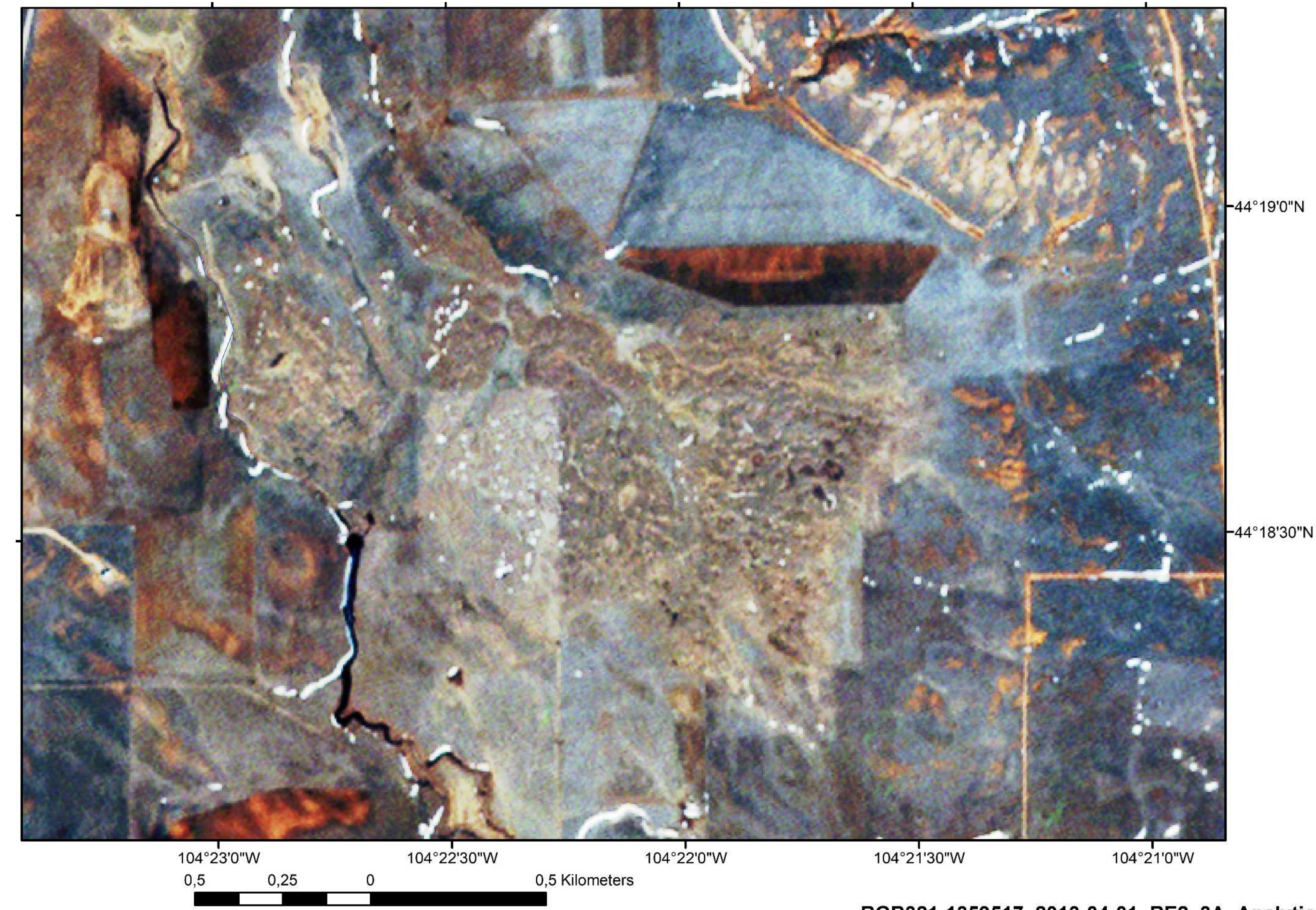


RGB531-1359517_2010-05-17_RE5_3A_Analytic

Structural Influence on Doline Distribution

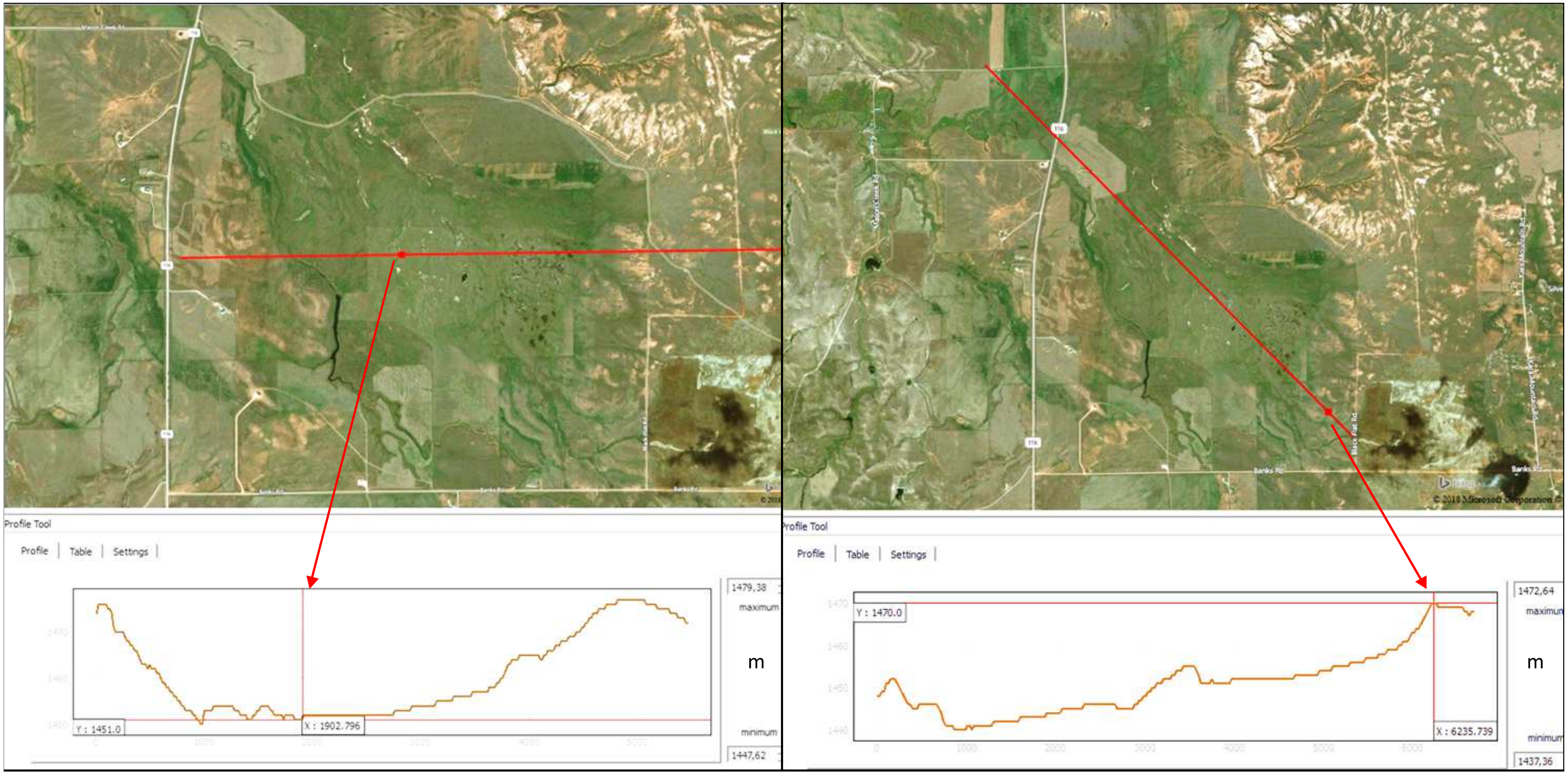


Dolines covered by Snow in April 2013



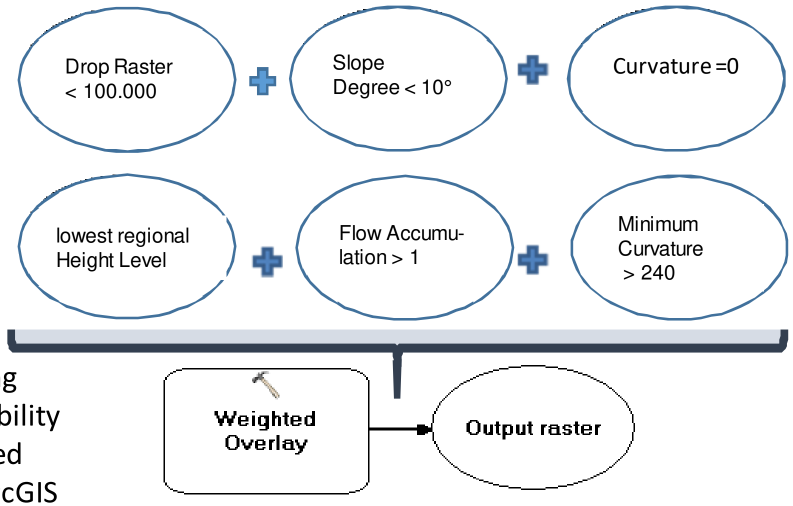
RGB321-1359517_2013-04-01_RE2_3A_Analytic.

Topographic Cross-Sections of the Doline Field



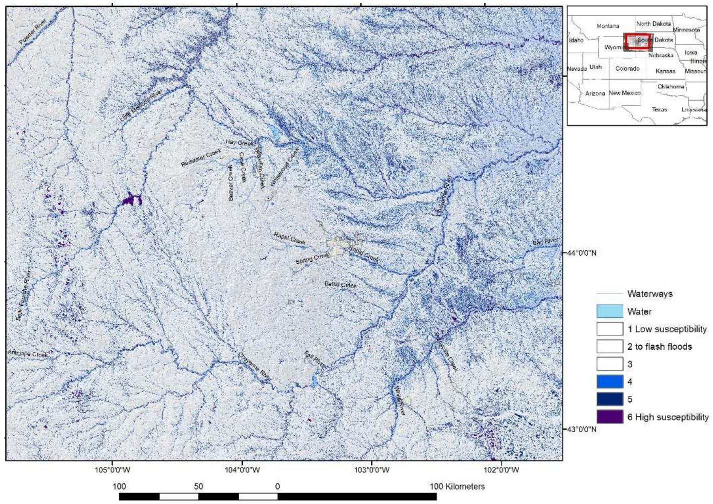
The doline fields are situated within larger valleys, however, most of the dolines are not concentrated in the lowest valley parts, but more near the foot slopes, where surface water run-off from the upper hills and infiltration into the down-slope sediments is providing the water for the dissolution processes.

Workflow of the Weighted Overlay of Causal / Preparatory Factors influencing the Susceptibility to a relatively higher Surface Water Input after Precipitations



Aggregation of causal, morphometric factors influencing flooding susceptibility using the weighted overlay-tool in ArcGIS

Result of the weighted overlay calculation



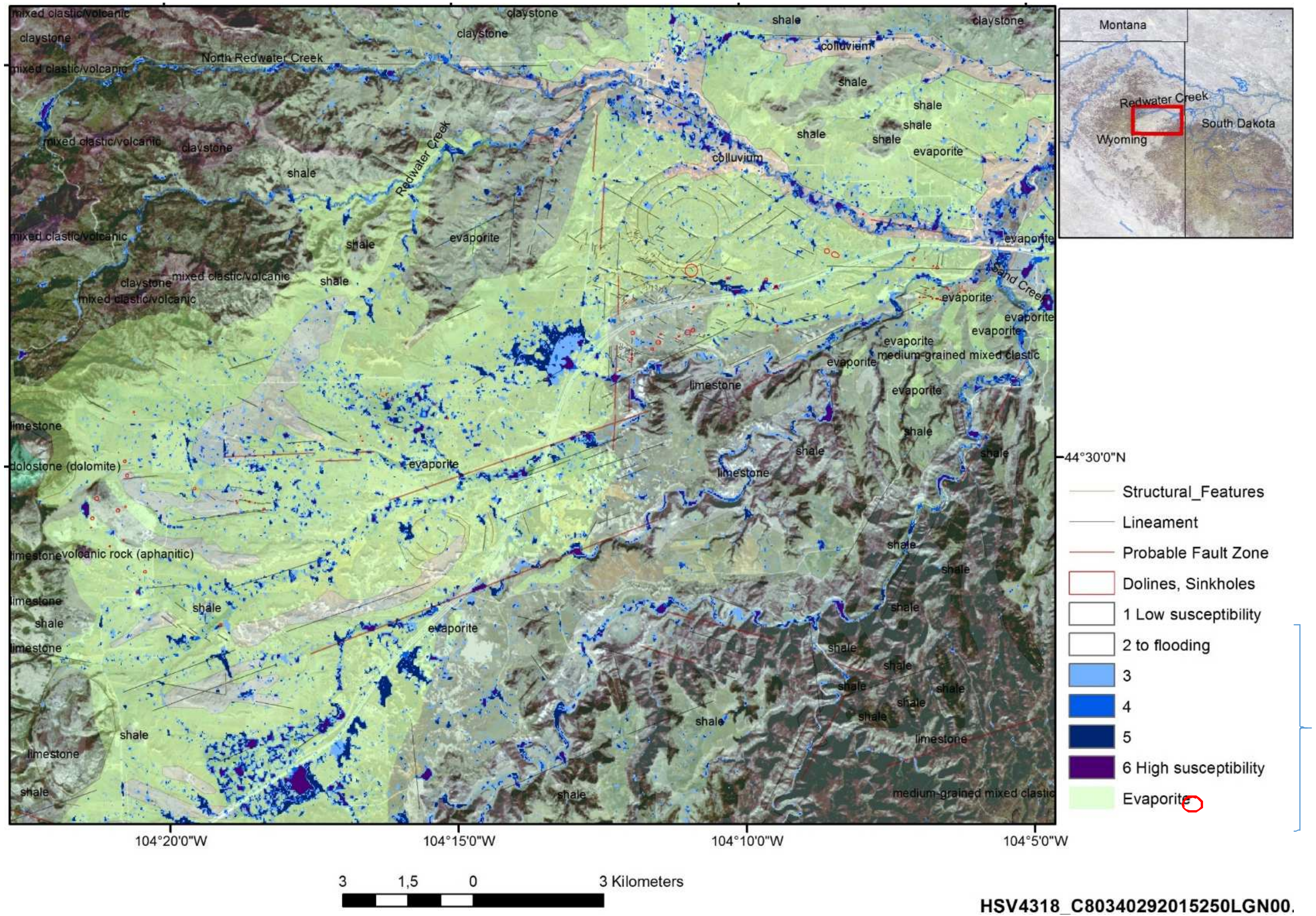
The resulting maps are divided into **susceptibility classes.** The susceptibility to flooding is classified by values from 0 to 6, whereby **the value 6** is standing for the **highest, assumed susceptibility due to the aggregation of causal / preparatory factors**.

The weighted overlay approach in a GIS can be used for the detection and identification of endangered lowland areas susceptible to higher surface water input and flooding. *Due to the aggregation of the below mentioned, morphologic factors these areas are more susceptible to higher water infiltration and flooding than the environment in case of flash floods.*

Based on Digital Elevation (DEM) data the following morphometric factors are extracted and then aggregated in the weighted overlay tool of ArcGIS:

- Lowest, local height levels
- flat terrain, calculating terrain curvature (curvature values= 0 , calculated in ArcMap, minimum curvature > 250 , calculated in ENVI)
- slope gradients < 10°
- drop raster < 100.000 and
- high flow accumulation value

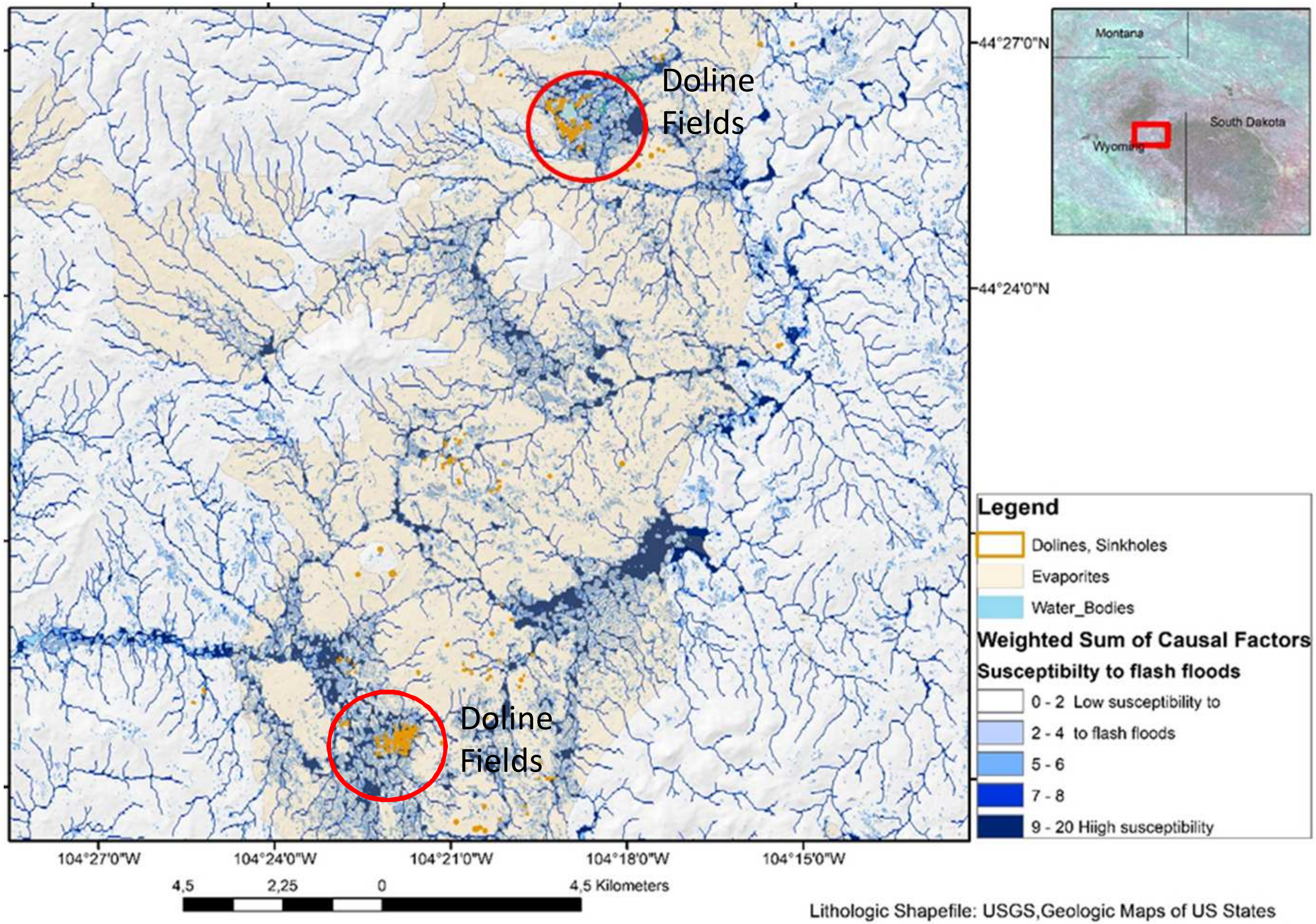
The identification of those areas supports the knowledge of areas where karstification processes might be more intense due to the higher water input.



Weighted overlay of morphometric factors influencing the amount of surface water input. Dark-blue areas are assumed to get higher surface water input after precipitations due to their geomorphologic disposition.

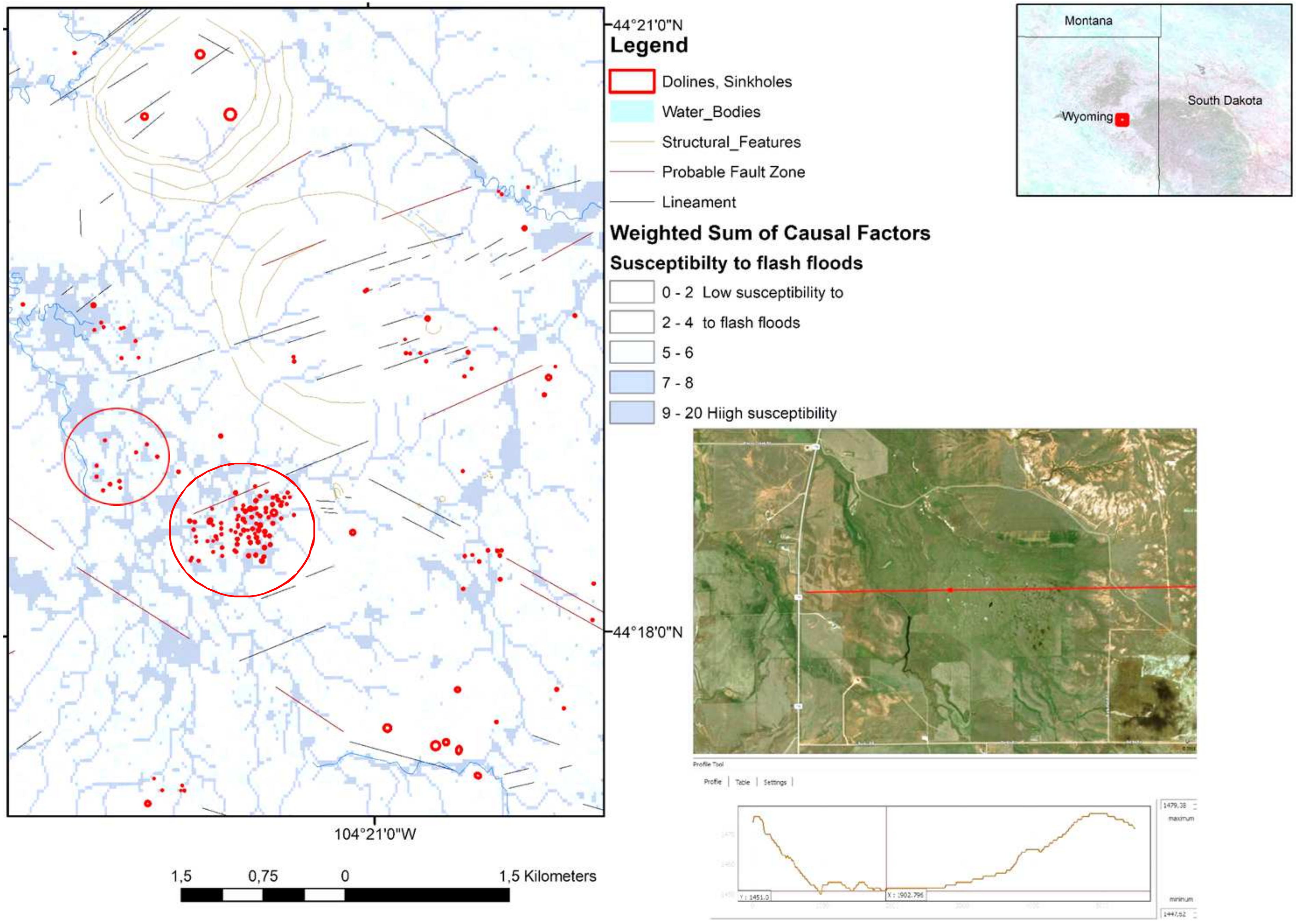
Some of the factors influencing the development of karst phenomena:

- Lithologic properties: evaporites, limestones, dolomites
- Structural pattern: fracture and fault zones, anticlines, synclines, etc.
- Surface water input: dissolution processes are likely to be more intense in areas with relatively higher surface water input after rain fall what can be derived from the terrain morphology



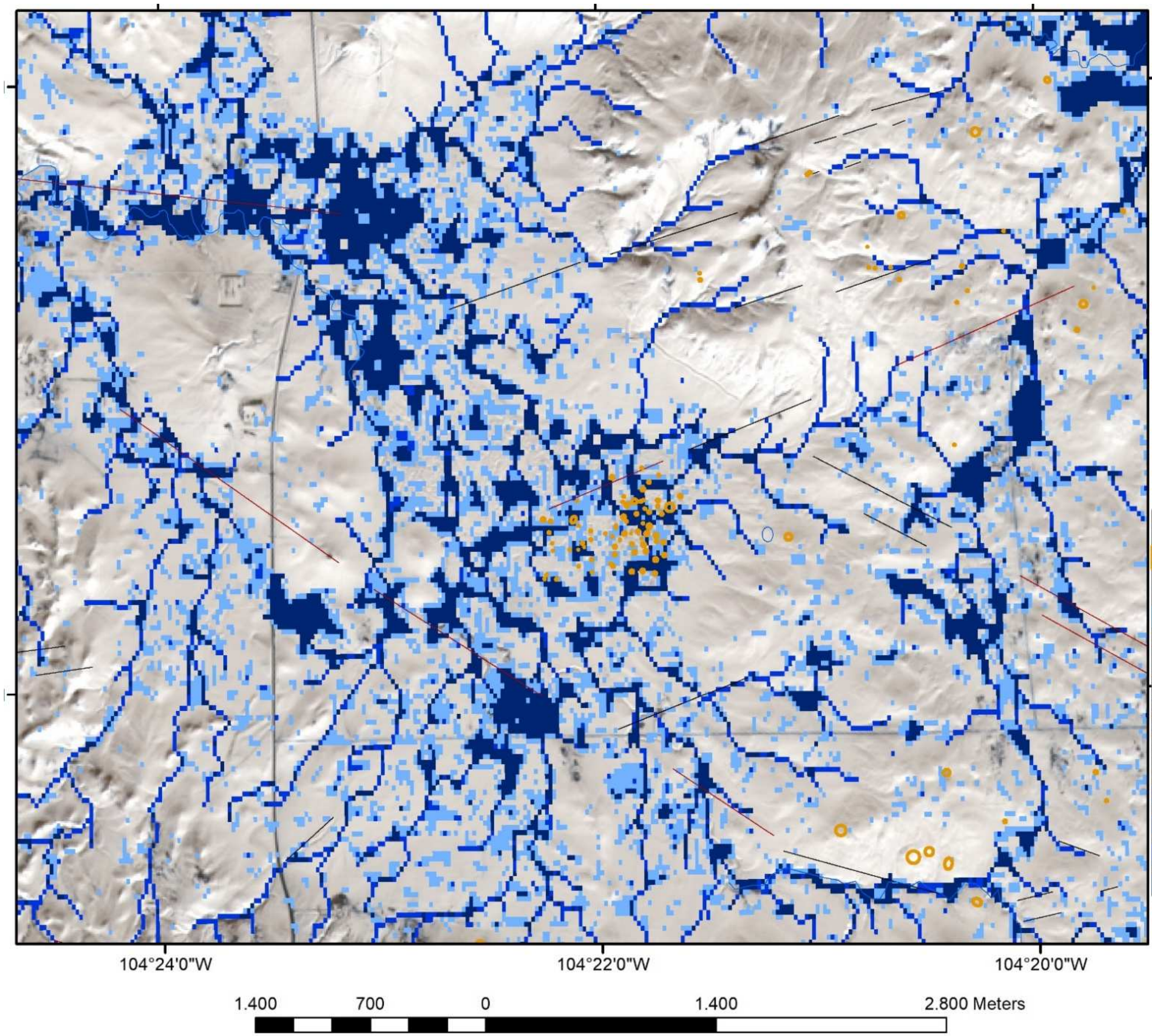
Weighted sum of causal, morphometric factors influencing surface water input and groundwater flow showing areas prone to higher suface water input in blue colors, doline fields occurring within broader valleys and depressions (visible in dark-blue, doline fields - red circle)

Doline Fields

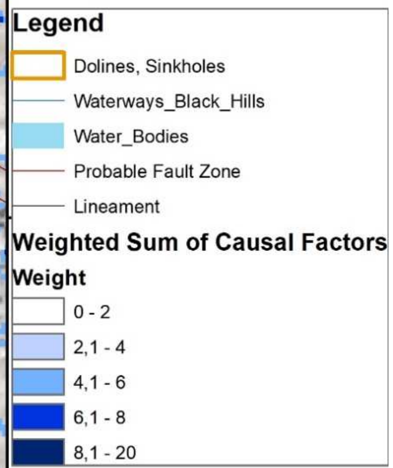


Weighted Sum of Causal Factors influencing the Susceptibility to Flash Floods

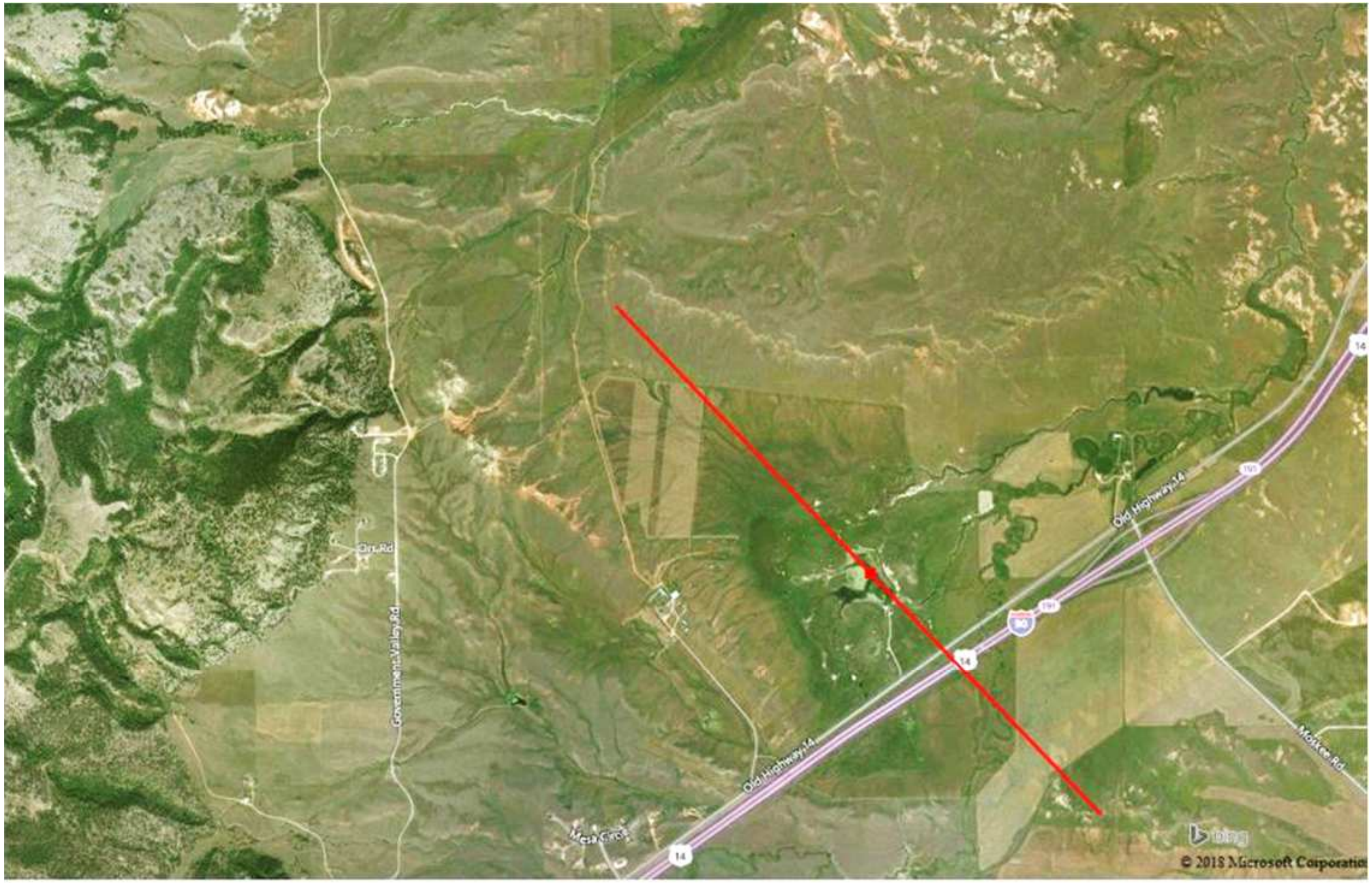
(slope ° < 10 ° + curvature=0 + aspect=(-1) + dropraster> 100.000 + flow accumulation >100 + lowest, local height level height level)

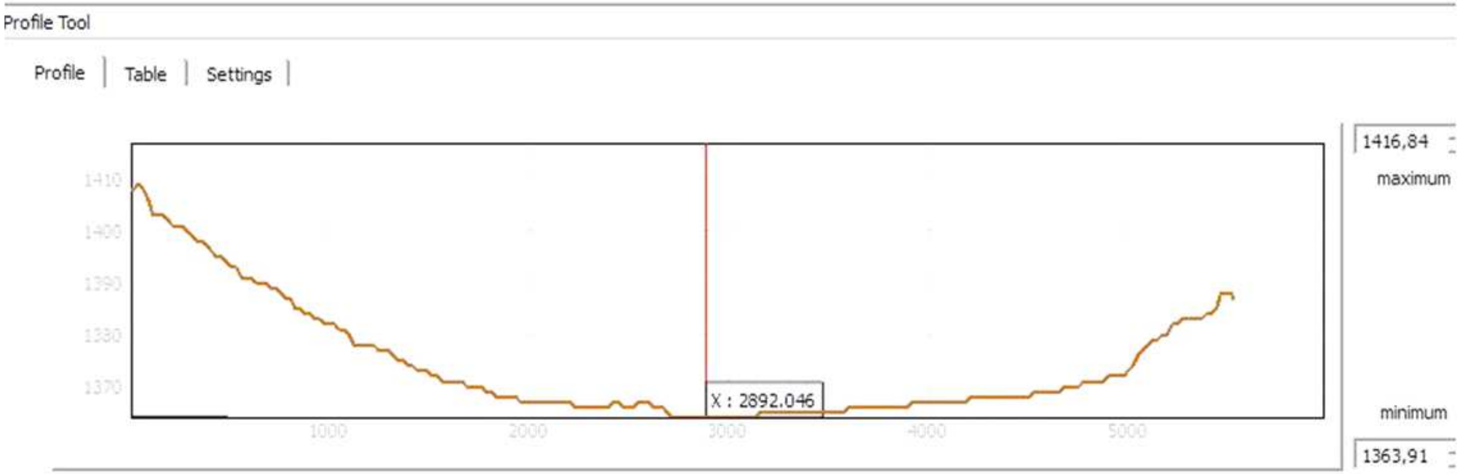


Doline fields occur concentrated in areas with higher surface water input due to the morphometric conditions.



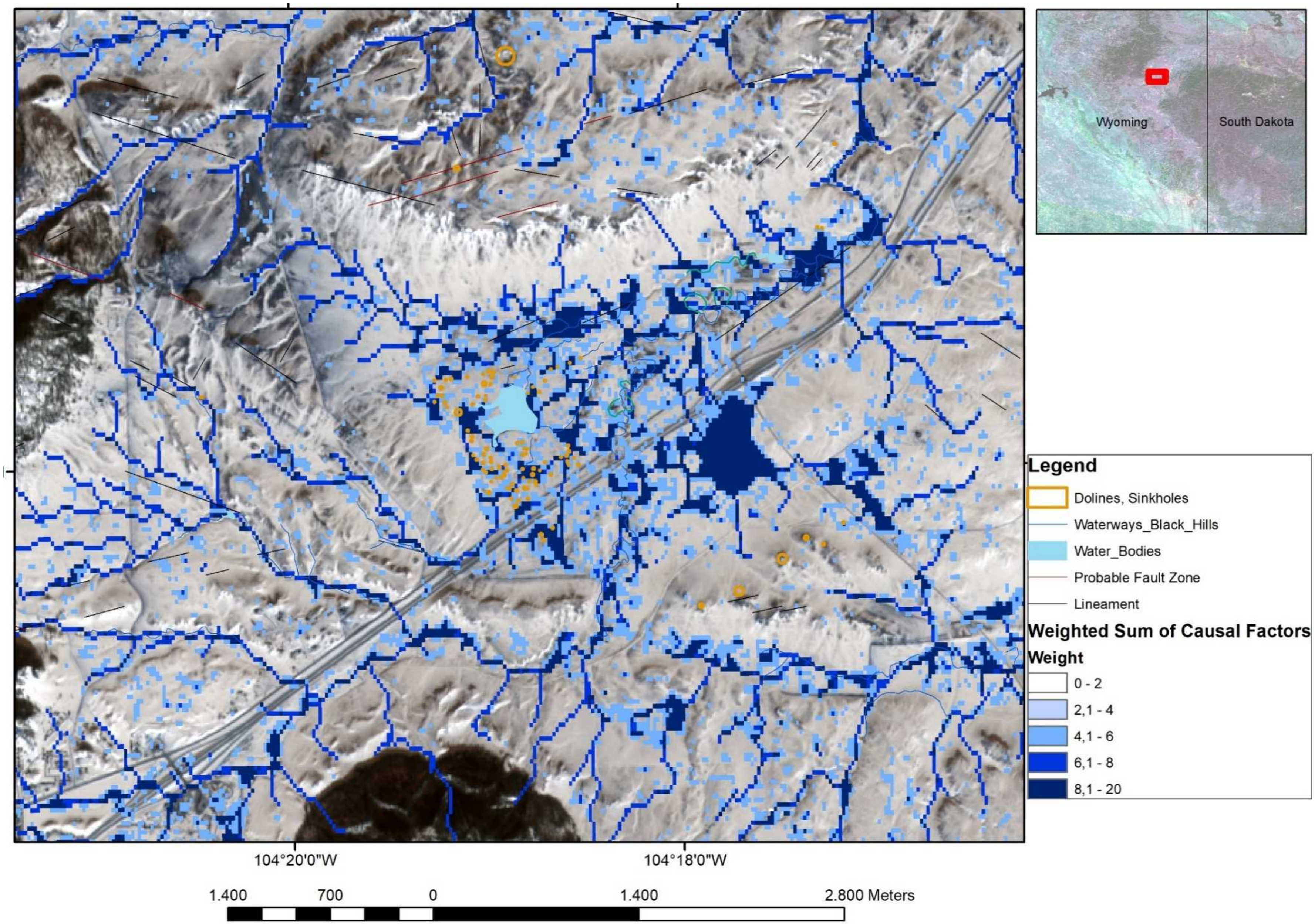
Topographic Cross-Section of the Doline Field Area





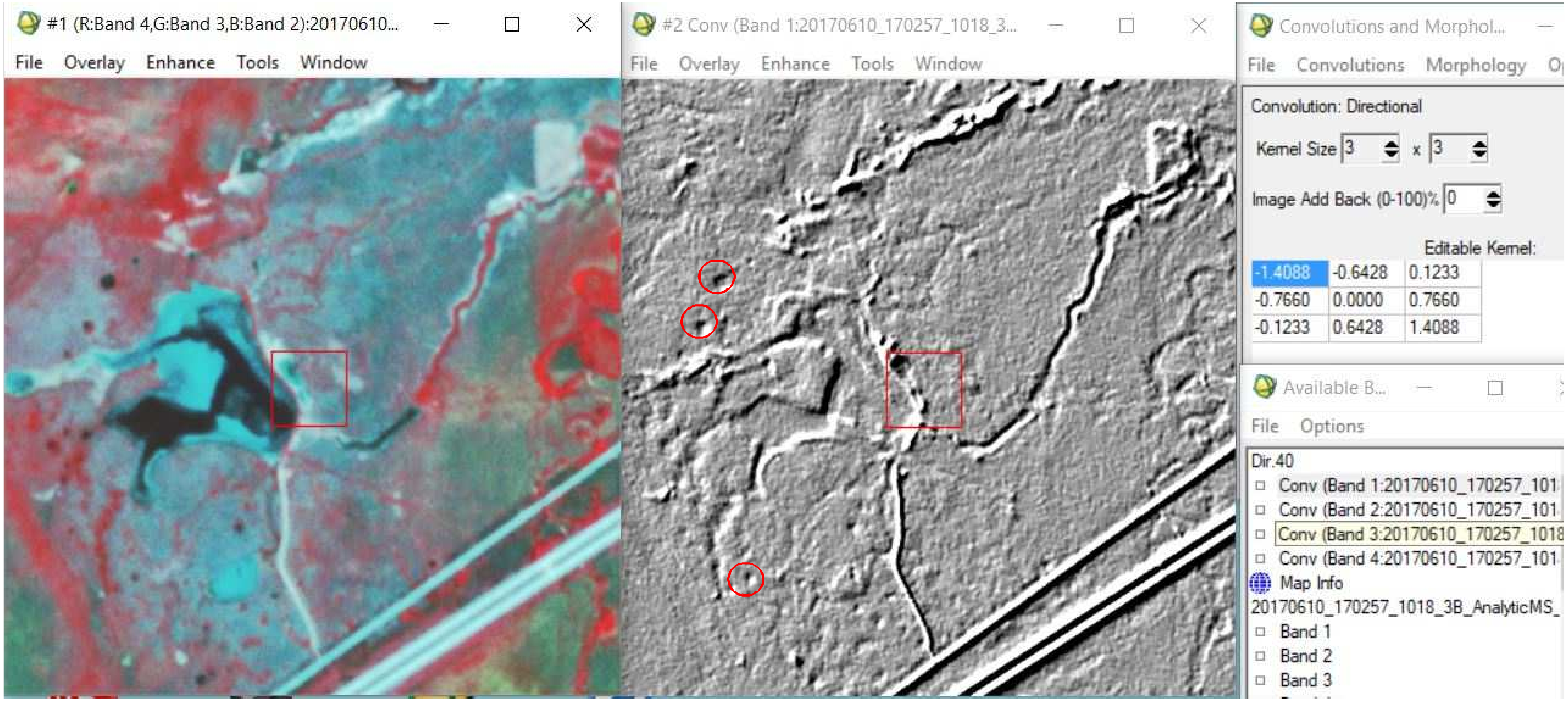
Doline Fields in Areas prone to Flash Floods

Weighted Sum of causal, morphometric Factors influencing the Susceptibility to Flash Floods



Doline Fields

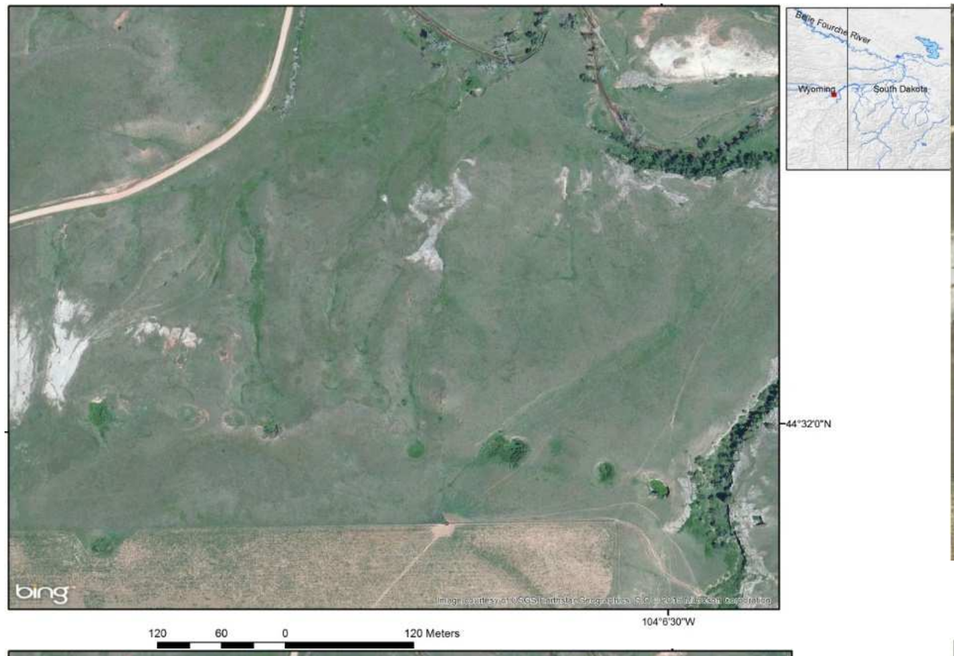
Merging RGB-PlanetScope-Images with Morphologic Convolution-Directional-Images

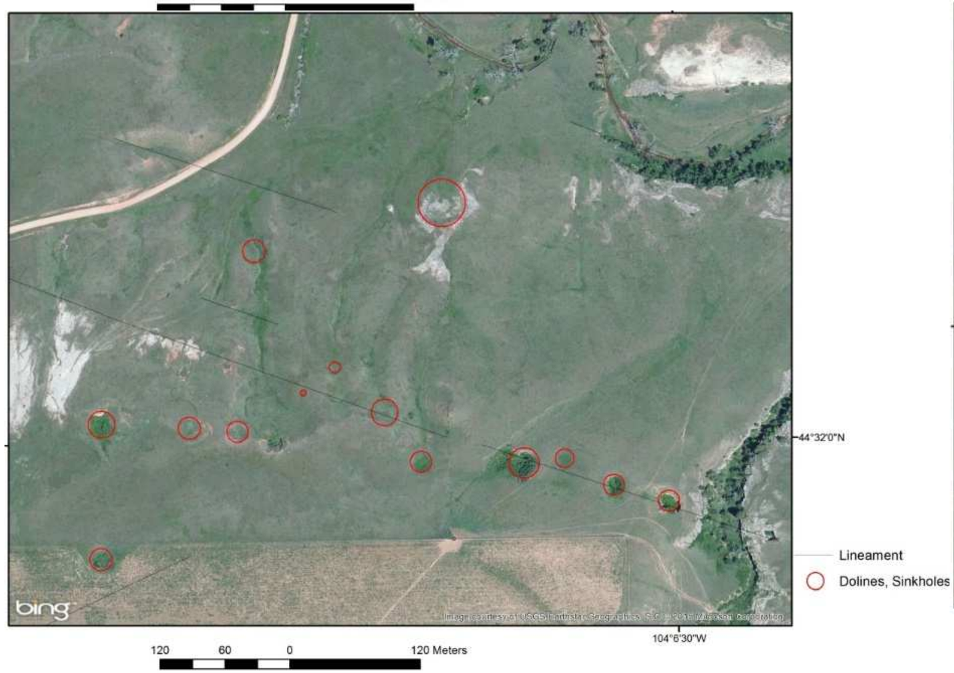


Dolines become visible.

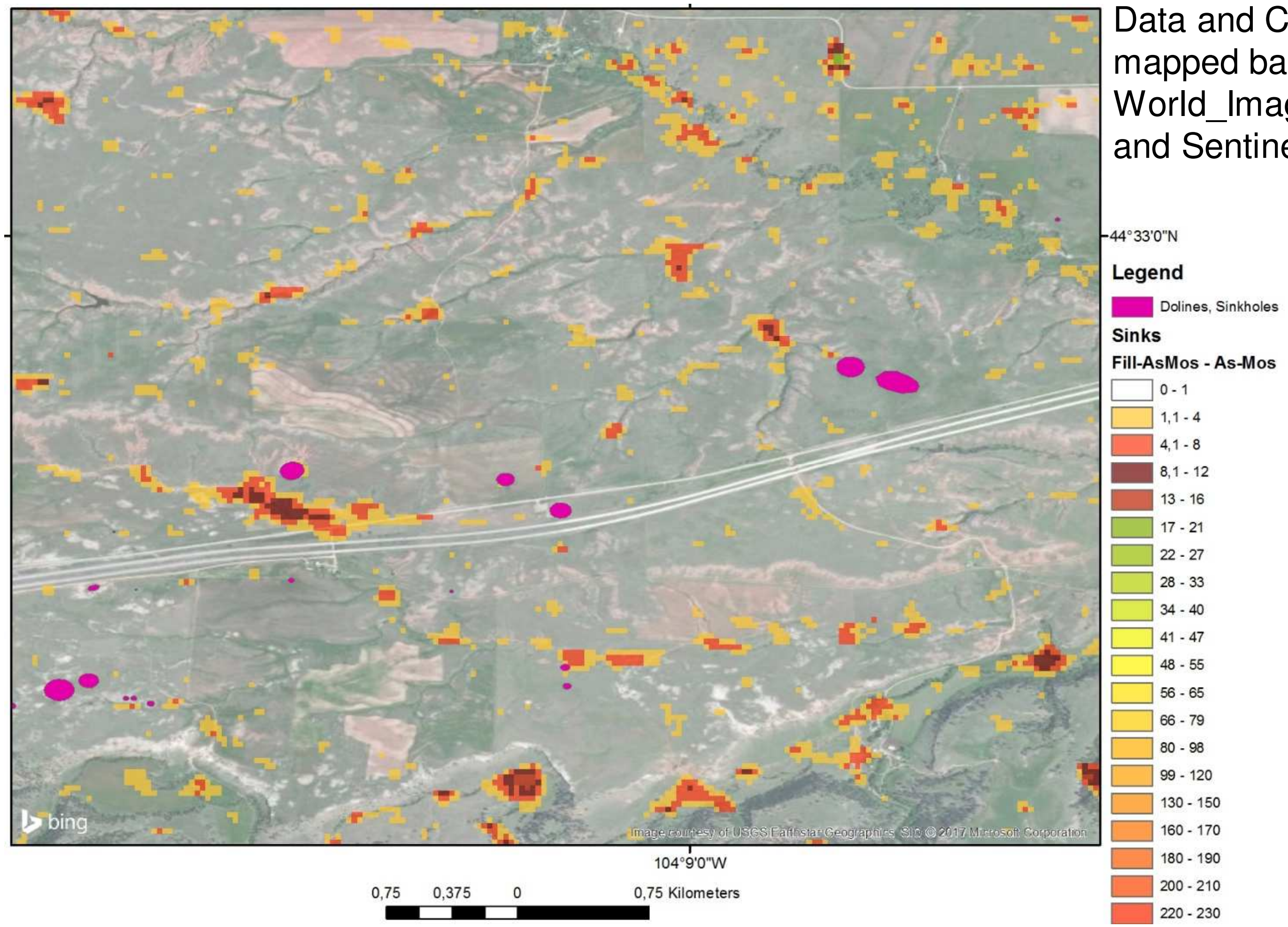
Fault and Fracture Zones influencing the linear Arrangement of Dolines in the Northern Black Hills

Fault and Fracture Zones influencing the linear Arrangement of Dolines in the Northern Black Hills





Detection of Depressions based on DEM-Data and Comparison with Depressions mapped based on BingMap_Aerial, World_Imagery, RapidEye, PlanetScope and Sentinel-2-Data

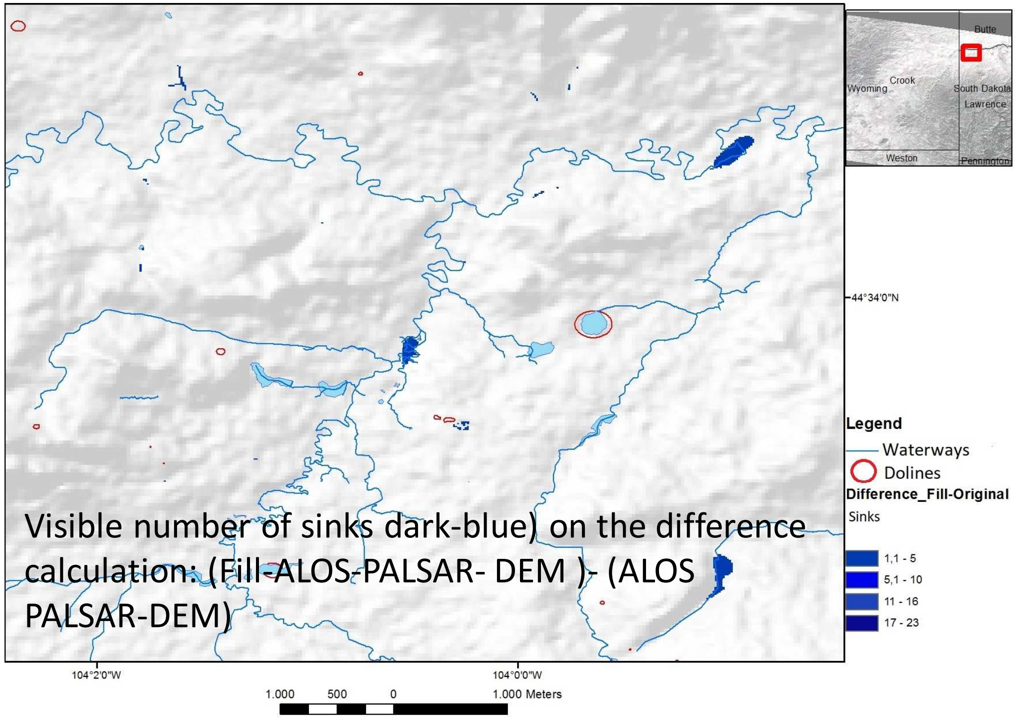


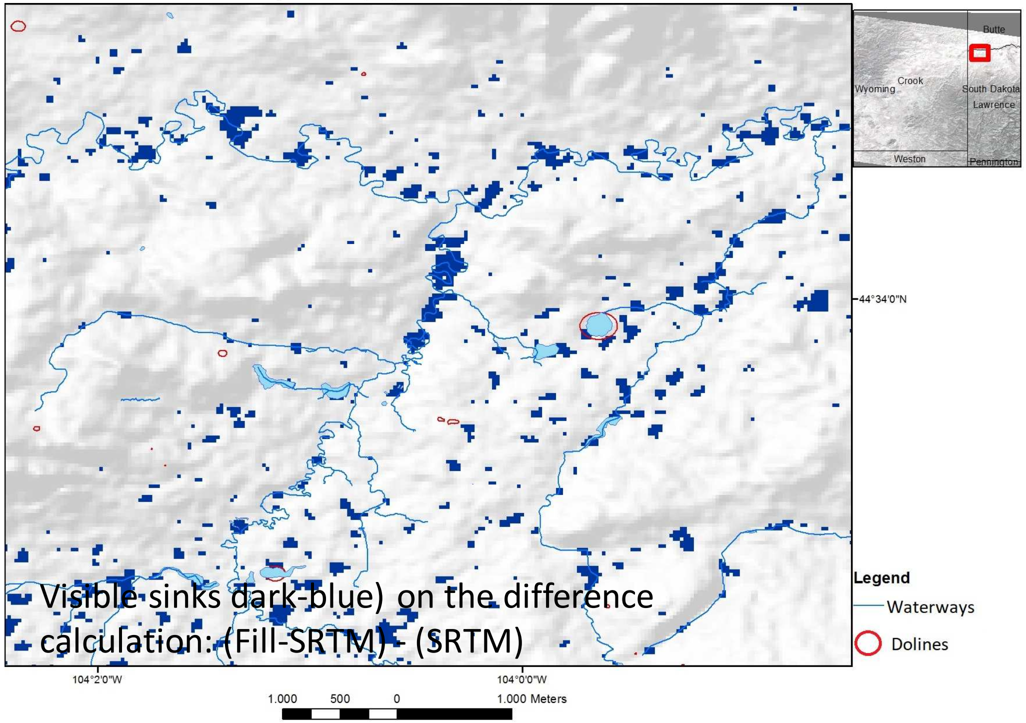
Several useful tools for processing digital elevation data exist in ArcGIS, especially the hydrology tools and the surface tools.

Aiming to detect circular or oval shaped depressions a digital map of depressions can be easily obtained by the map algebra operation of subtracting the depression-free DEM from the original DEM:

(Fill-Aster-Mosaic) - (Aster-Mosaic)

Detection of Depressions based on DEM-Data

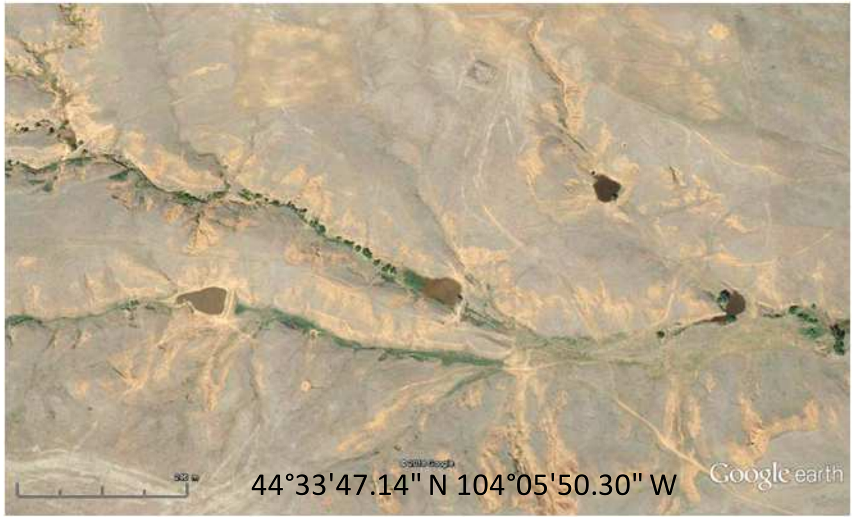




Trying to detect collapsed dolines on DEM derived data based on DEM data derived maps such as the sink calculation, it does not provide results related to dolines in the investigation area. The difference between the Fill-DEM and the original DEM shows the sinks, situated mostly within river beds on both, SRTM and ASTER DEM derived sink calculations. Although presenting a higher spatial resolution, the ALOS-PALSAR DEM derived maps show even less evidence and correlation with depressions and sinkholes related to karst. The ALOS-PALSAR-calculated sinks are situated within riverbeds and drainage courses as well. Thus, the sink calculation seems not to be suited for the detection and inventory of sinkholes in this area.

Man-made Sinks

Reservoirs



Natural Sinks

Doline

It is sometimes difficult to detect based on remote sensing data alone whether artificial water bodies as reservoirs were built in natural depressions or were man-made only.

Karst features in the McNenny National Fish Hatchery

Visual evaluation has to be carried out in order to prevent errors in the inventory of karst features. Often reservoirs have been created in depression related to karst, such as in the case of the Mirror Lake.

Gully Soil Erosion in the Northern Part of the Black Hills in Limestones and Dolomites

Increasing extreme weather events such as flash floods will intensify erosion and, thus,the infiltration of surface water into the subsurface and solution processes

Images: Theilen-Willige, 27.05.2017

Conclusions

Evaluations of different satellite data have contributed to the systematic inventory and mapping of surface-near karst features in the Black Hills area. When analyzing circular and oval-shaped forms visible on satellite images within lithologic units prone to karst development such as limestones, evaporites and dolostones, several types could be distinguished: larger circular features, enclosed depressions and sinkholes / dolines. The complex origin and development of the larger circular features will need further investigations for detailed clarification.

Enclosed depressions, partly with complex origin, are the prevailing forms within the karst prone lithologic units. After precipitation during the humid season, especially after flash floods, depressions are partly flooded. Dolines and depressions are filled then with surface water and form temporary ponds. As soil moisture is retained longer in sinkholes and depressions than in the flatter environment, the photosynthetic activity of vegetation is more intense, what leads to the visibility of circular depressions on satellite images. Thus, depressions can be detected on satellite images that are often not visible in the field during dryer seasons. Further on, wintertime images showing snow covers support as well the delineation and mapping of the smaller, circular karst features.

Several doline fields were mapped at the northwestern and western margin of the Black Hills, situated within broader valleys and depressions. SRTM-, ASTER-, and ALOS POLSAR-DEM data provide morphometric information about these areas, as well as about the length and diameter of karst features as far as the spatial resolution of the satellite data allows their detection. By aggregating causal, morphometric factors influencing surface water input after precipitations the resulting maps of weighted overlay calculations contribute to a better understanding of the development of doline fields, focusing on the relatively lowest and flattest areas. The systematic, standardized approach according to the weighted overlay contributes to the detection of areas prone to flash floods and higher surface water input due to their morphometric disposition. Within karst affected areas this approach helps to identify those areas where karstification processes might be more intense because of the higher water availability for rock dissolution.

Sentinel-1 and ALOS PALSAR radar images help to identify the structural pattern of the Black Hills. The lineament analysis contributes to a better understanding of the influence of the structural pattern on karst development.

When dealing with the impact of climate change on karst development in this area, long-term reliable observations on karst processes have still to be documented. It can be assumed, however, taking into consideration observations in other karst areas, that in case of intensified extreme weather events with flash floods, dissolution processes and doline collapse will be affected. Therefore, the areas susceptible to flash floods should be monitored continuously.