New Evidence for Long-Term, Salt-Related Deformation at Upheaval Dome, SE Utah*

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Abstract

Upheaval Dome is an eroded structural dome that exposes Mesozoic strata along with associated folds, faults and sand injectites in the Paradox basin, SE Utah. Multiple interpretations for its origin have been proposed, but the two remaining viable hypotheses are at opposite ends of the geologic spectrum: one proposing long-term salt-related deformation and growth of the structure, the other a catastrophic meteorite impact. Analysis of stratigraphic field data collected in Triassic to Jurassic-aged strata adjacent to Upheaval Dome reveals: (1) stratigraphic thicknesses from measured sections for the Kayenta Formation (~199 to ~195 Ma) that range from 7 meters to 224 meters, and projected thicknesses in cross section that can exceed 400 meters; (2) distinct changes in facies distributions in relation to mapped structures; (3) localized angular unconformities and stratal-onlap surfaces; (4) blocks of Triassic Chinle Formation encased in younger Jurassic Wingate Sandstone adjacent to thinned, Wingate lobes, that apparently downlap onto the underlying Chinle. Structural analysis at Upheaval Dome reveals: (1) synclinal growth axes and associated depositional centers shift away from the center of the dome throughout the Late Triassic/Early Jurassic; (2) stratigraphic thicknesses increase across normal faults on the scale of meters to tens of meters; (3) thrust faults within the Kayenta Formation verge to the southeast regardless of location around the structure. These structural features and associated growth strata offer compelling evidence for long-term deformation compatible with salt tectonics at Upheaval Dome during the Late Triassic/Early Jurassic. Sparse indicators of catastrophic impact are present in the Kayenta Formation in the form of two shocked quartz grains, orders of magnitude less than would be expected <1 km from a meteorite impact site. We interpret these grains to be detrital and sourced from outside the Paradox basin. In our interpretation of salt-related deformation, we discuss the merits and drawbacks of a model invoking collapse over a buried salt high to a prior model of a pinched-off diapiric feeder to an eroded salt glacier. The possibility that a meteorite impact of Late Permian to Early Triassic age initiated the growth of an isolated salt pillow in the western part of the northern Paradox Basin requires further investigation.

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AAPG Meeting 2015

A long studied, much disputed structure in SE Utah

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Why should we care about a hole in the ground out in the Utah Desert?

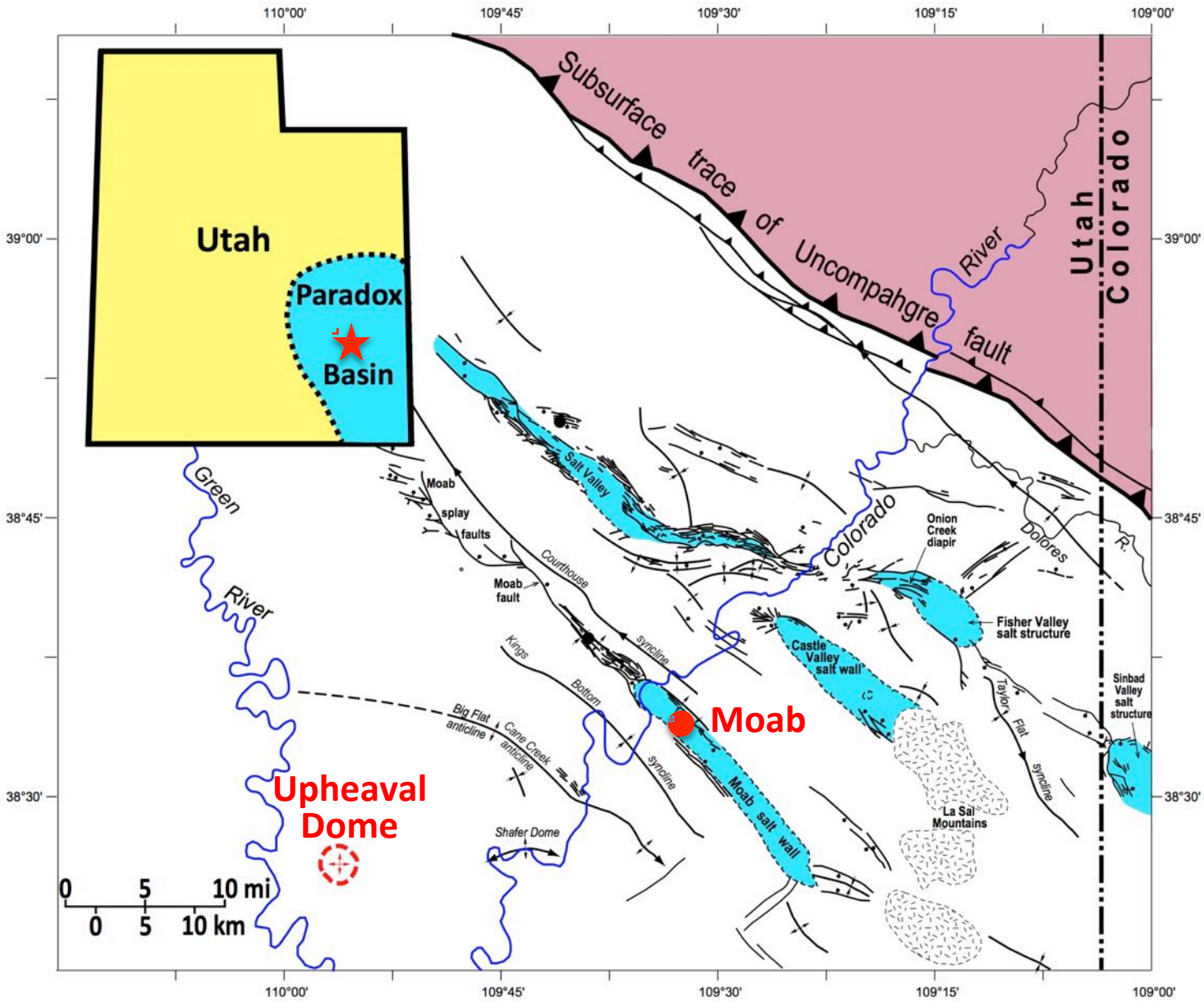
Over the past century or so, various hypotheses have been put for the origin of Upheaval Dome.

In the late 1990s, narrowed to two primary interpretations:

1) A post-Jurassic impact structure, formed within a couple of minutes (e.g., Kriens et al., 1999)

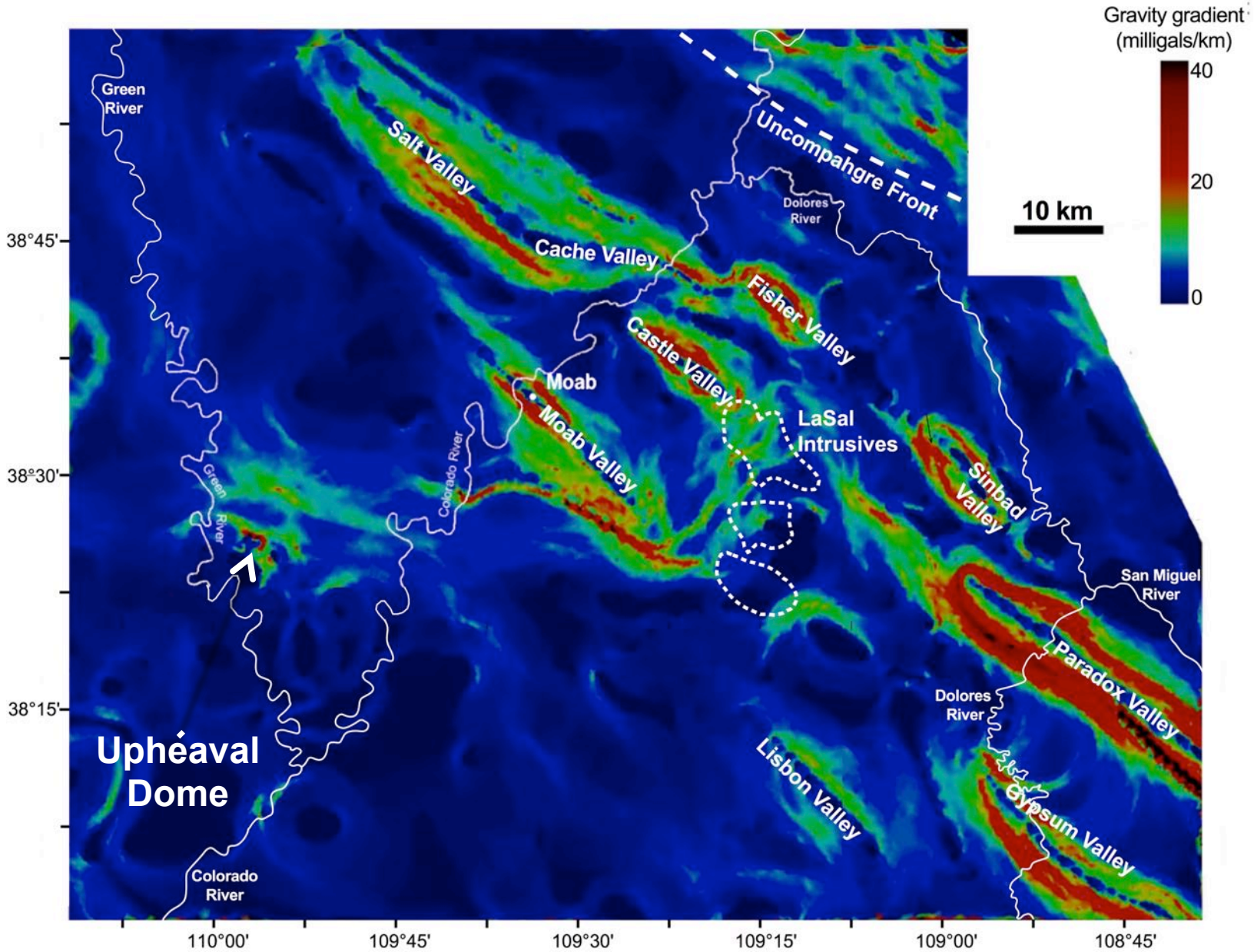
2) A pinched-off salt diapir developed over ~160 million years i.e., late Pennsylvanian-Middle Jurassic (Jackson et al., 1998)

Location and Surface Geology



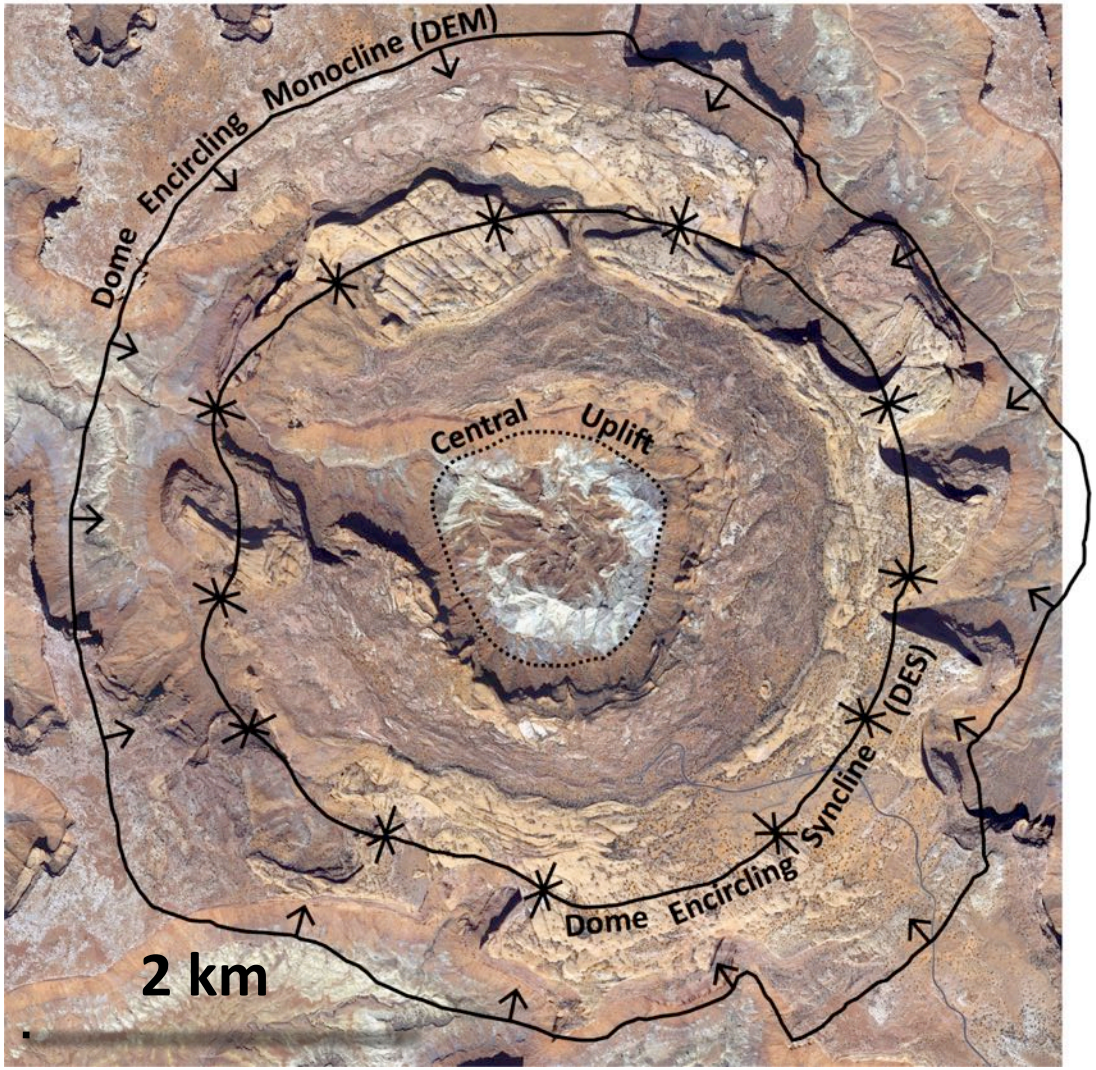
after Doelling, 2001

Gravity gradient map of the northern Paradox Basin



after Banbury, PhD thesis, Univ of Edinburgh, 2005

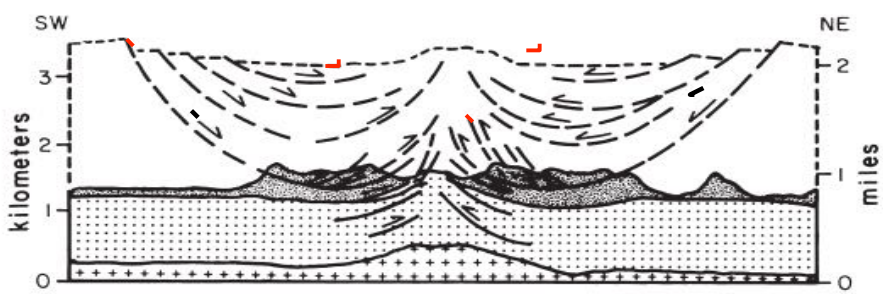
Upheaval Dome: General Information



- Located in Canyonlands National Park, SE Utah
- Cuts 300 meters into surrounding stratigraphy
- Dome Encircling Monocline (DEM) is 5.2 km in diameter
- Dome Encircling Syncline (DES) is 3.6 km in diameter
- Sparsely developed listric normal faults around the syncline and monocline
- Imbricated thrust faults dominate within central uplift
- No Paradox salt in the core of the central uplift

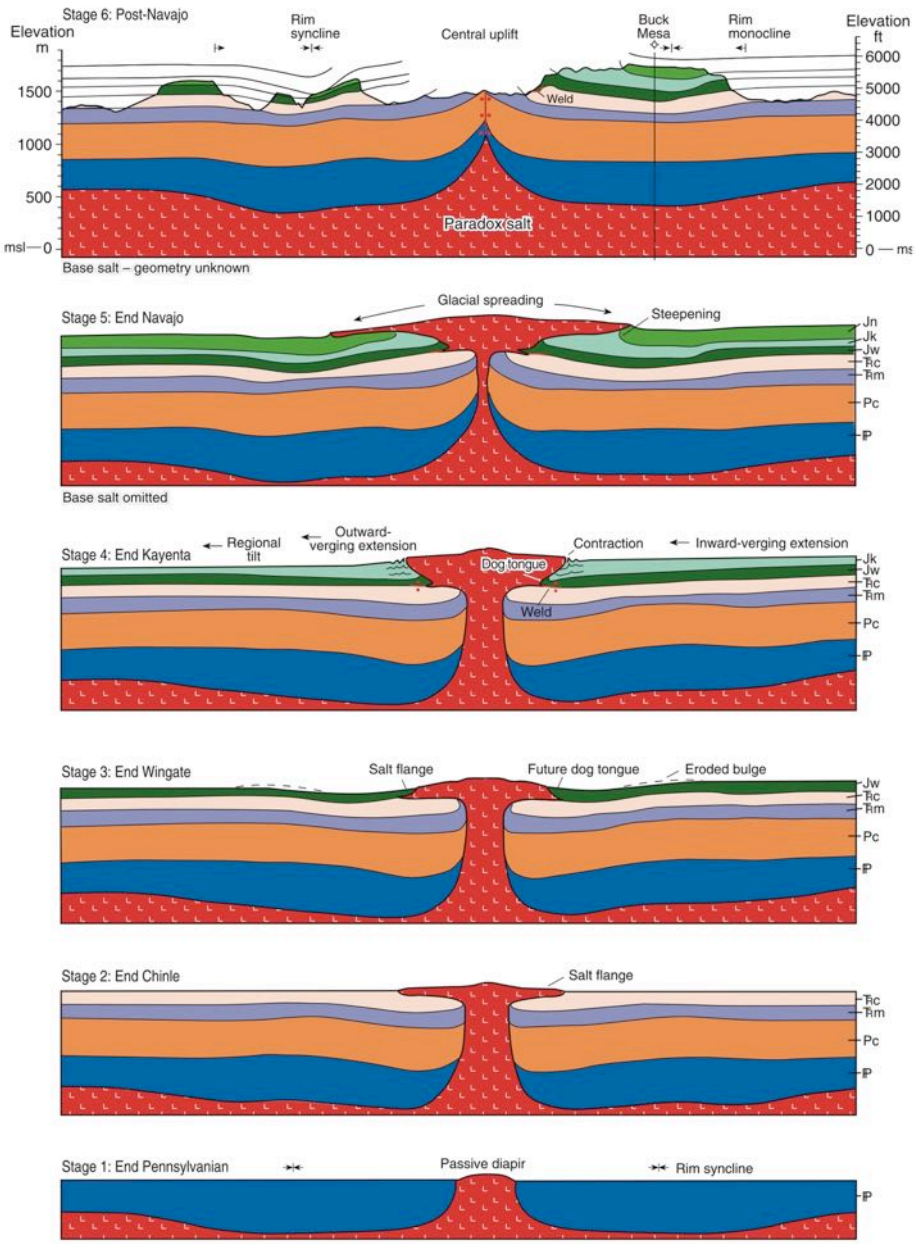
Recent Hypotheses: Impact

- Post-Jurassic Meteorite Impact only (Kriens et al, 1999; Buchner and Kenkmann, 2008;)
  - Circular
  - Central uplift
  - Clastic dikes
  - Outer extensional zone
  - Inner constrictional zone
  - Dome encircling syncline
  - Gravity and magnetic anomalies
  - Rare poorly developed shatter cones
  - Shocked quartz grains (PDFs)
    - ✓ 2 quartz grains out of 120 thin sections (Buchner and Kenkmann, 2008)

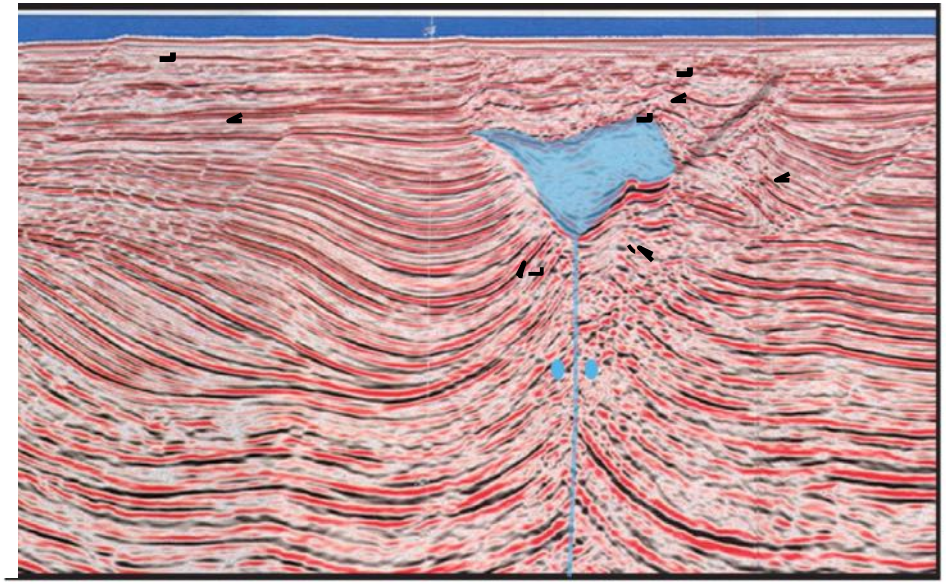


- Post-Jurassic Meteorite Impact followed by Salt Diapirism (Daly and Kattenhorn, 2010; Kattenhorn and Daly, 2011;)
  - Circular
  - Central uplift
  - Clastic dikes
  - Outer extensional zone
  - Inner constrictional zone
  - Dome encircling syncline
  - Gravity and magnetic anomalies
  - Shear fractures represent dynamic deformation features associated with an impact event. Deformation bands formed later during long-lived salt diapirism below the original impact site.
  - This post-Jurassic impact followed by salt diapirism hypothesis is however, at odds with the field observations within the Triassic-Jurassic strata.

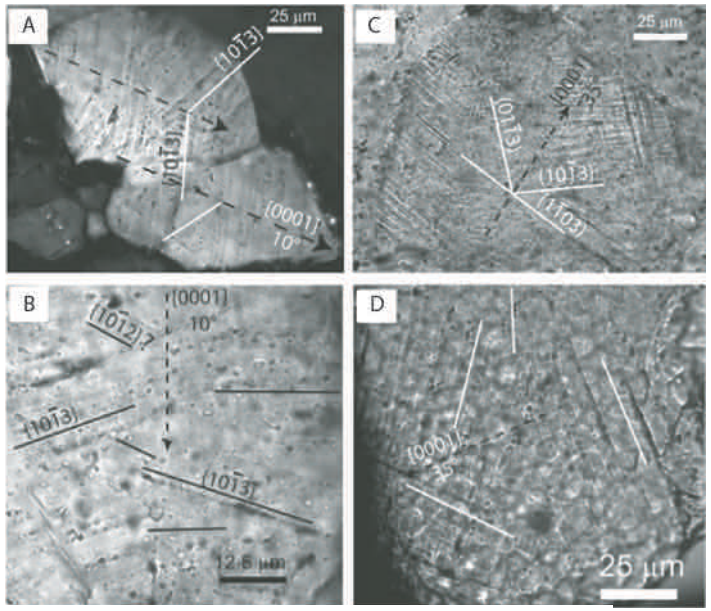
Recent Hypotheses: Pinched-off Salt Diapir



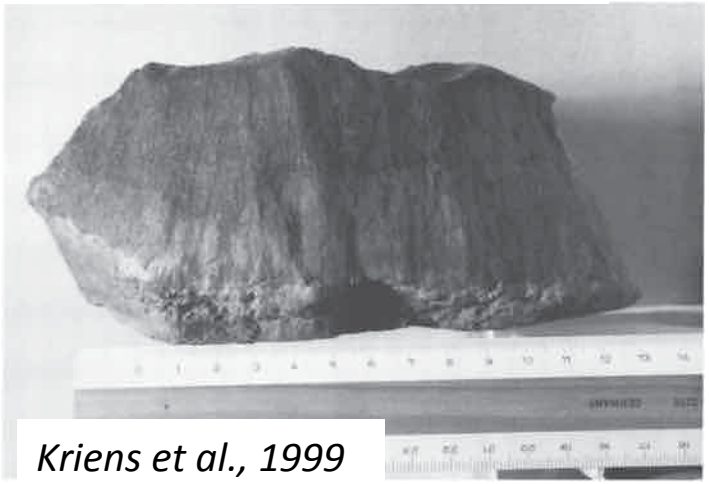
- Pinched-off Salt Diapir (Jackson *et al.*, 1998)
  - Circular
  - Central uplift
  - Clastic dikes
  - Outer extensional /Inner constrictional zone
  - Dome encircling syncline
  - Gravity and magnetic anomalies
  - Truncation, onlap and channeling
  - Growth faults and folds
  - Shifting rim synclines
  - Outward-verging extension



Petrographic / Lithologic Evidence for Impact



Buchner and Kenkmann, 2008



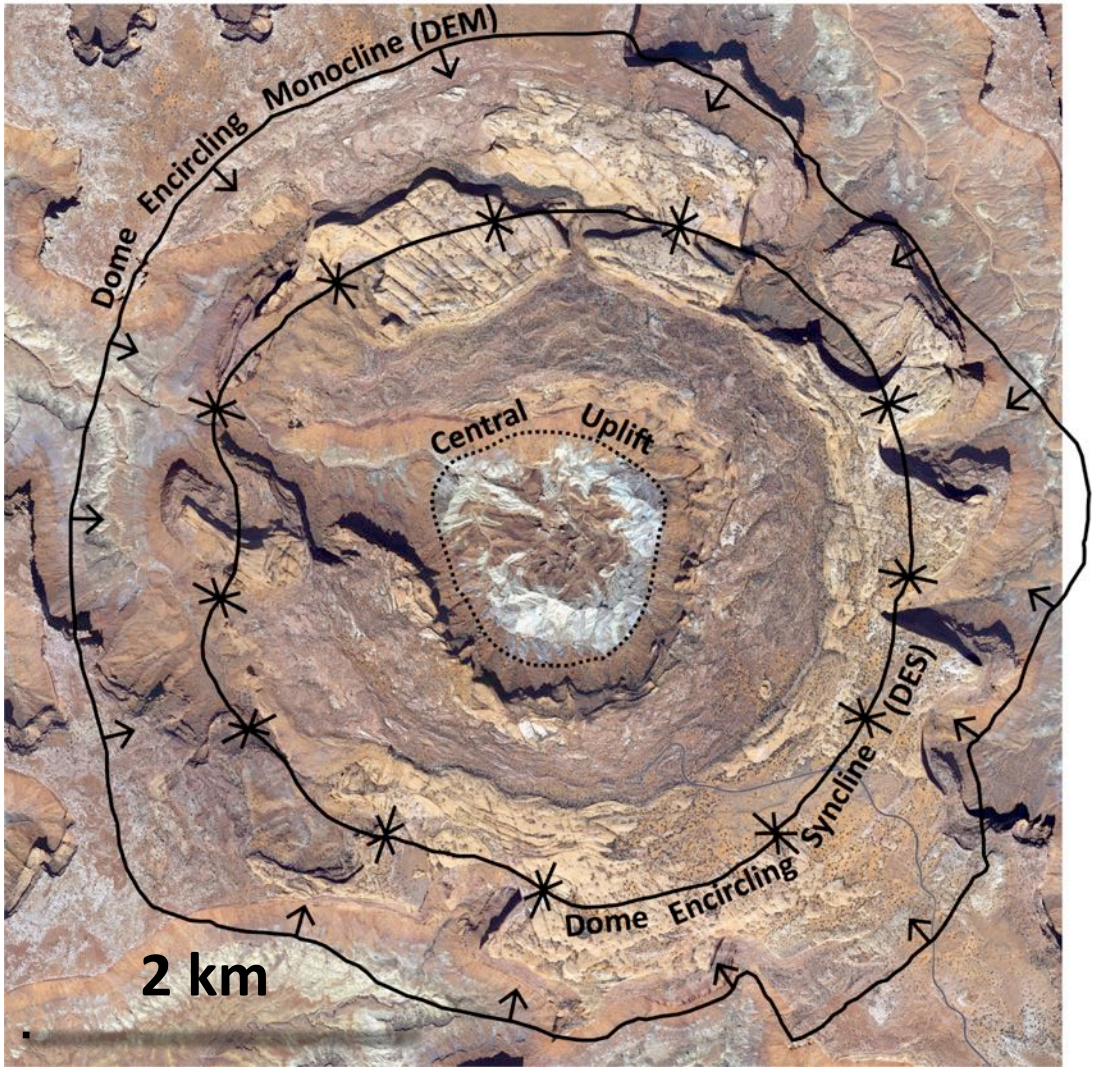
Kriens et al., 1999

"Upheaval Dome, Utah, USA: Impact origin confirmed"

(Buchner and Kenkmann, *Geology*, 2008)

- Shocked quartz grains (PDFs)
  - 2 grains out of 120 thin sections (~0.0003% of grains analyzed)
  - 2-5% of grains should show PDFs to be considered a diagnostic shock indicator (French and Koeberl, 2010)
- Rare poorly developed shatter cones?
  - Siltstone beds of the Moenkopi Formation near the central uplift
  - Formed in earliest excavation stage of impact (Huntoon, 2000)
  - 10-20% by volume to be considered diagnostic shock indicator (French and Koeberl, 2010)

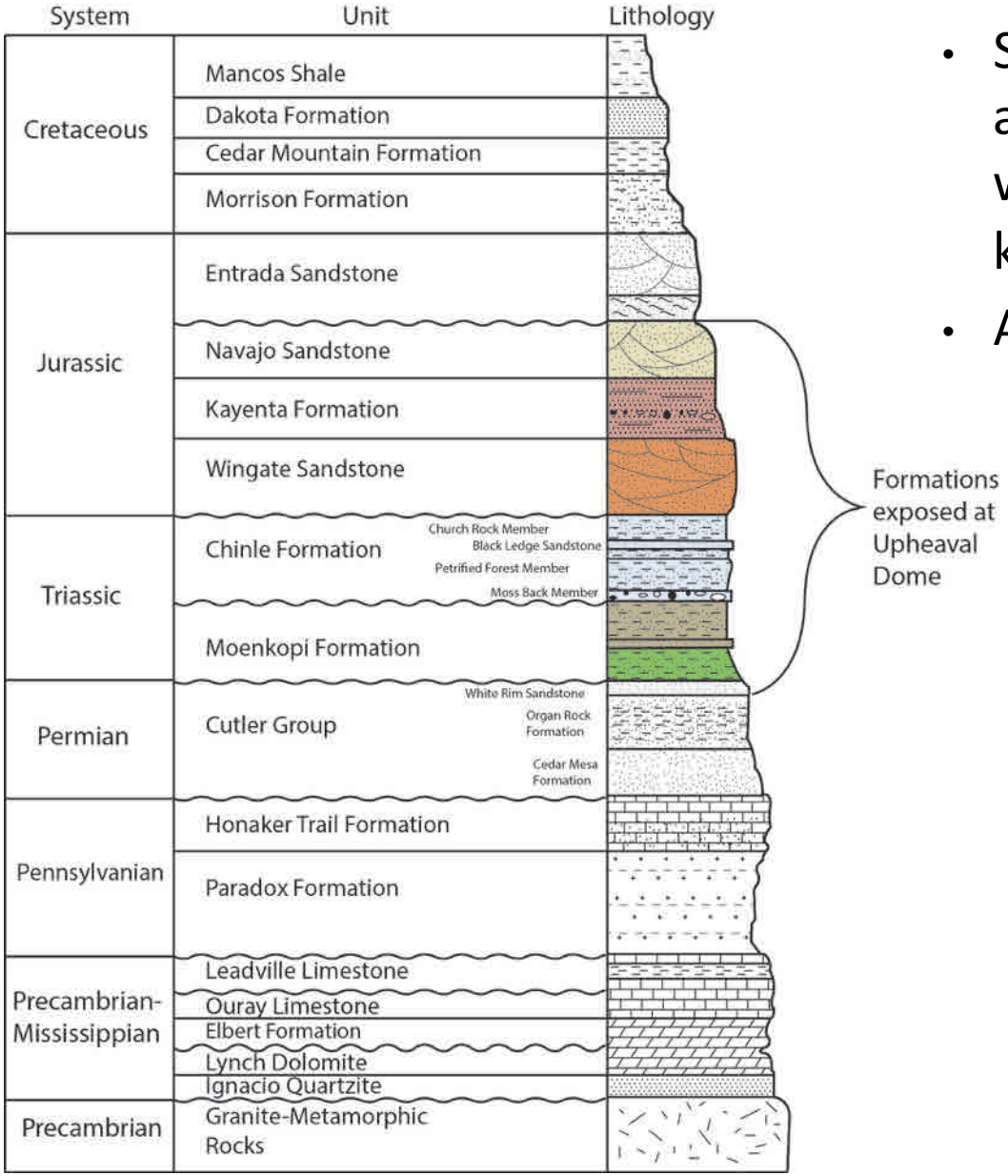
This Study: Objectives and Purpose



- Document stratigraphic and structural features:
  - Thickness and facies changes in the Jurassic Kayenta Formation (15 logged sections inside the DEM + 1 baseline logged section ~10km to ENE)
  - Surfaces of angular discordance (unconformities and onlaps)
  - Growth faults between the DEM and DES
- Focus of this study is *outside* the Central Uplift

Geesaman, 2013; MS thesis, Colorado School of Mines

Northern Paradox Stratigraphy



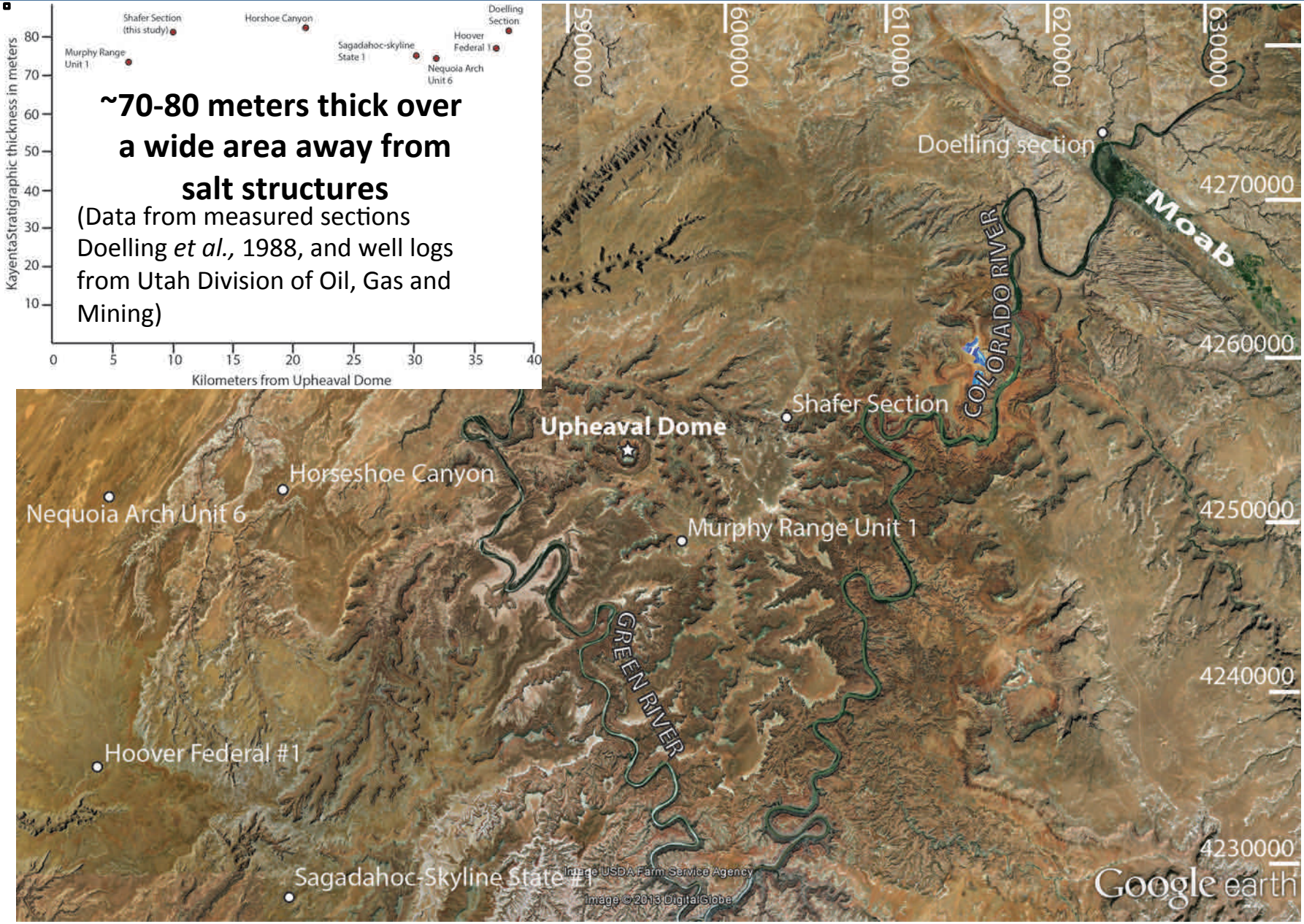
Modified from (Jackson et al., 1998)

- Stratigraphic thickness and facies are generally consistent over a wide area of SE Utah away from known salt structures
- At Upheaval Dome:
  - Latest Permian to Middle Jurassic aged strata exposed
  - Variable depositional environments
  - This study focussed on the sandy-fluvial Jurassic Kayenta Formation and the thick eolian Triassic-Jurassic Wingate Formation
  - Additional recent work on the Navajo Sandstone

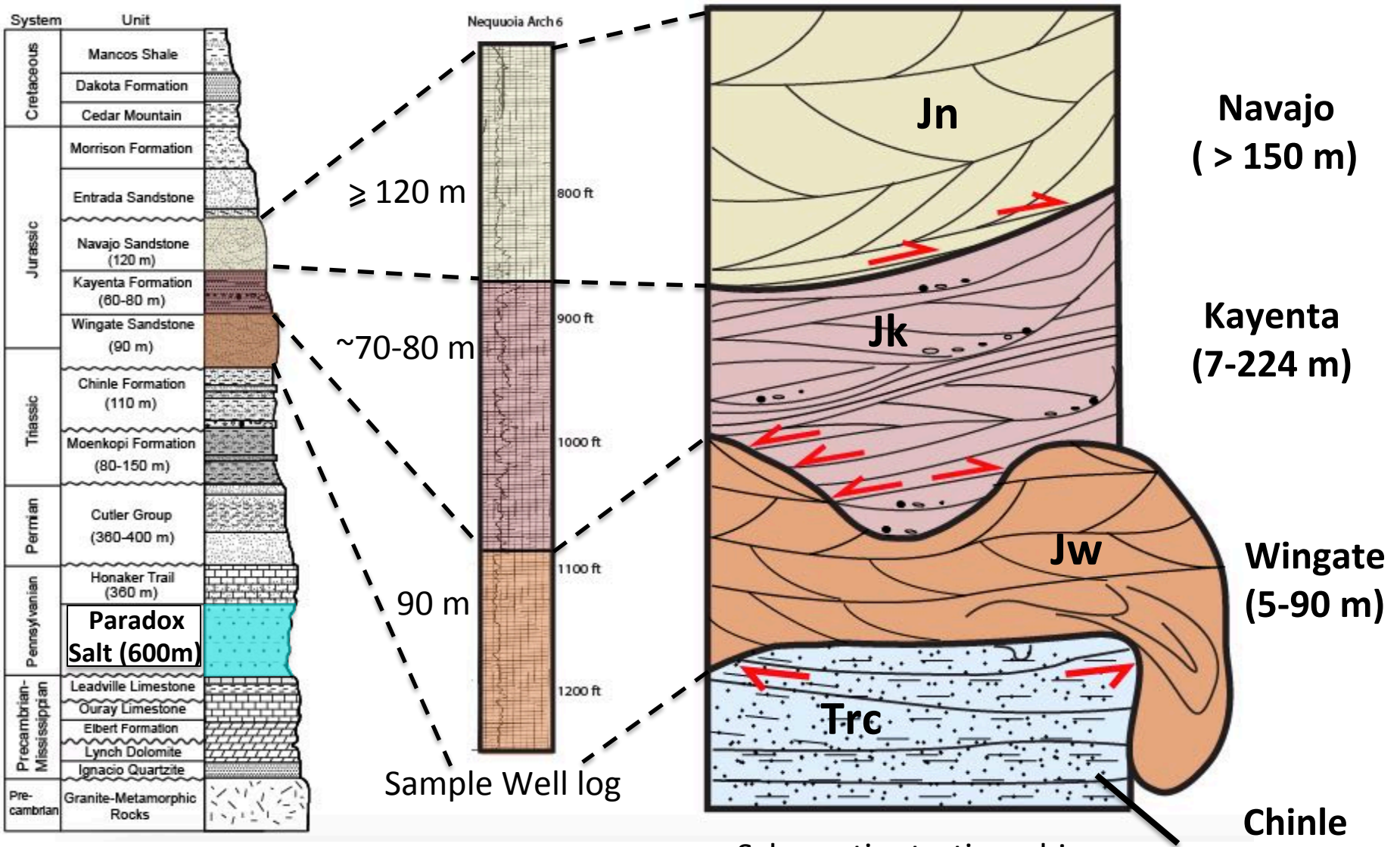
Kayenta Thickness Around the Northern Paradox Basin

~70-80 meters thick over a wide area away from salt structures

(Data from measured sections Doelling *et al.,* 1988, and well logs from Utah Division of Oil, Gas and Mining)



Upheaval Dome Stratigraphy



Stratigraphy (modified from (Jackson et al., 1998)

Schematic stratigraphic relationships at Upheaval Dome

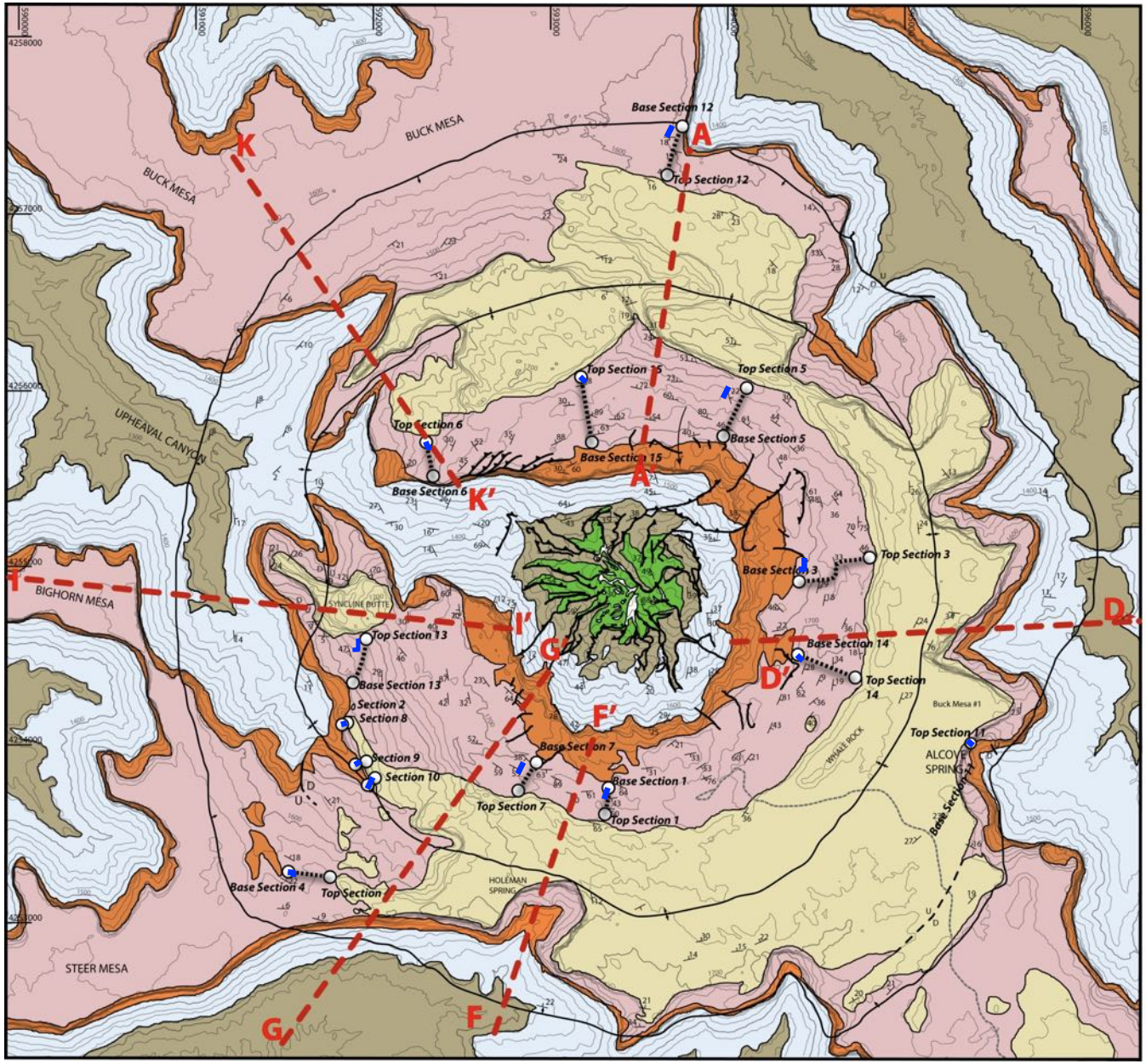
Stratigraphic Ages Data Table

	Time span	Reference	Age (Ma) from Cohen et al	~ Age (Ma) from Blakey and Ranney
Navajo Formation	mid Sinemurian to mid Aalenian	Lucas et al., 2005	~ 195 to ~ 172 Ma = **23 My**	~ 195 to ~ 172 Ma = **23 My**
Kayenta Formation	early Sinemurian	Lucas et al., 2005	~ 199 to ~ 195 Ma = **4 My**	~ 200 to ~ 195 Ma = **4 My**
Hiatus	Hettangian to early Sinemurian	Lucas & Tanner, 2007; Lucas et al, 2011	*~ 201.3 to ~ 199 .3Ma* = ***2 My***	No Hiatus
Wingate Formation	Rhaetian to Hettangian	Lucas et al., 2005	~ 205 to ~ 200 Ma = **5 My**	~ 205 to ~ 200 Ma = **5 My**
Chinle Formation	Norian to Rhaetian	Irmis et al., 2011/Ramezani et al., 2014	~ 230 to ~ 205 Ma = **25 My**	~ 225 to ~ 205 Ma = **20My**
Hiatus	Ladinian-late Carnian	Ramezani et al., 2014	~ 242 to ~ 230 Ma = **12 My**	~ 227 to ~ 225Ma = **2 My**
Moenkopi Formation	late Induan to end Anisian	Ramezani et al., 2014	~ 251.5 to ~ 242 Ma = **9.5 My**	~ 245 to ~ 227Ma? = **18 My**
Note that in Canyonlands NP and surrounding area the Chinle Fmn is comprised of he following members				
Church Rock Member	late Norian to Rhaetian	Martz et al_2014	~ 209-205 Ma	
Kane Springs Beds	middle to late Norian	Martz et al_2014	~ 213-207 Ma	
Hiatus between Moenkopi and Chinle = ~ 242 to ~ 213 Ma = **29 My**				

Age of Units exposed at Upheaval Dome is ~ 250 to 172 Ma

Glen Canyon Group strata exposed at Upheaval Dome (Wingate, Kayenta and Navajo) represent at least 20 million years!

Geological Map

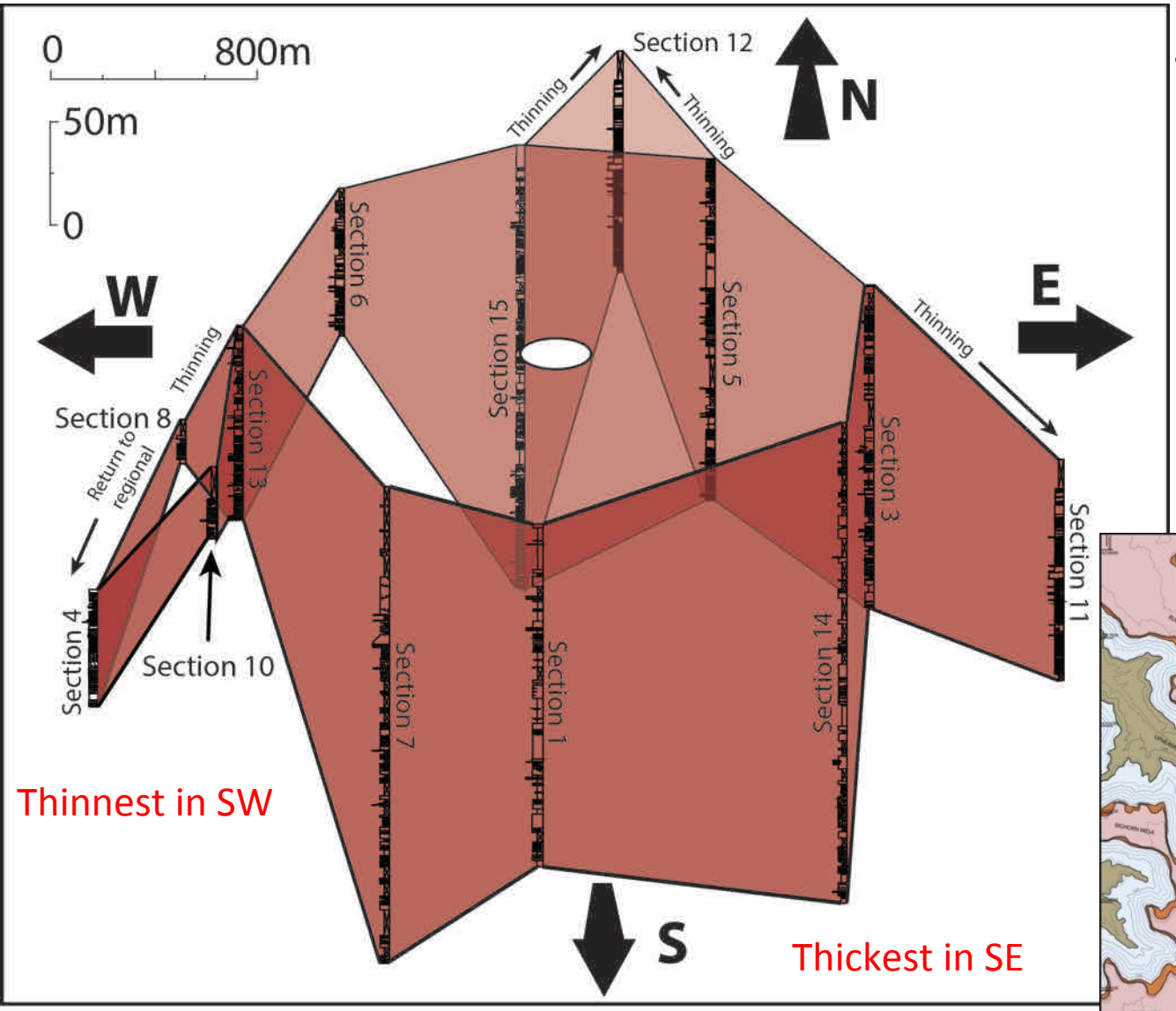


Navajo Sandstone
Kayenta Formation
Wingate Sandstone
Chinle Formation
Upper Moenkopi Formation
Lower Moenkopi Formation
White Rim Sandstone
Roads
Syncline
Monocline
Thrust Fault, teeth are on hanging wall
Normal fault, D designates the down-dropped side
Strike and dip
Section traces
Cross section lines

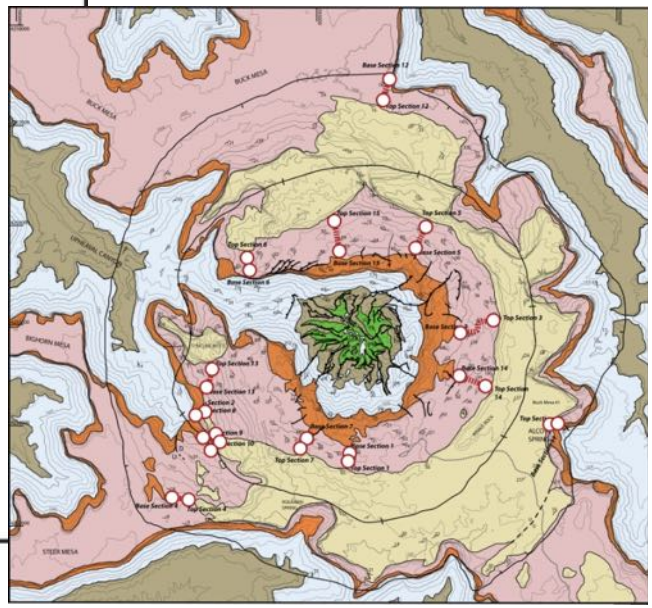
Geesaman, 2013; MS thesis, Colorado School of Mines

(Modified from Jackson et al., 1998; and Kriens et al., 1999)

Kayenta Formation Thickness Variability

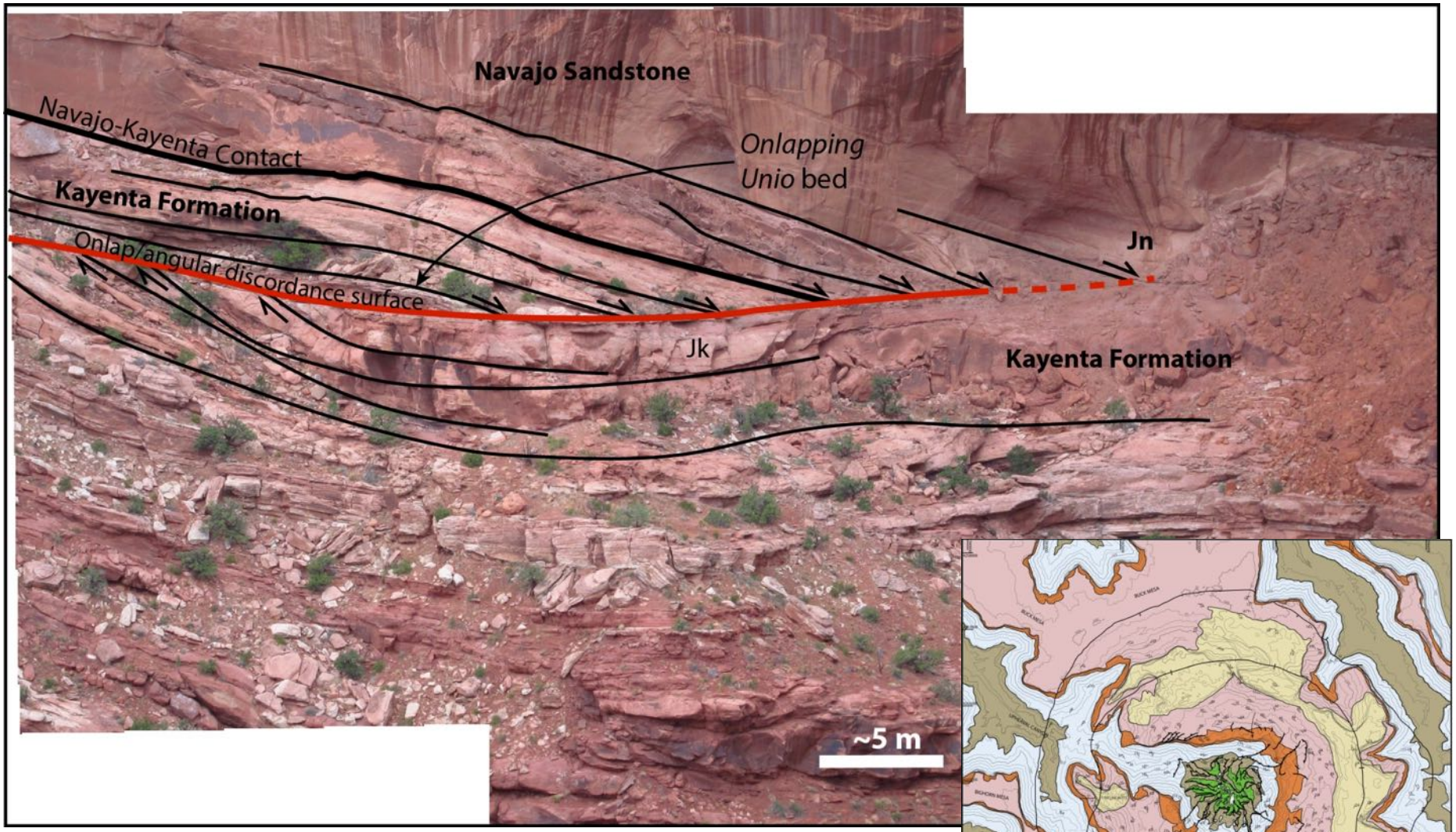


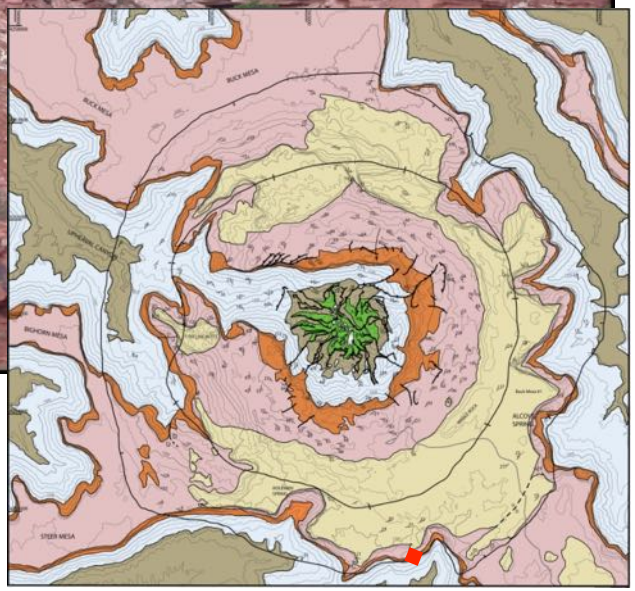
- Measured thickness varies significantly
  - **Thickest = 224 m**
  - **Thinnest = 7 m**



Geesaman, 2013; MS thesis, Colorado School of Mines

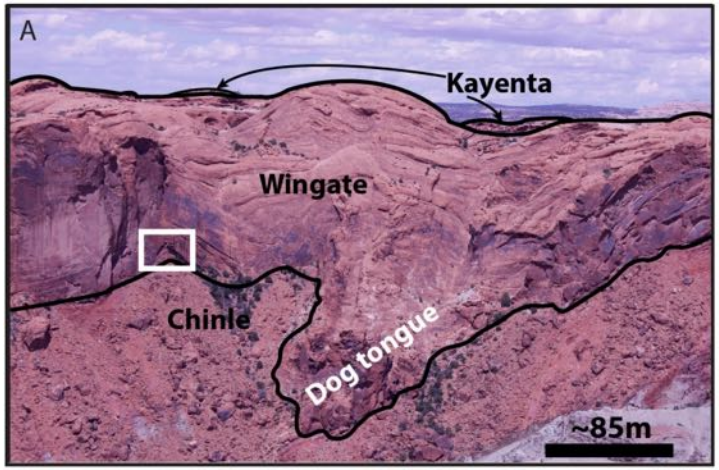
Stratigraphic Surfaces: Truncation and Onlaps



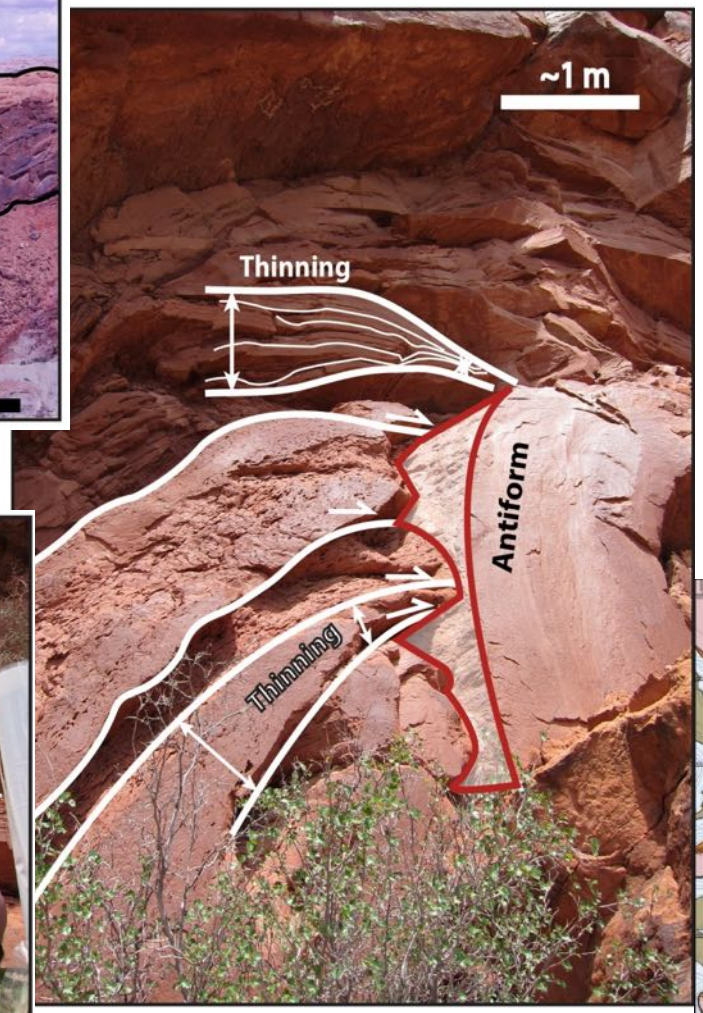


Distinct truncation and onlap surfaces present around Upheaval Dome within Chinle-Navajo formations implying long-term deformation and growth

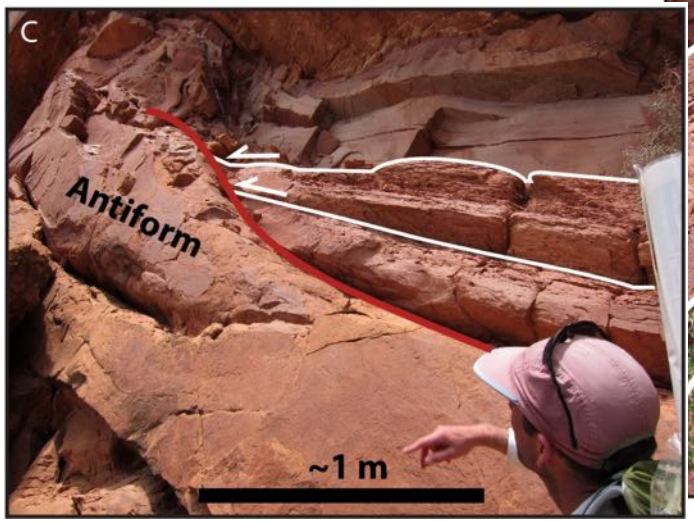
Stratigraphy: Onlapping Relationships



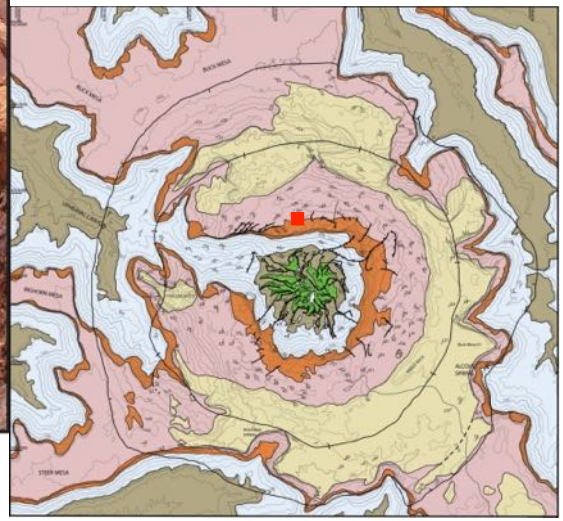
West side



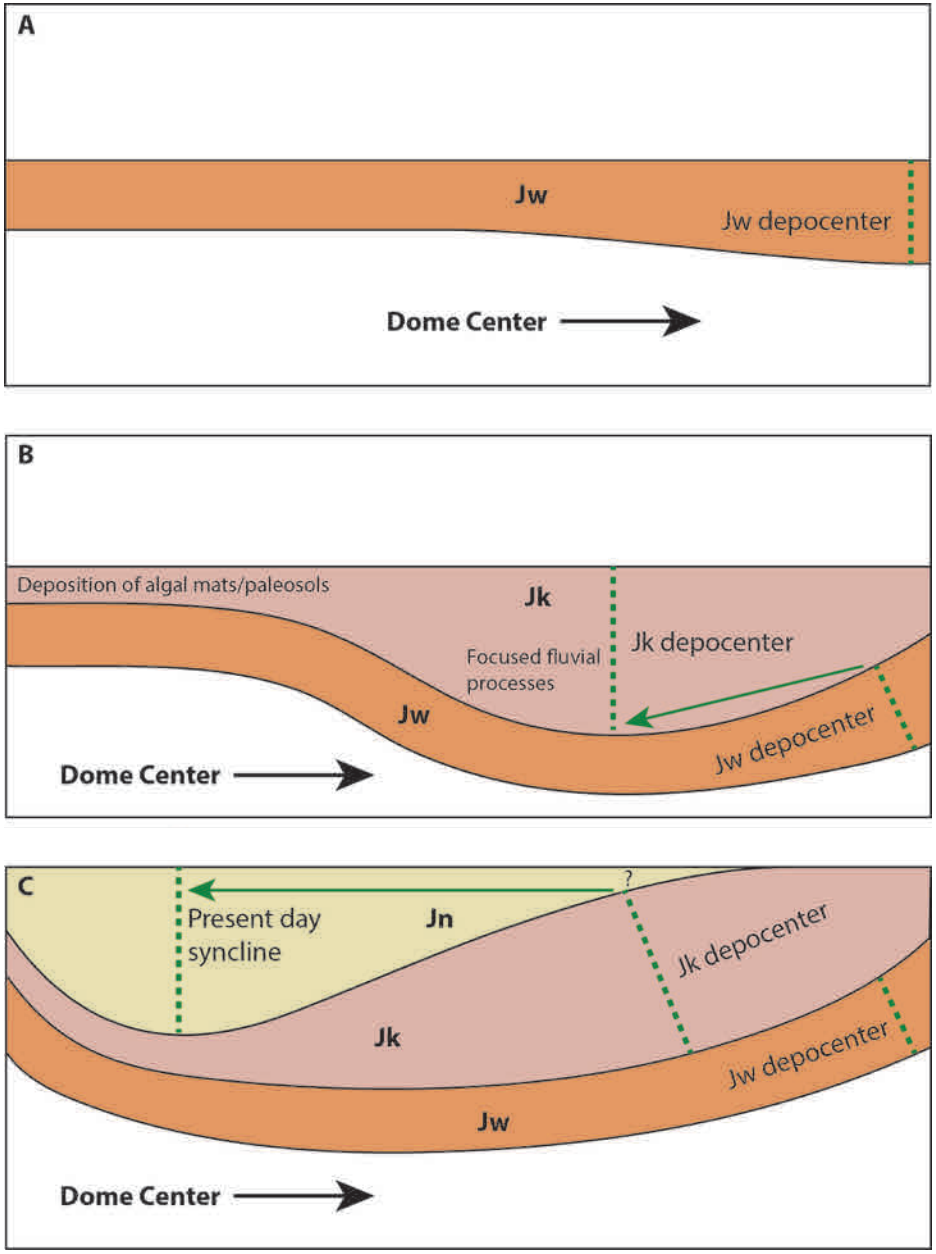
East side



- Distinct onlap surfaces onto fold structures
  - Base of Wingate Sandstone
  - Beds approach antiform, thin, and onlap
  - Implies long-term deformation

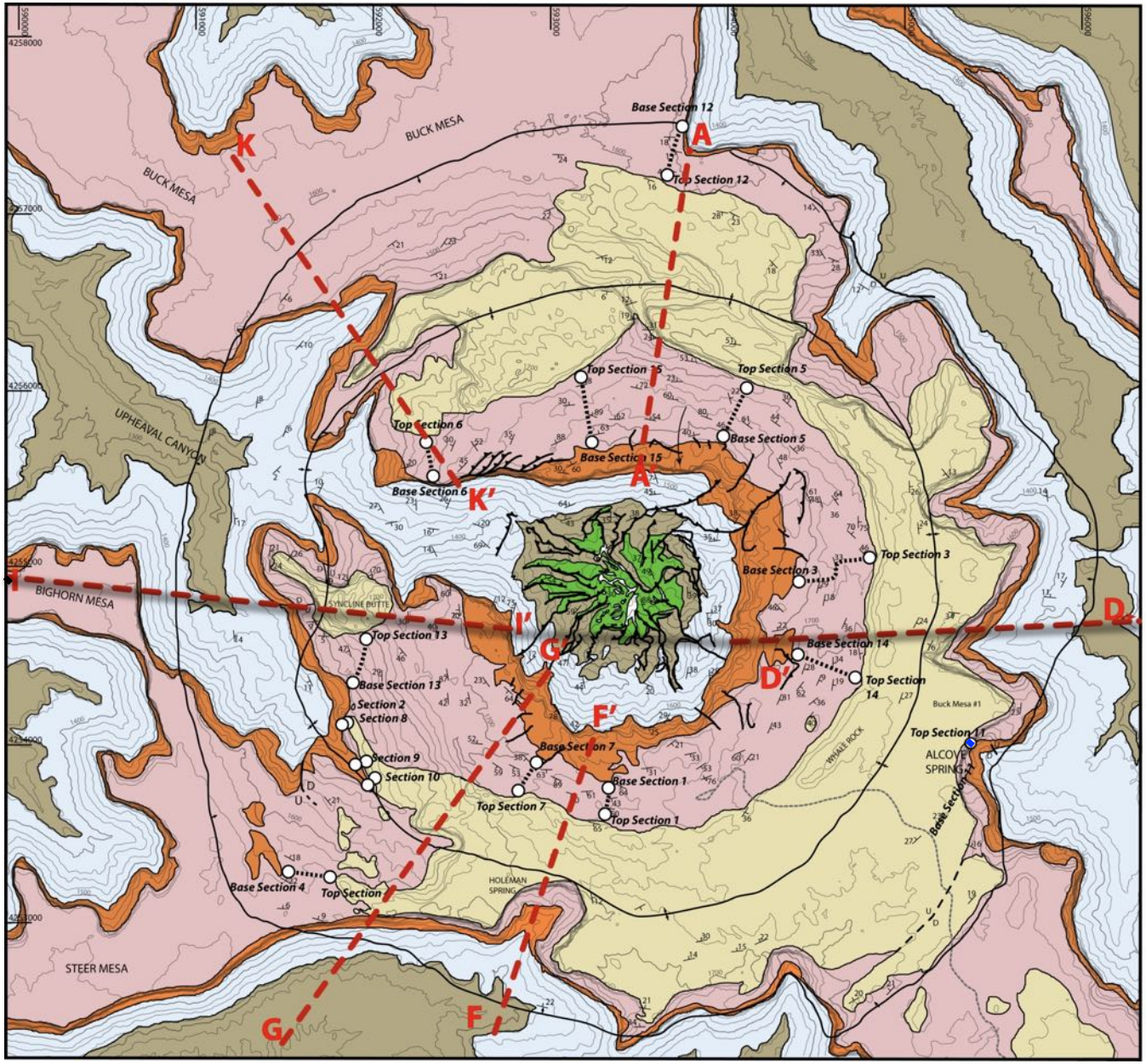


Shifting Synclinal Axial Traces / Depocenters



- Shifting synclinal axes and formation depocenters through Jurassic formations exposed at Upheaval Dome
  - ➢ Depocenters shift away from the dome center over time
  - ➢ Localizes environments of deposition through time (e.g., braided stream channels and paleosols in Jk, limestones in Jn)

Geological Map

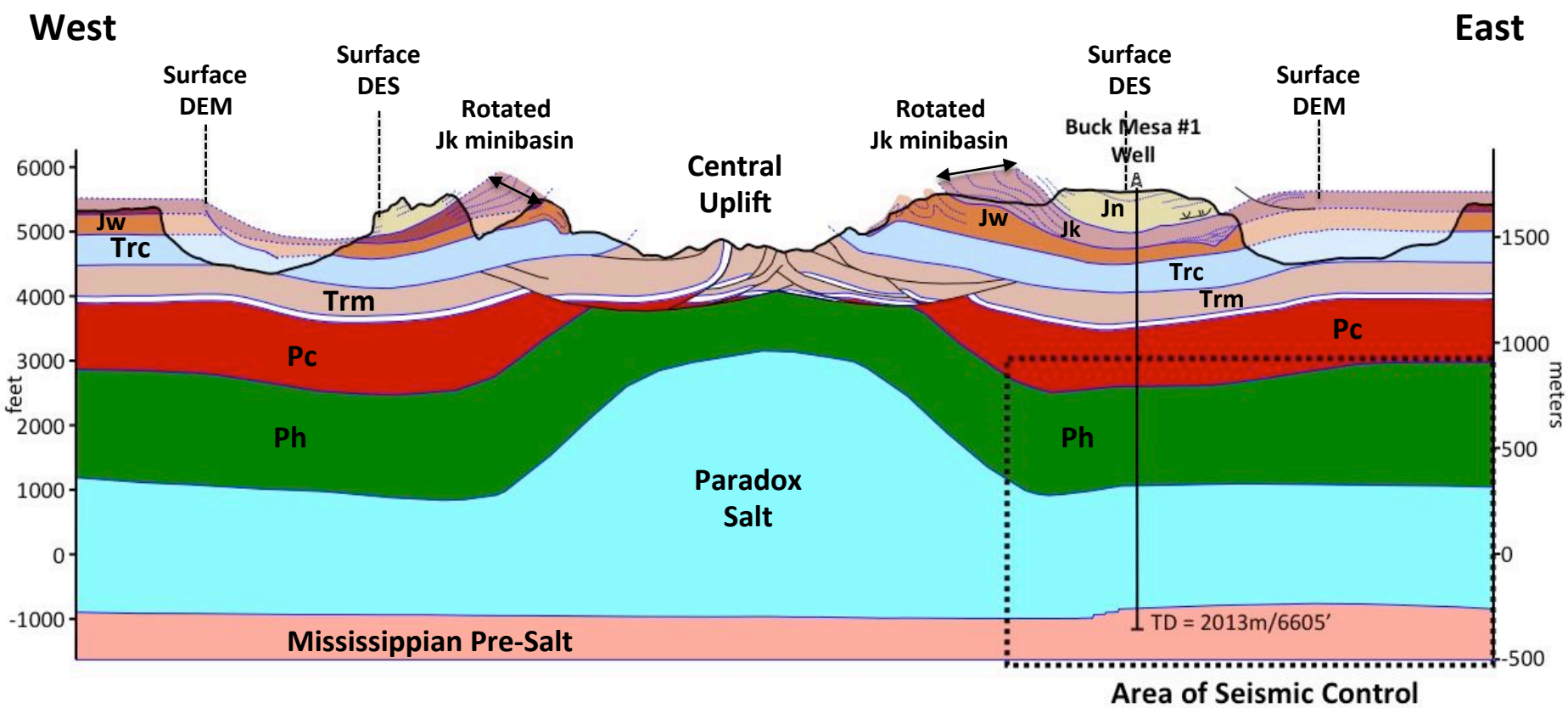


(Modified from Jackson et al., 1998; and Kriens et al., 1999)

Geesaman, 2013; MS thesis, Colorado School of Mines

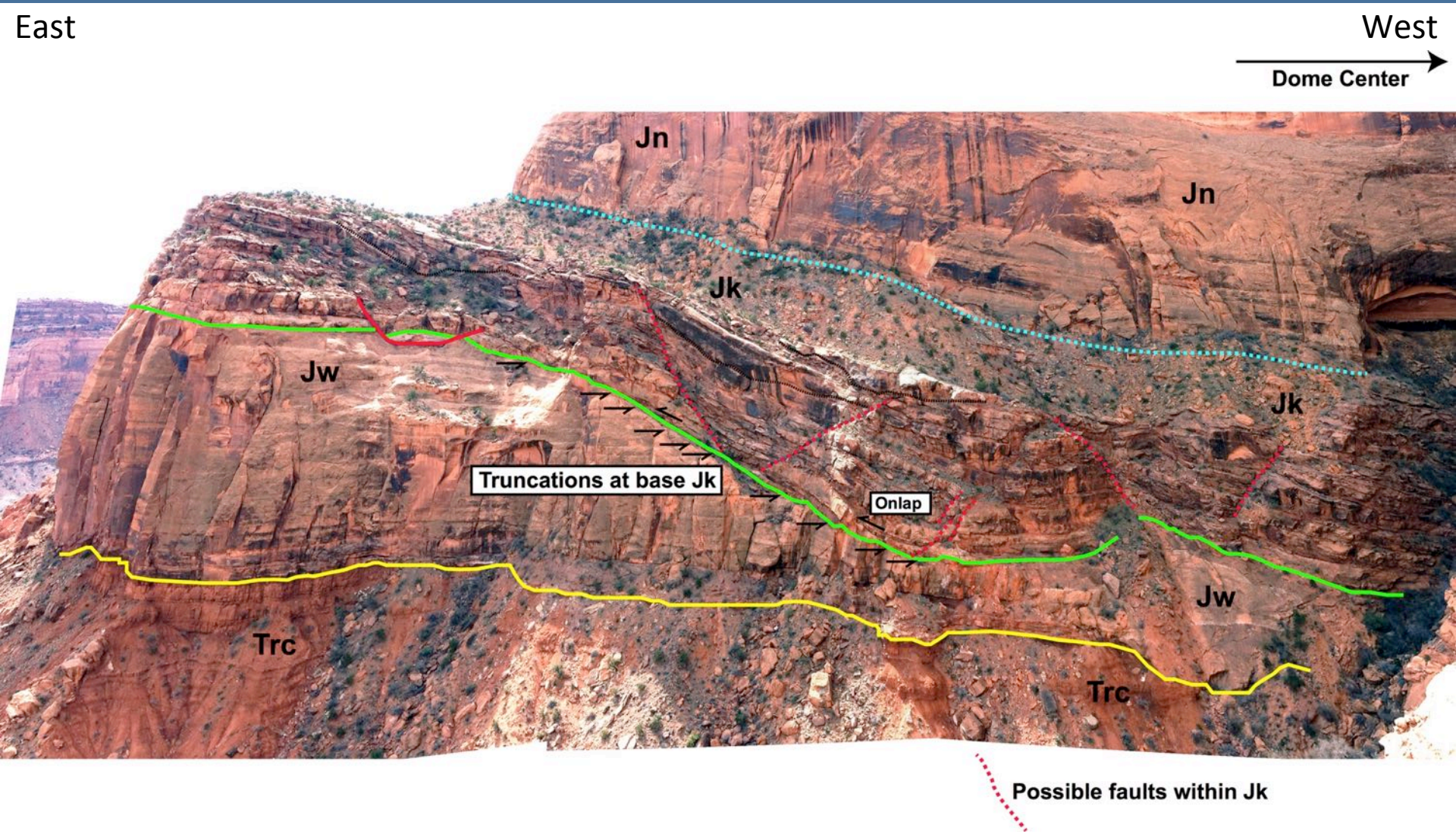
Composite East-West Cross Section

1:1 Cross section based on field and sub-surface data



Cross section modified from Geesaman, 2013, with additional information from Jackson et al., 1998; Kriens et al., 1999; Kanbur et al., 1999.

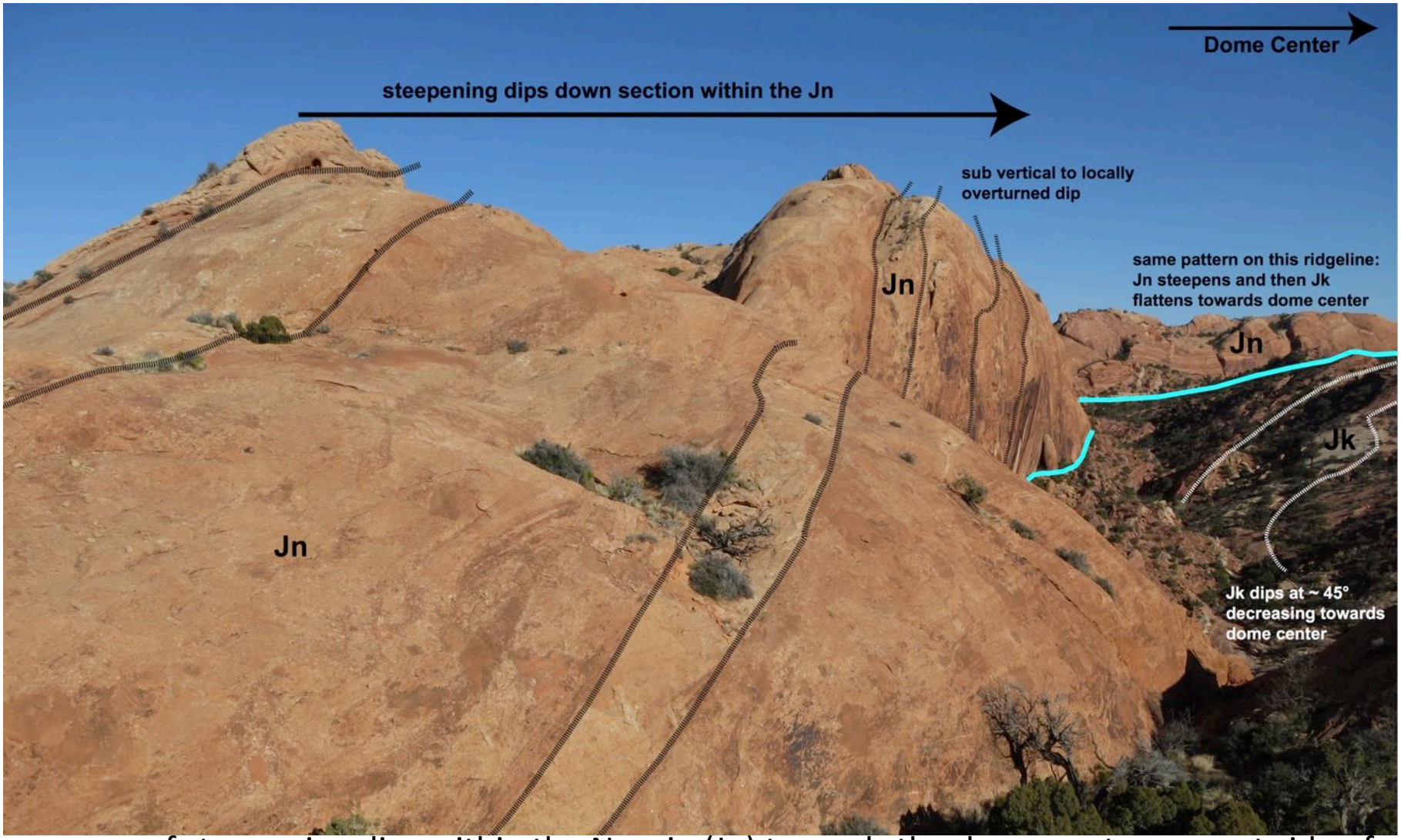
Evidence for Long-Term Deformation



Panorama of the south side of Alcove B on the east side of Upheaval Dome between the DEM and DES. Deeply eroded Jw with rotated and stacked Jk channels.

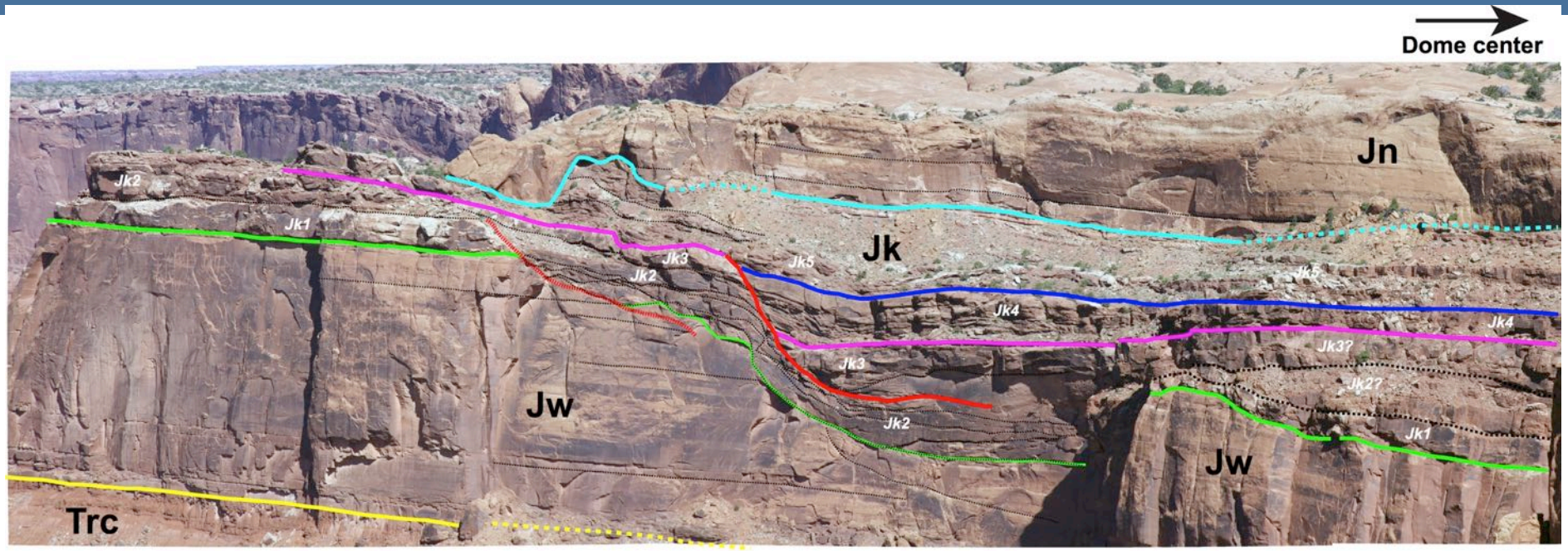
Evidence for Long-Term Deformation

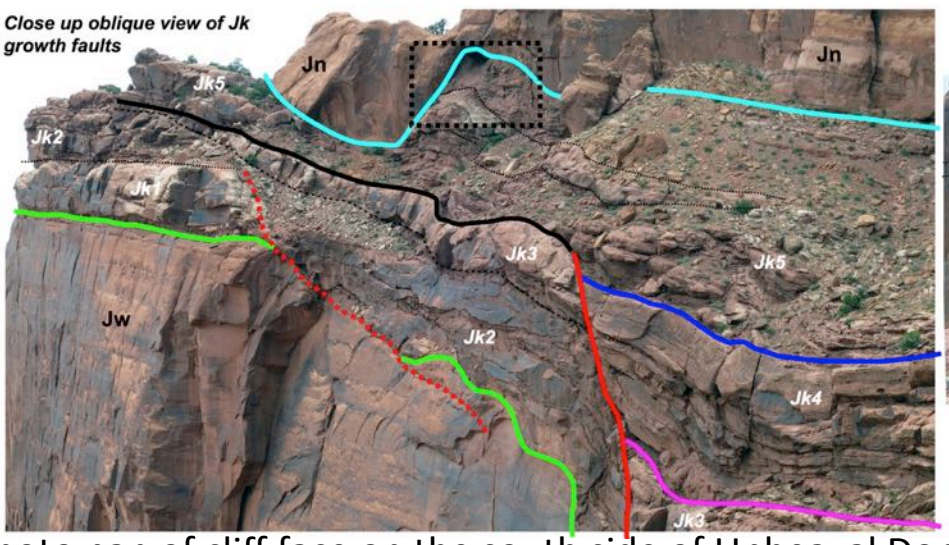
East West



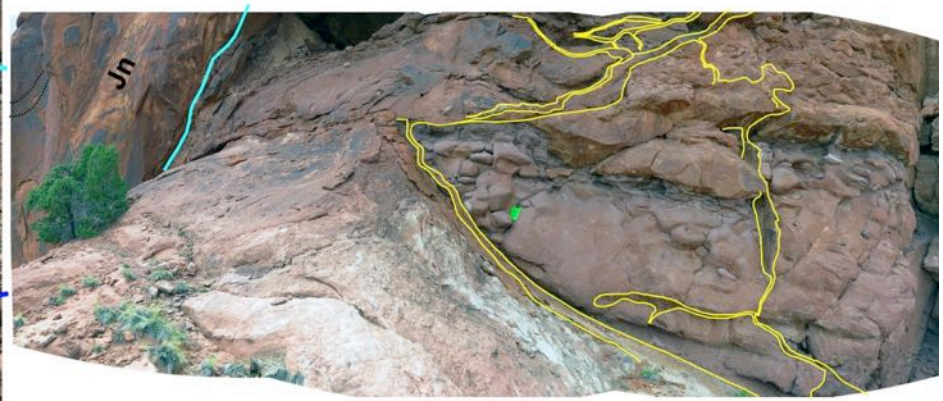
Panorama of steepening dips within the Navajo (Jn) towards the dome center on east side of Upheaval Dome. Dips steepen from DES down section within the Navajo and then decrease again in the underlying Kayenta. This pattern is repeated around much of Upheaval Dome

Evidence for Long-Term Deformation





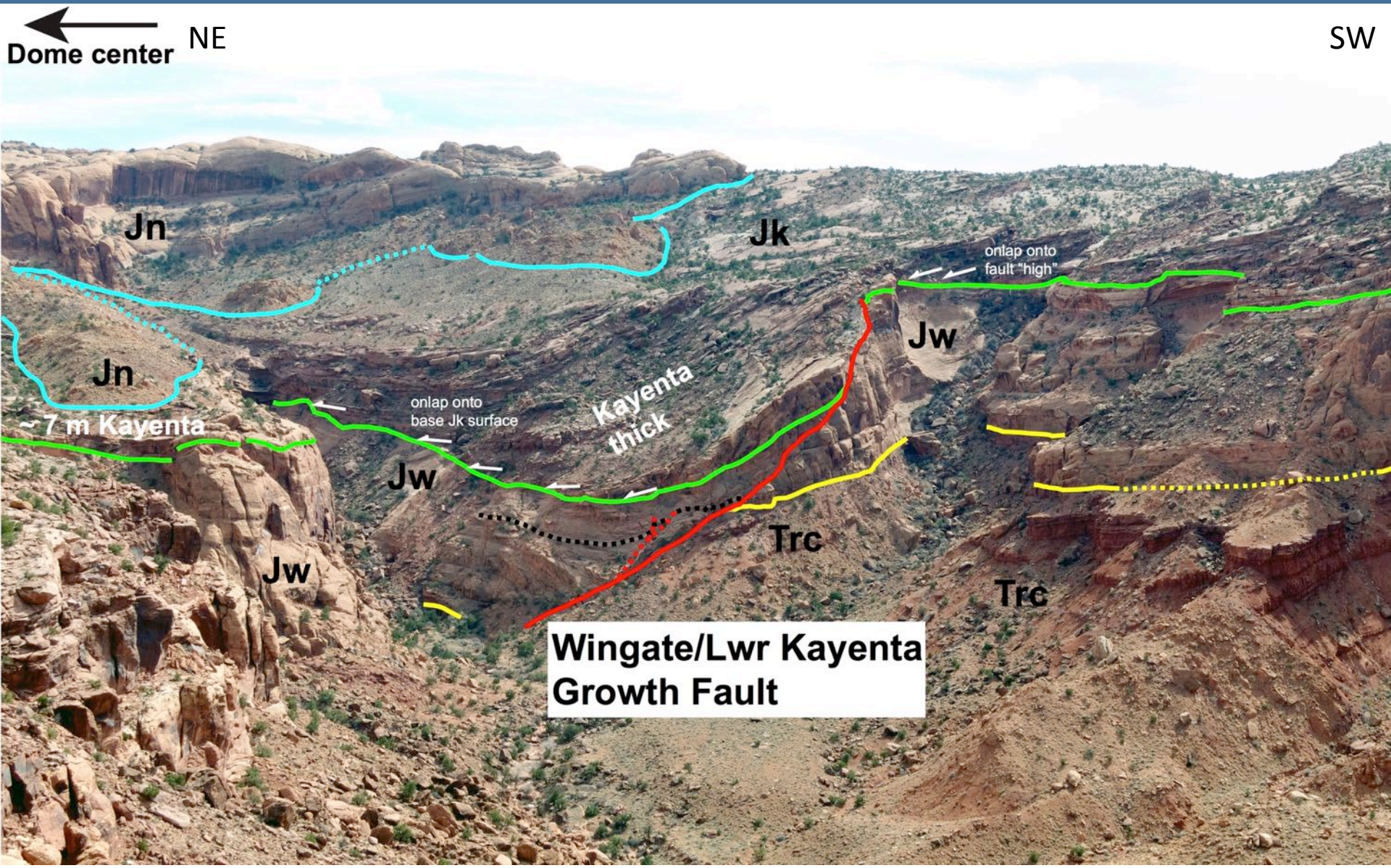
Injected sands in Jk5 unit



Close up of injected sand systems within Jk5 unit. Complex network of cross-cutting injectites and faults suggest multiple phases of deformation. Note "warping" of base Jn over the injected rock mass.

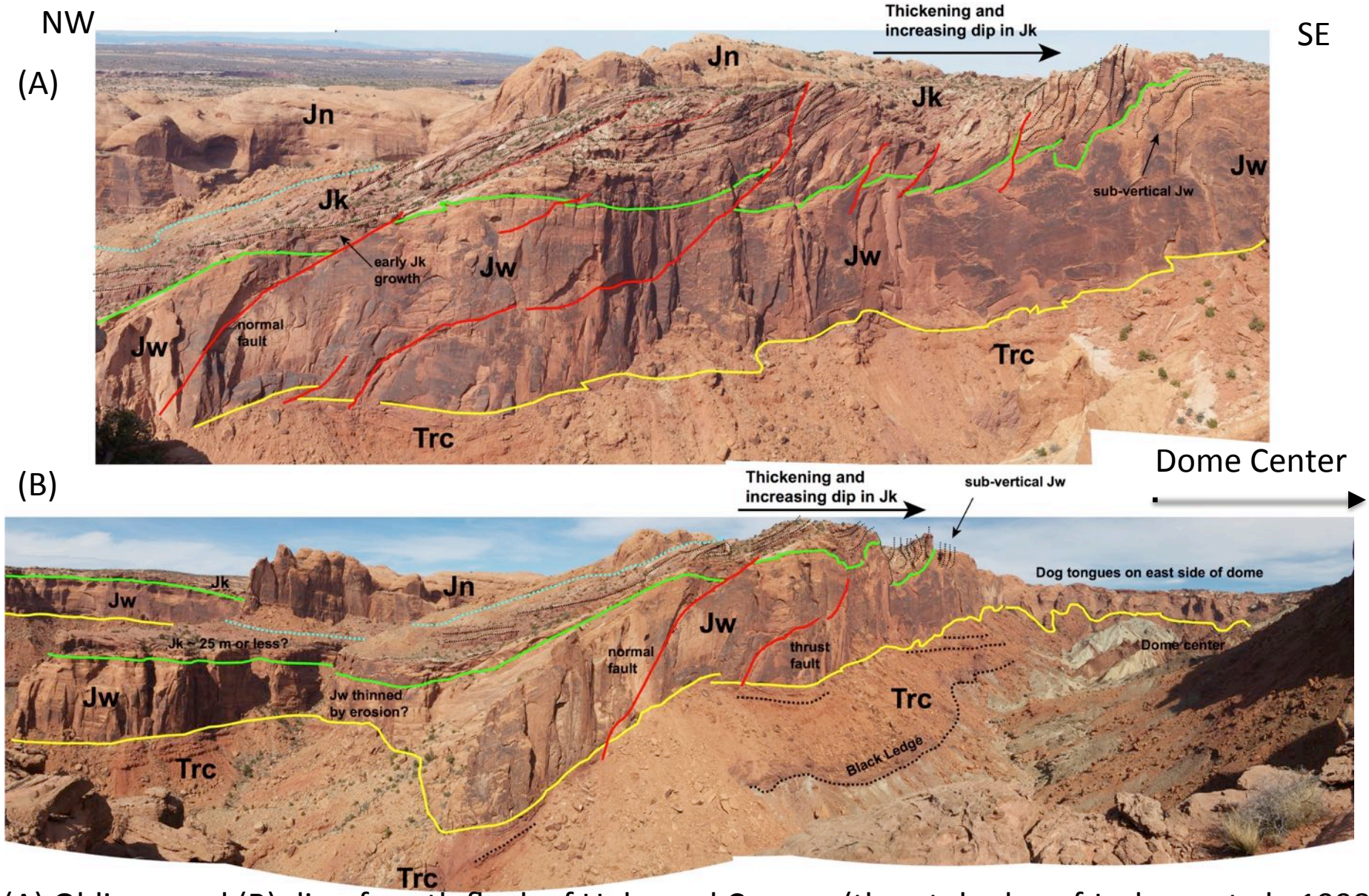
Photo pan of cliff face on the south side of Upheaval Dome. Base Jk surface is significantly eroded into Jw with draped + stacked channels in Jk. Small (m to 20 m) normal faults show hw growth in Jk2, Jk3 and Jk4 packages

Evidence for Long-Term Deformation



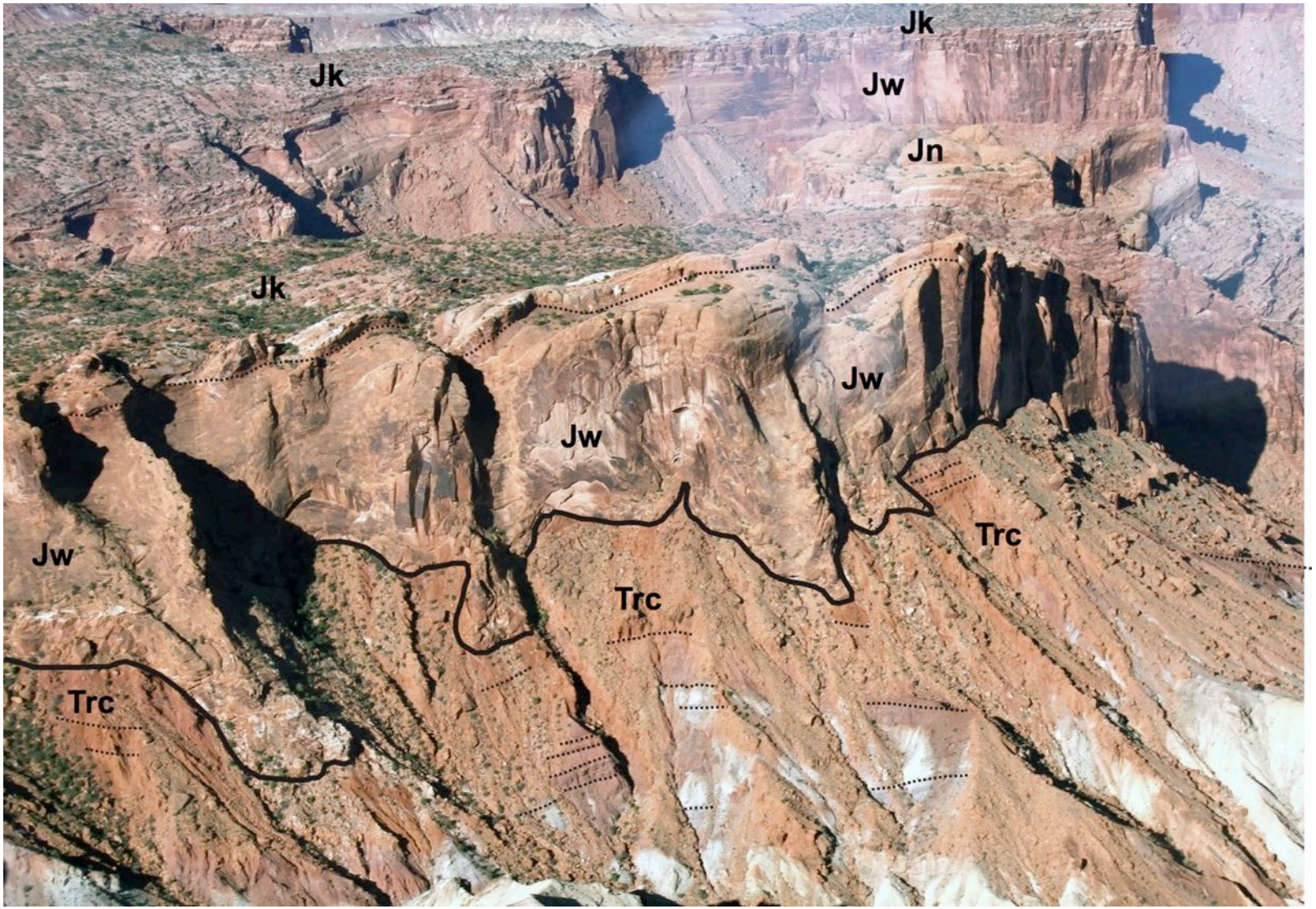
Panorama of the southwest side of Upheaval Dome between the DEM and DES. Jw and lwr Jk growth fault shows thickened hanging wall packages. Minimum 7m measured thickness of Jk

Evidence for Long-Term Deformation



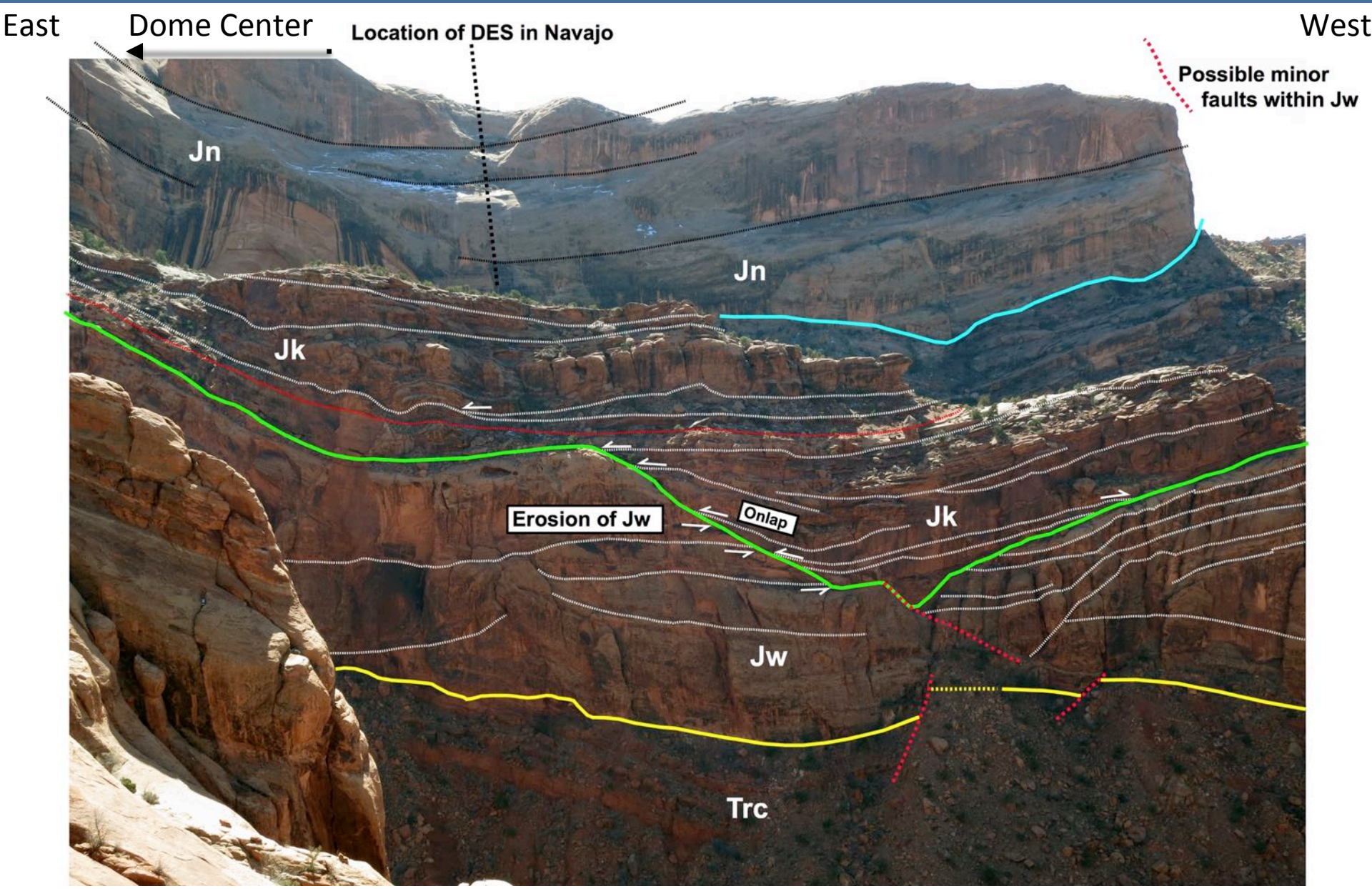
(A) Oblique and (B) dip of north flank of Upheaval Canyon (thrust duplex of Jackson et al., 1998) that illustrate thickening and increasing dip within the Kayenta toward the dome center)

Evidence for Long-Term Deformation



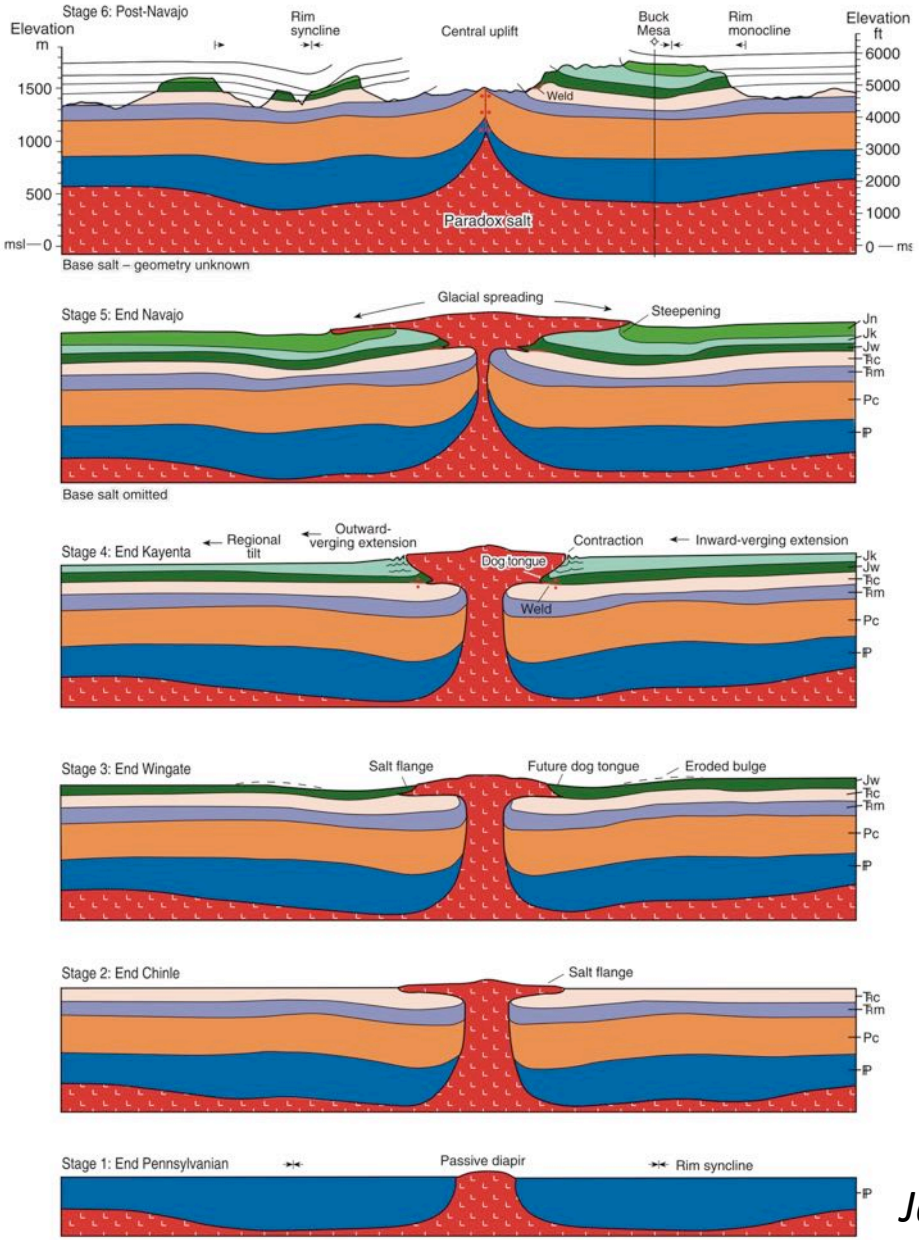
"Dog Tongues" (Jackson et al., 1998) on the western flank Upheaval Dome record collapse of thinned Wingate (Jw) onto underlying Chinle (Trc). Note the regionally characteristic smooth, conformable Trc/Jw contact in the background (outside the DEM).

Evidence for Long-Term Deformation



Overstepping Jk channels filling deeply eroded Jw topography on west side of Upheaval Dome

Pinched-off Salt Diapir Hypothesis

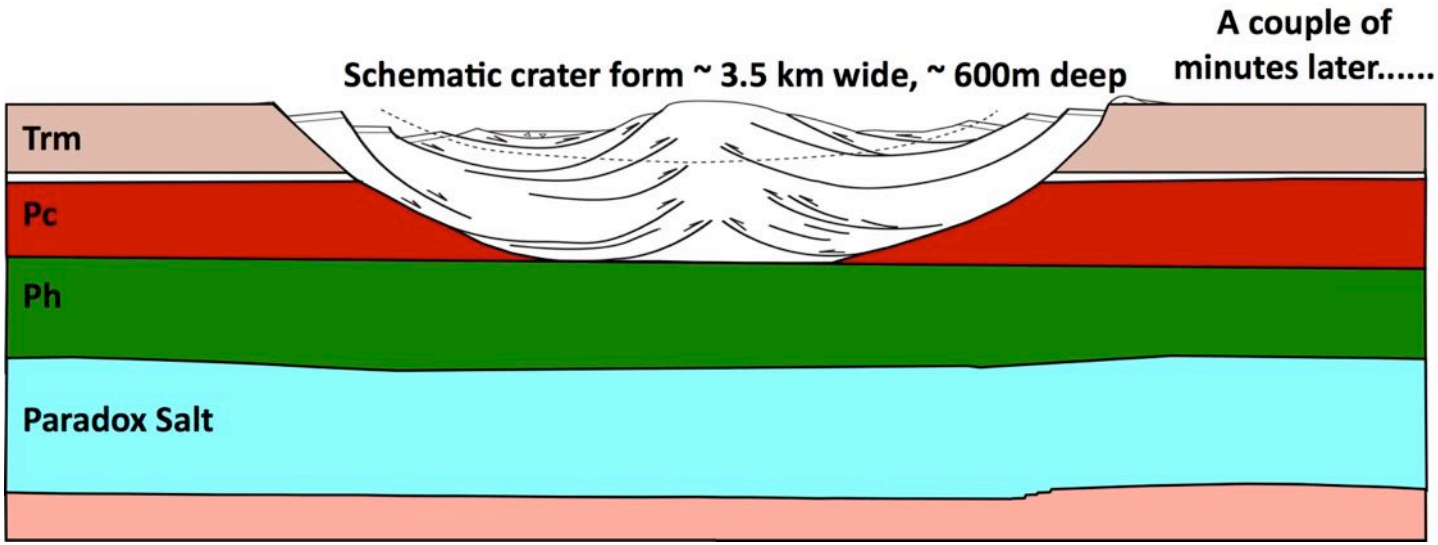


- Problems with the Pinched-off Salt Diapir
  - No remnant Paradox Fmn in dome center (requires perfect closure)
  - No remnant Paradox at base of dog tongues (requires complete weld)
  - No described halokinetic sequences
  - No described diapir-derived detritus in flanking stratigraphy
  - (Vertical) welding of diapir while still plenty of Paradox Fmn at depth (~ 600m in Buck Mesa #1 well)
  - No obvious mechanism for initiation of a small, circular salt structure in this distal part of the Paradox Basin

Jackson et al., 1998

A New Hypothesis: Early Triassic Impact

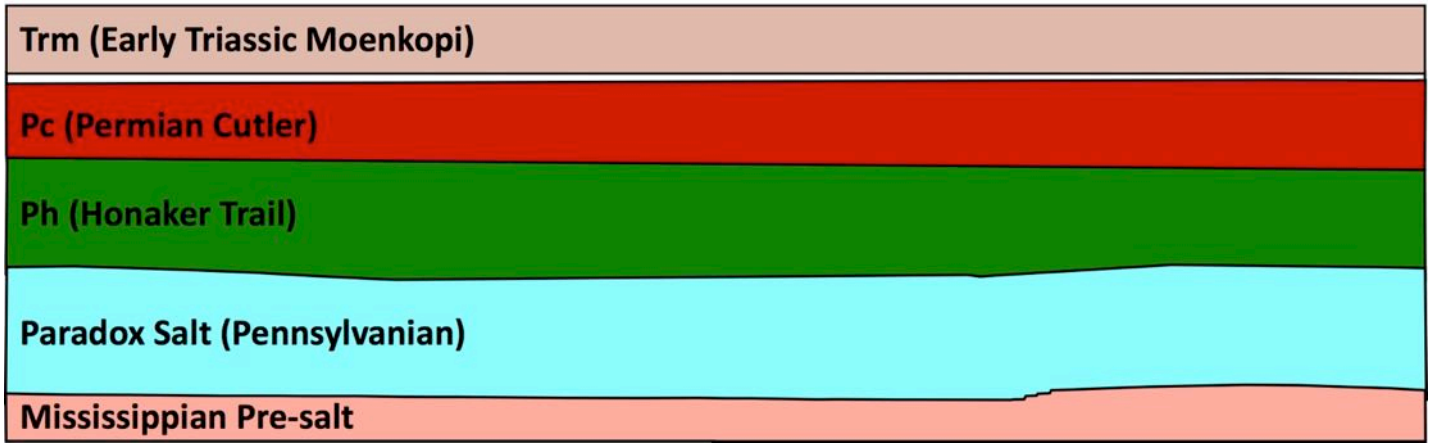
(2)



Meteorite ~ 200m in diameter

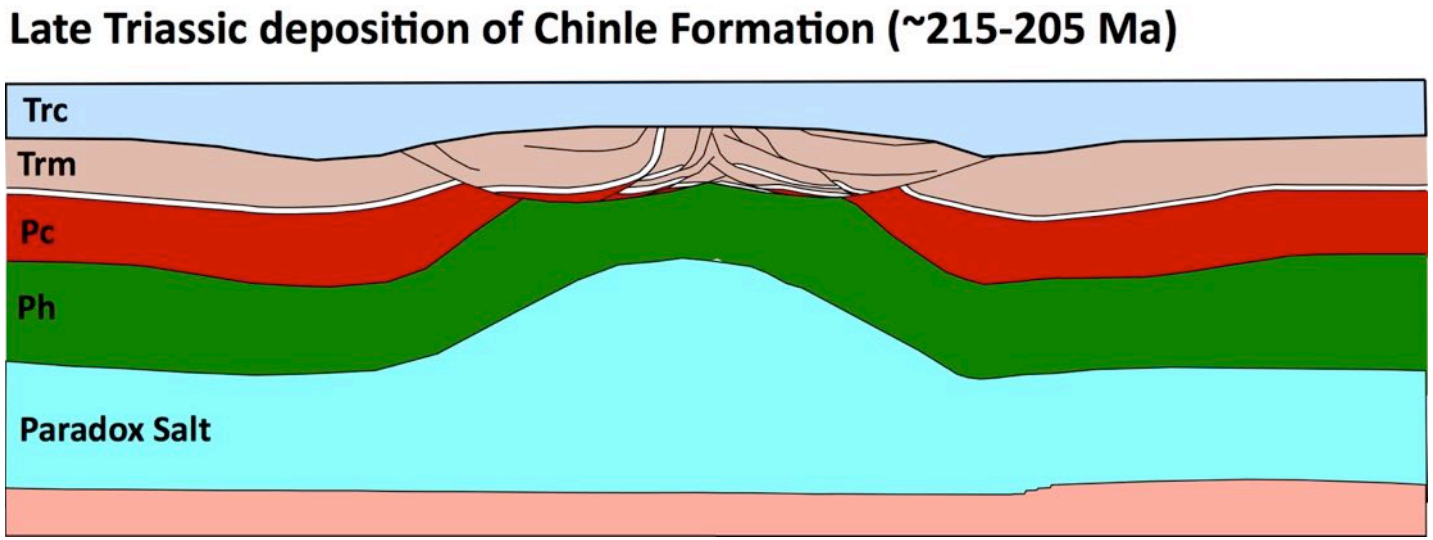
One day in the Early Triassic..... some 250-240 million years ago

(1)

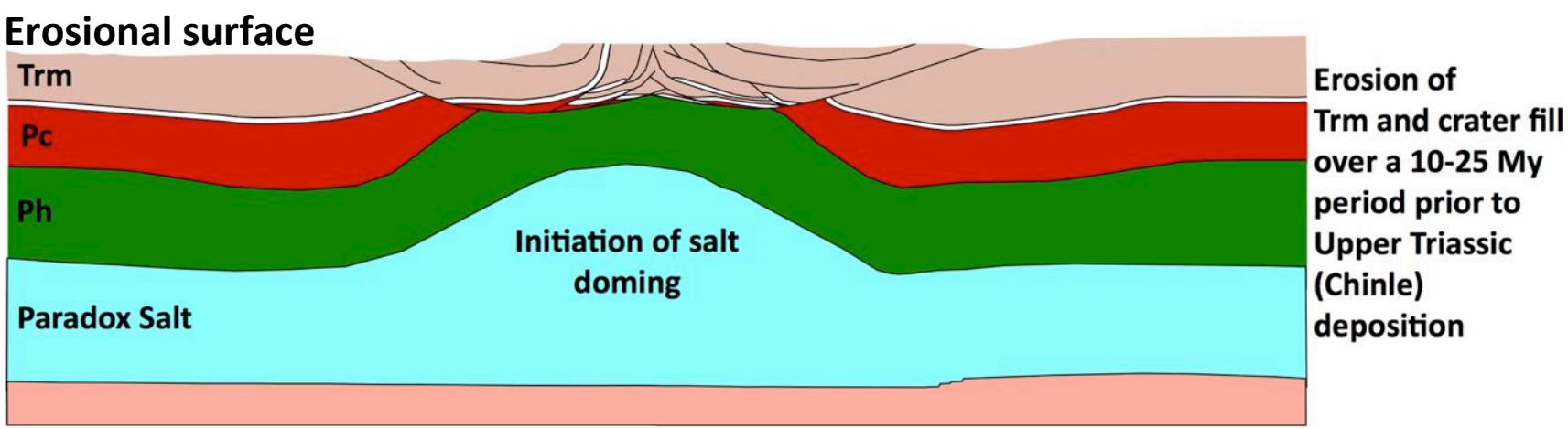


A New Hypothesis: Late Tr-Middle Jr Salt Doming

(4)

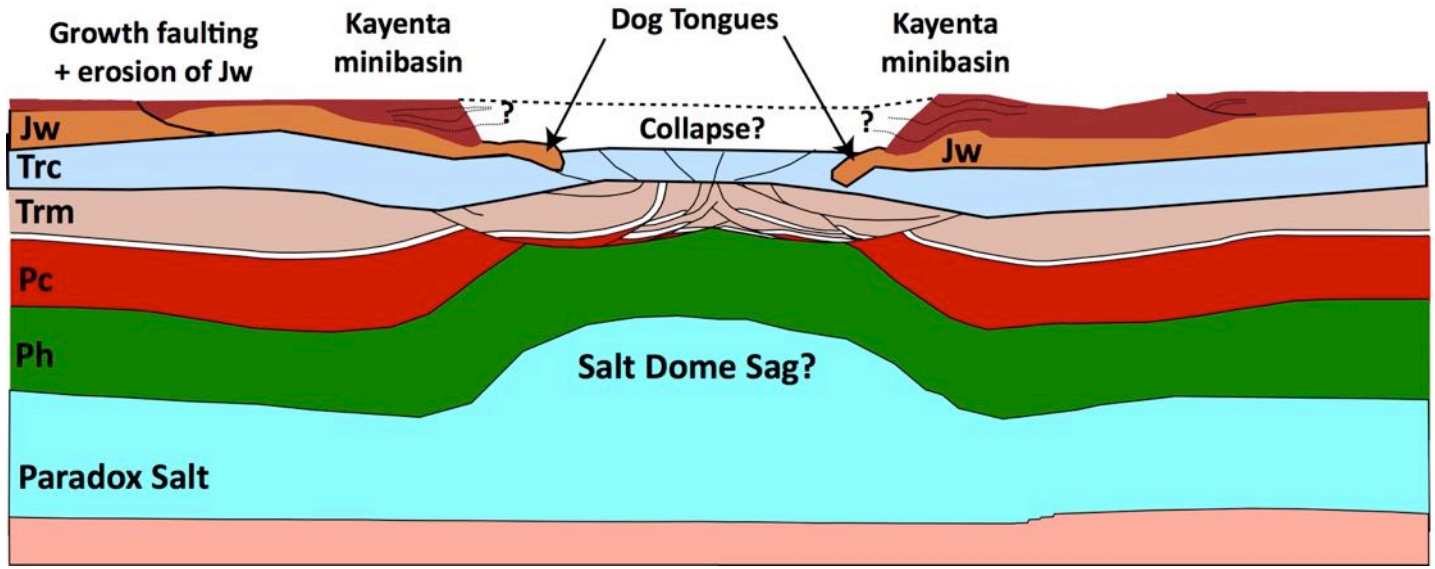


(3)



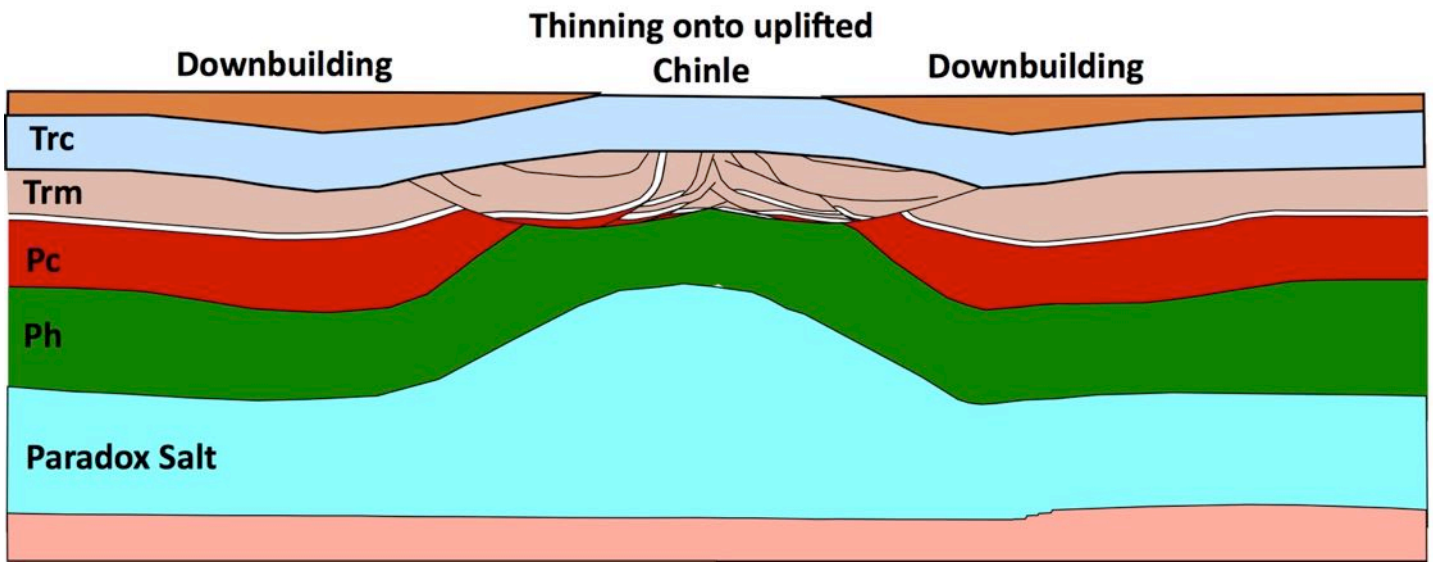
A New Hypothesis: Late Tr-Middle Jr Salt Doming

(6)



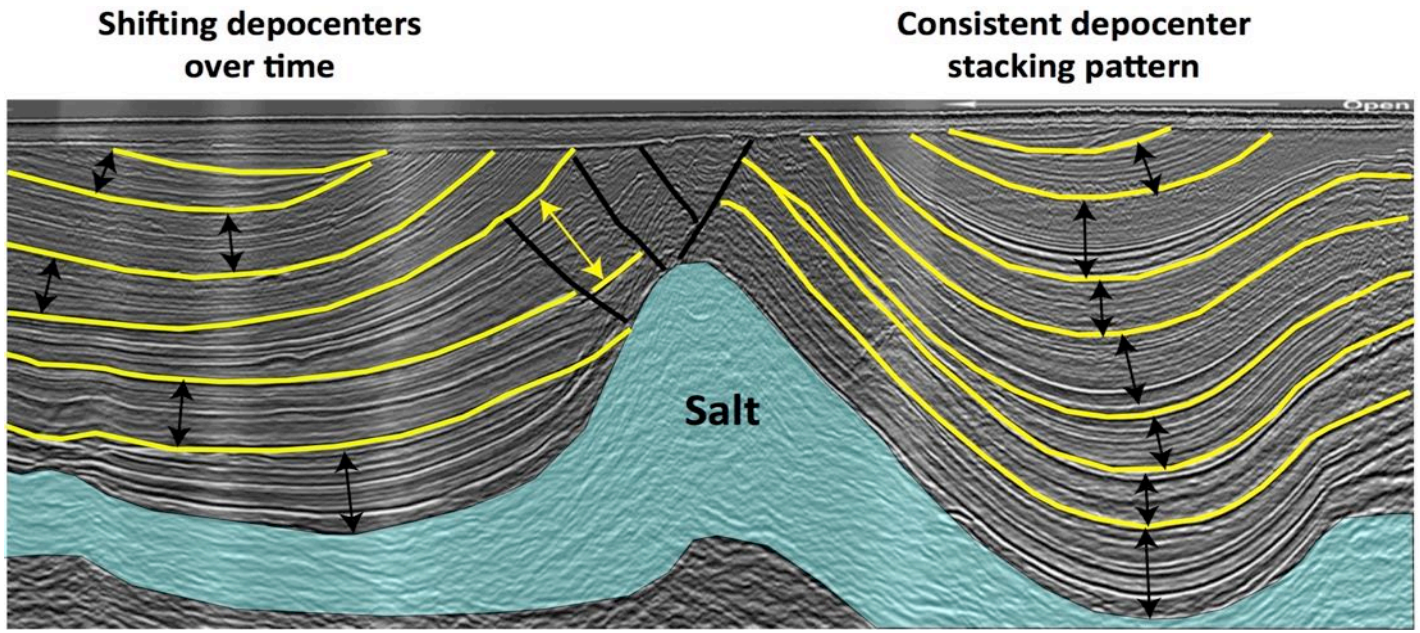
Deposition of Kayenta Formation (~199-195 Ma)

(5)



Early Jurassic deposition of Wingate Formation (~205-200 Ma)

A New Hypothesis: Late Tr-Middle Jr Salt Doming

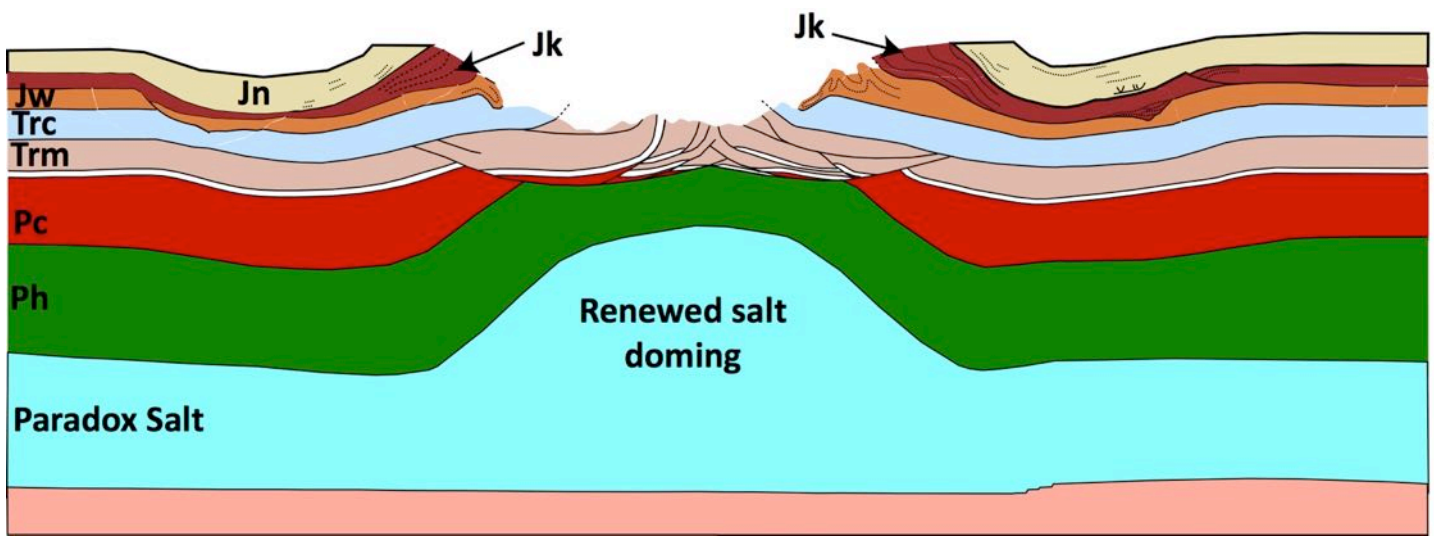


Analogue?

Barents Sea time data

Salt doming possibly continued after Navajo time but no outcrop record present

(7)



Deposition of Navajo Formation (~195-172 Ma)

Conclusions

- The Kayenta Formation away from Upheaval Dome (and other salt structures) is ~70-80 meters thick
- The Kayenta Formation at Upheaval Dome displays significant thickness variation
  - Minimum thickness = 7 meters
  - Maximum thickness = 224 meters
- Presence of surfaces of angular discordance (truncation and onlap) suggest long-term deformation
- Normal growth faults suggest deformation over long periods of time
- Shifting of depocenters through the exposed Jurassic formations and localization of distinct facies suggests long-term deformation
- New hypothesis of Early Triassic (~250-240 Ma) impact followed by salt doming through to at least Middle Jurassic times (~195-172 Ma) attempts to explain the wide range of geological observations at Upheaval Dome

Acknowledgments

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- + anyone else who has added their “two cents” worth along the way (even the tourists at the Upheaval Dome overlook!)