# Remarkable Penecontemporaneous Deformation Features Produced by Seismic Waves in Cambrian Carbonate Deposits, Western Colorado, USA*

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## Abstract

Penecontemporaneous deformation features preserved in Upper Cambrian grainstone and flat-pebble conglomerate beds in western Colorado, USA, include slide scarps, thrusted beds, irregular blocks, and internally deformed beds. Slide scarps are sharply defined, concave-up surfaces that truncate underlying bedding. Thrusted beds capture movement of a part of a bed onto itself, generally along a moderately to steeply inclined (generally 25°–40°) ramp. Lenses in the hanging wall of these thrusts show fault-bend geometries and mildly deformed bedding that mimic their geometry. Isolated irregular blocks with variable internal structure rest on flat upper bedding surfaces and are similar in composition to the underlying beds. In this case, parts of beds detached, moved-up onto, and some distances across, the laterally adjacent undisturbed bed surfaces. Blocks moved both at the sediment-water interface and intrastratally at shallow depths within overlying muddy deposits. Internally deformed beds have large blocks, fitted fabrics of highly irregular fragments, and contorted lamination, which represent heterogeneous deformation, such as brecciation and liquefaction. These deformation structures were triggered by earthquakes, based on the nature of deformation, regional distribution of liquefaction structures, and their relationships to overlying and underlying beds. The earthquakes represent reactivation of Mesoproterozoic, crustal-scale shear zones in the central Rockies during the Late Cambrian. Features produced by initial brittle deformation are unusual relative to most reported seismites, and they may represent poorly recognized to unrecognized seismogenic structures in the rock record.

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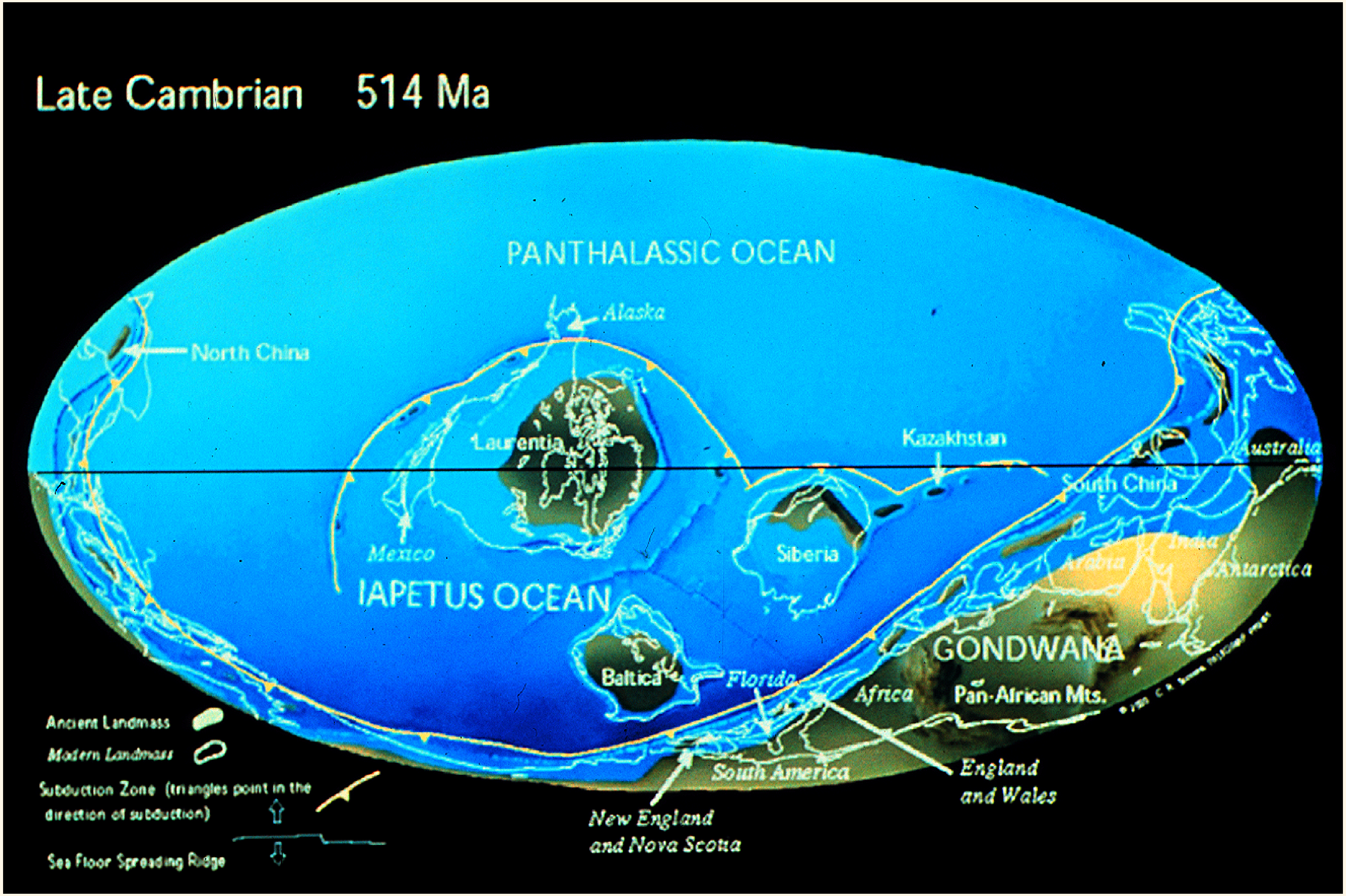
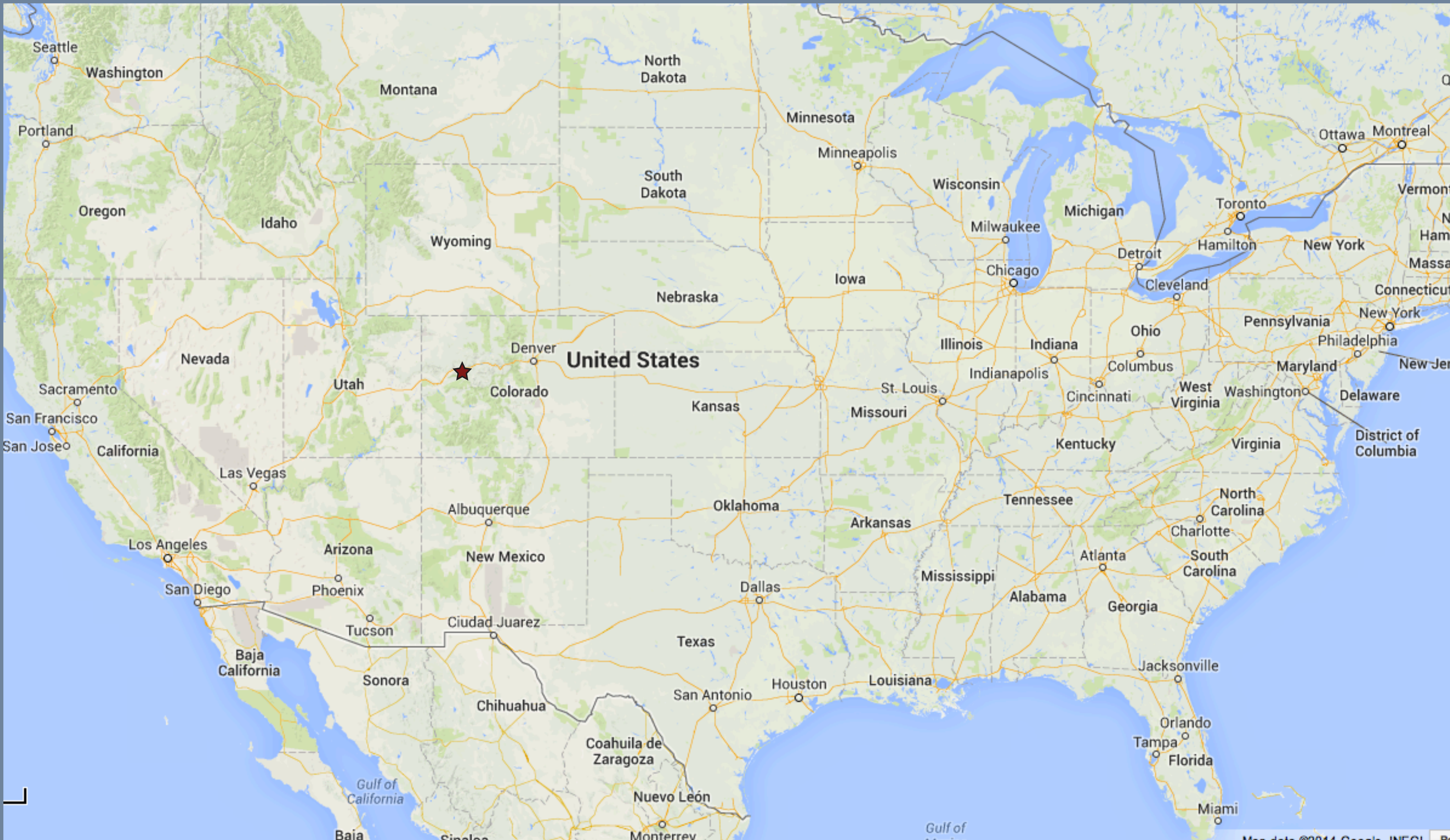

Late Cambrian 514 Ma
PANTHALASSIC OCEAN
Alaska
North China
Laurentia
Kazakhstan
Australia
South China
Mexico
Siberia
IAPETUS OCEAN
India
Arabia
Antarctica
GONDWANA
Baltica
Florida
Africa
Pan-African Mts.
South America
England
and Wales
New England
and Nova Scotia
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge


Seattle
Washington
Montana
North Dakota
Minnesota
Portland
Oregon
Idaho
Wyoming
South Dakota
Minneapolis
Wisconsin
Michigan
Milwaukee
Toronto
Ottawa
Montreal
Vermont
Hamilton
New York
Detroit
Chicago
Iowa
Nebraska
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Nevada
Utah
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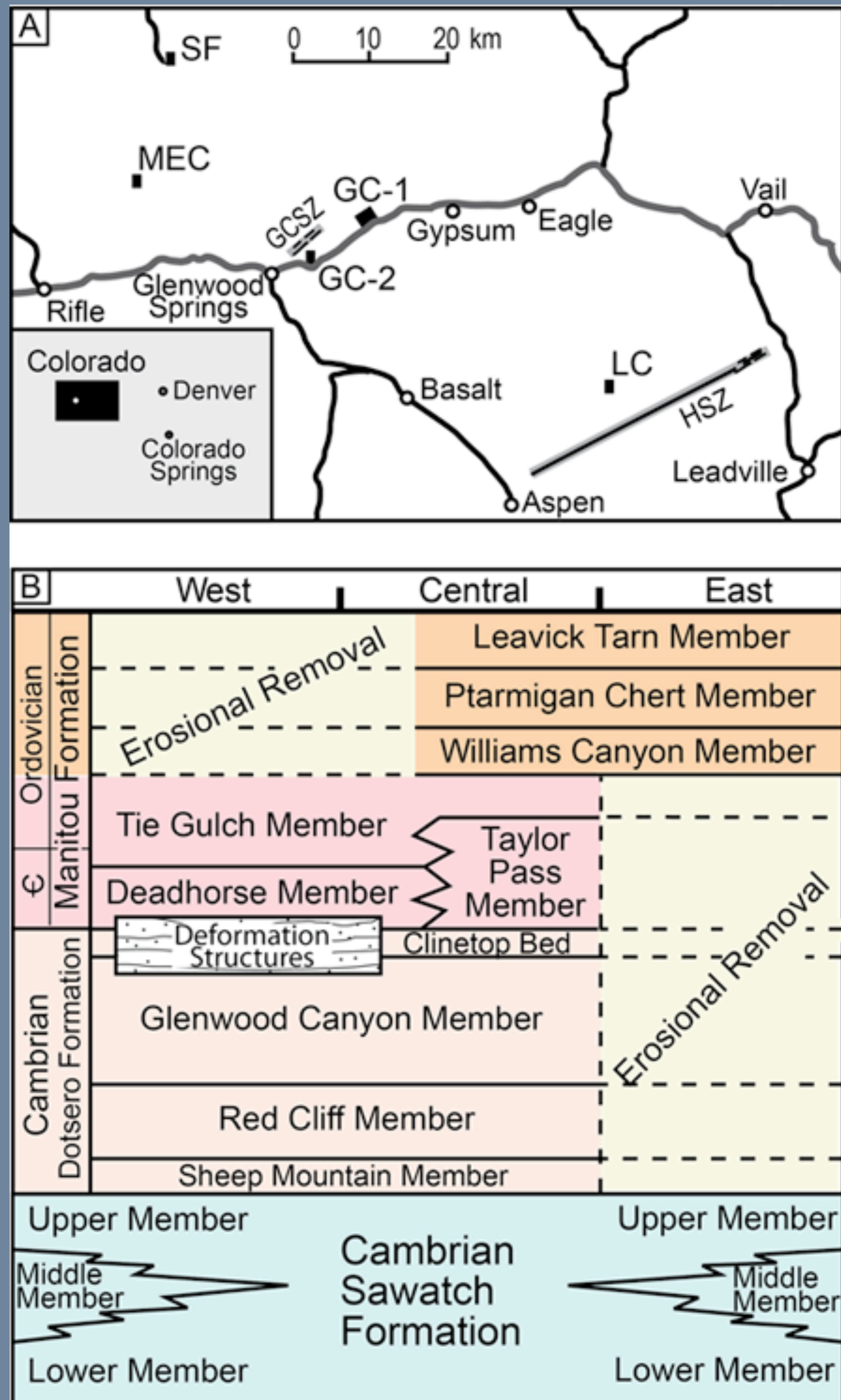
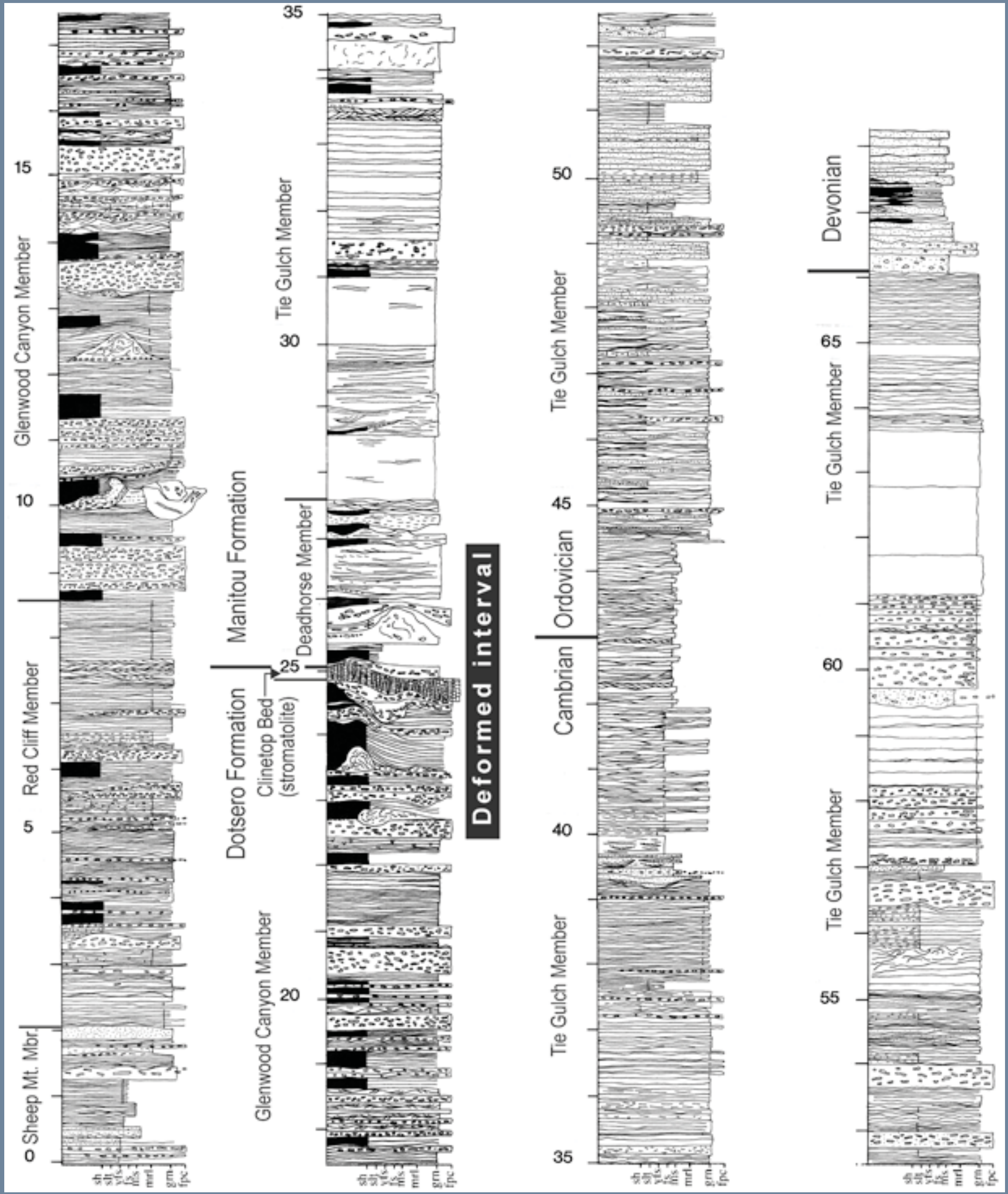
Colorado
Illinois
Indiana
Ohio
Pennsylvania
New York
Philadelphia
Sacramento
San Francisco
San Jose
California
Kansas
Missouri
St. Louis
Indianapolis
Columbus
Cincinnati
West Virginia
Maryland
Washington
Delaware
District of Columbia
Kentucky
Virginia
Las Vegas
Albuquerque
Oklahoma
Tennessee
Arkansas
North Carolina
Charlotte
Los Angeles
Arizona
New Mexico
Atlanta
South Carolina
San Diego
Phoenix
Mississippi
Alabama
Dallas
Georgia
Tucson
Ciudad Juarez
Texas
Baja California
Sonora
Jacksonville
San Antonio
Houston
Louisiana
Chihuahua
Orlando
Tampa
Florida
Coahuila de Zaragoza
Gulf of California
Nuevo León
Miami
Baja
Sinaloa
Monterrey
Gulf of Mexico
Map data ©2014 Google, INEGI




Location

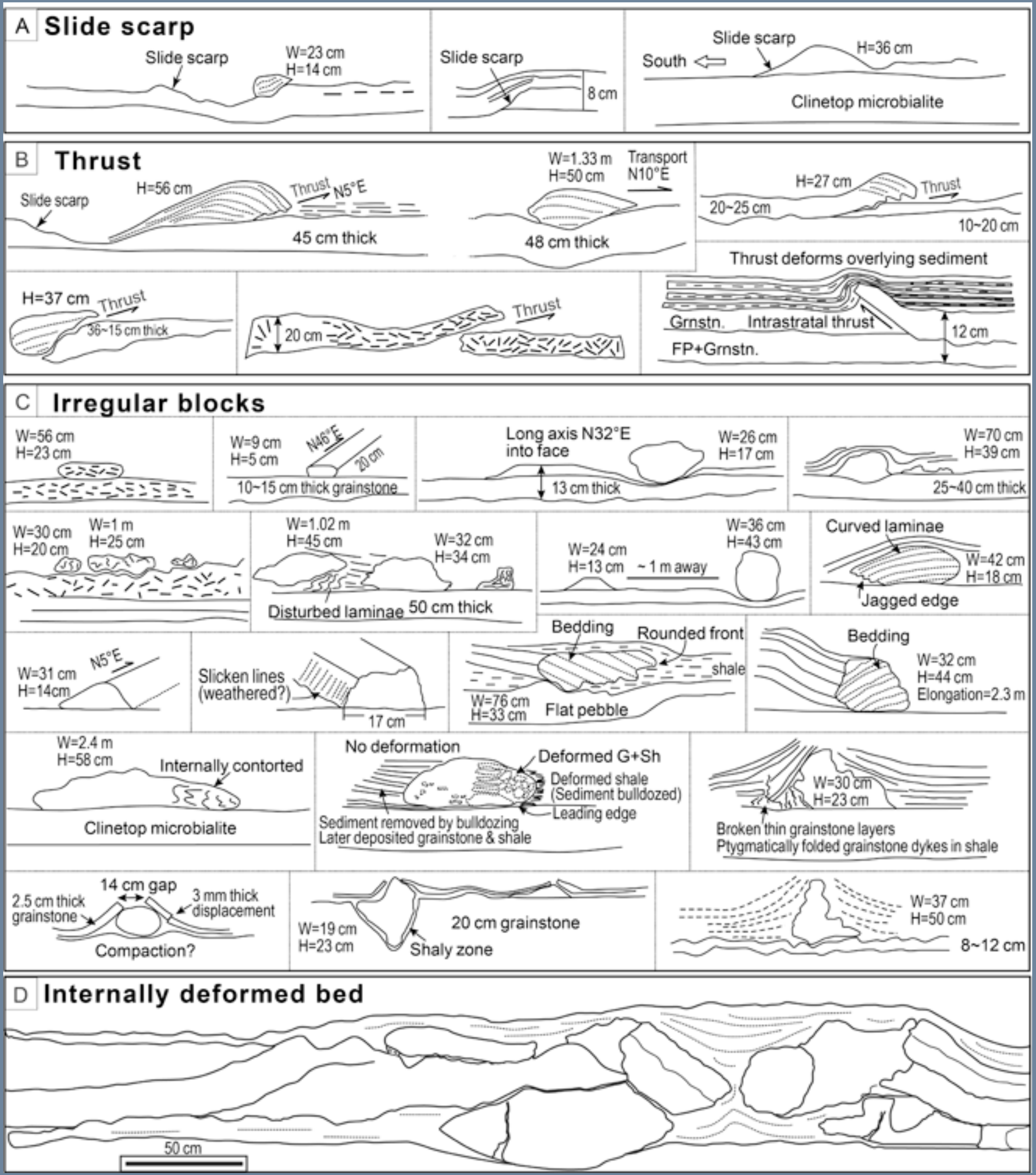
Stratigraphy

# Glenwood Canyon, Colorado




# Glenwood Canyon, CO

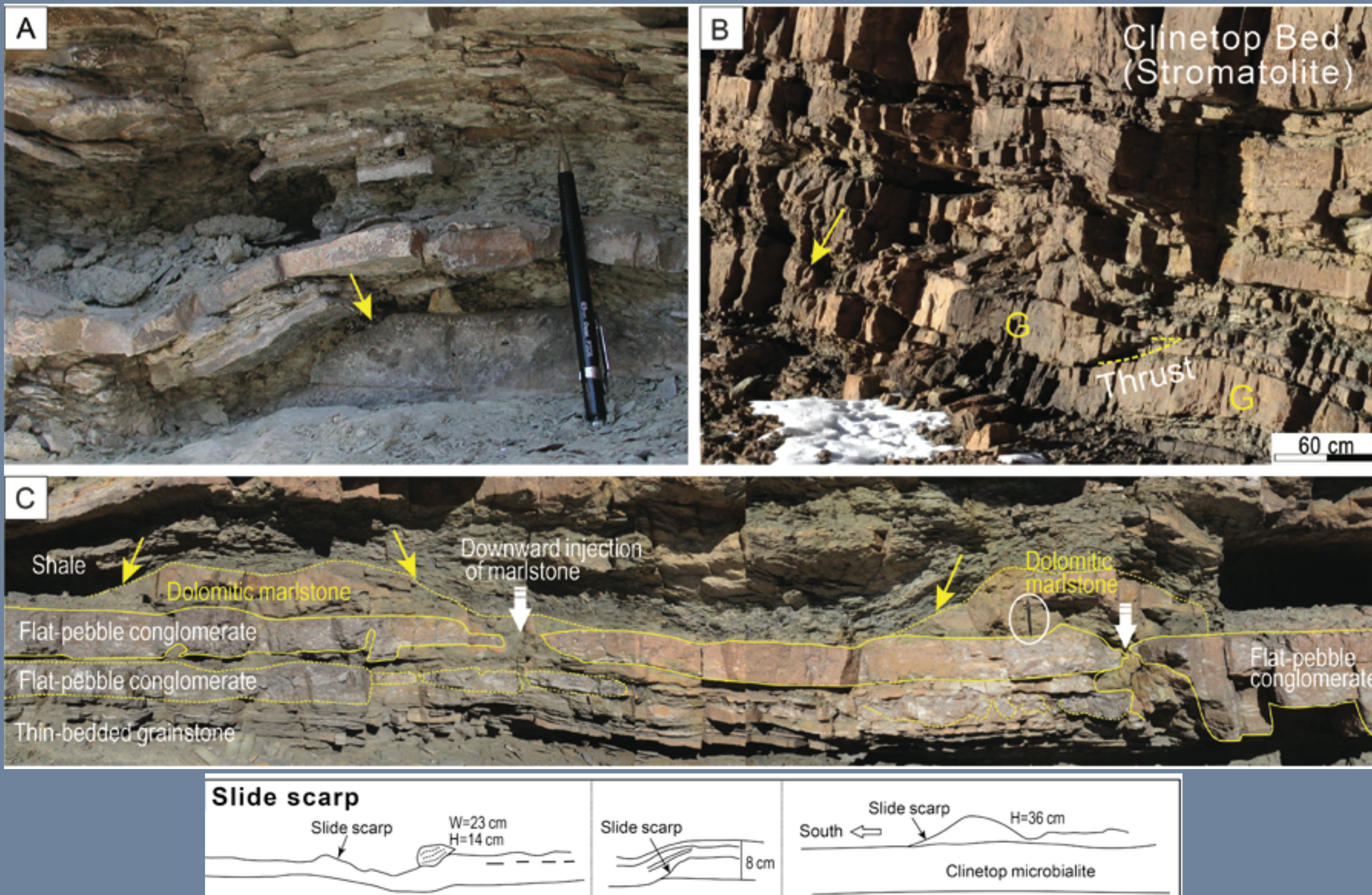
# Variety of Synsedimentary Deformation Features



# Slide Scarps

Sharply defined, concave-up surfaces that truncate underlying bedding.

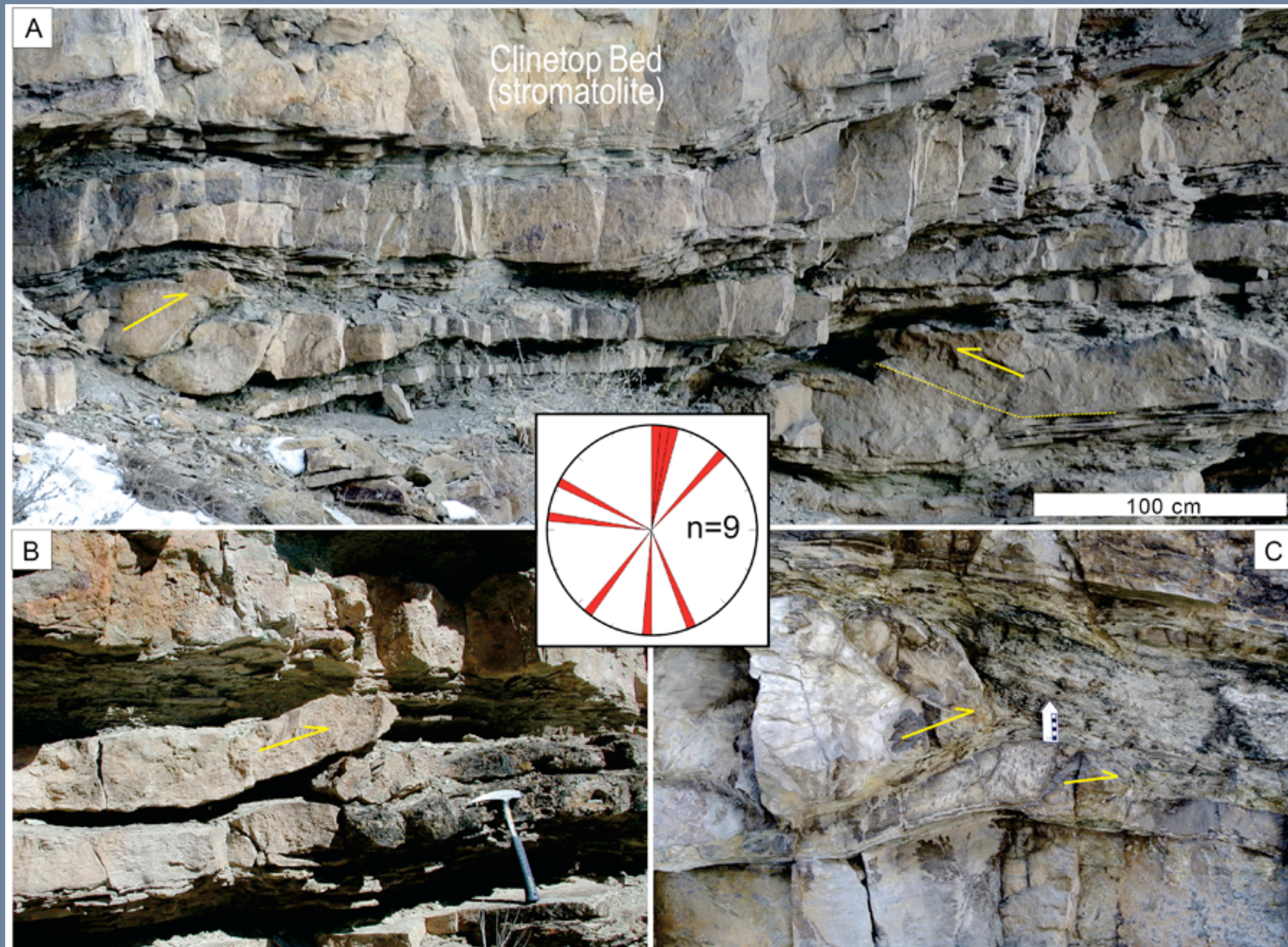
# Slide Scarps

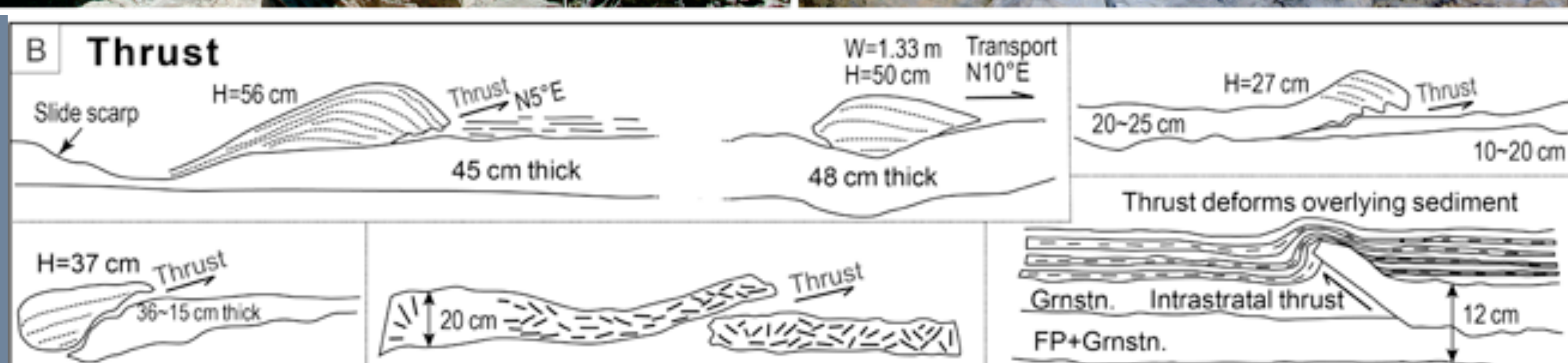


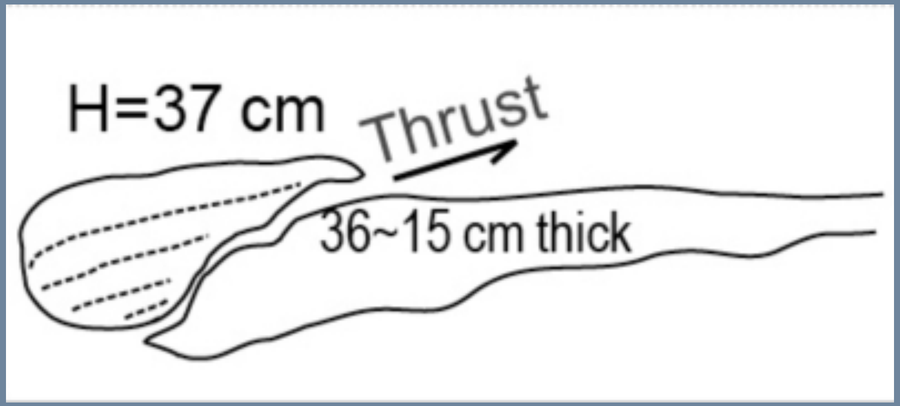
# Thrusted Beds

- Movement of a part of a bed onto itself
- Moderate to steeply inclined (generally 25°–40°) ramp.
- Hanging wall lenses: fault-bend geometries and deformed bedding that mimic their geometry.

# Thrusted Beds

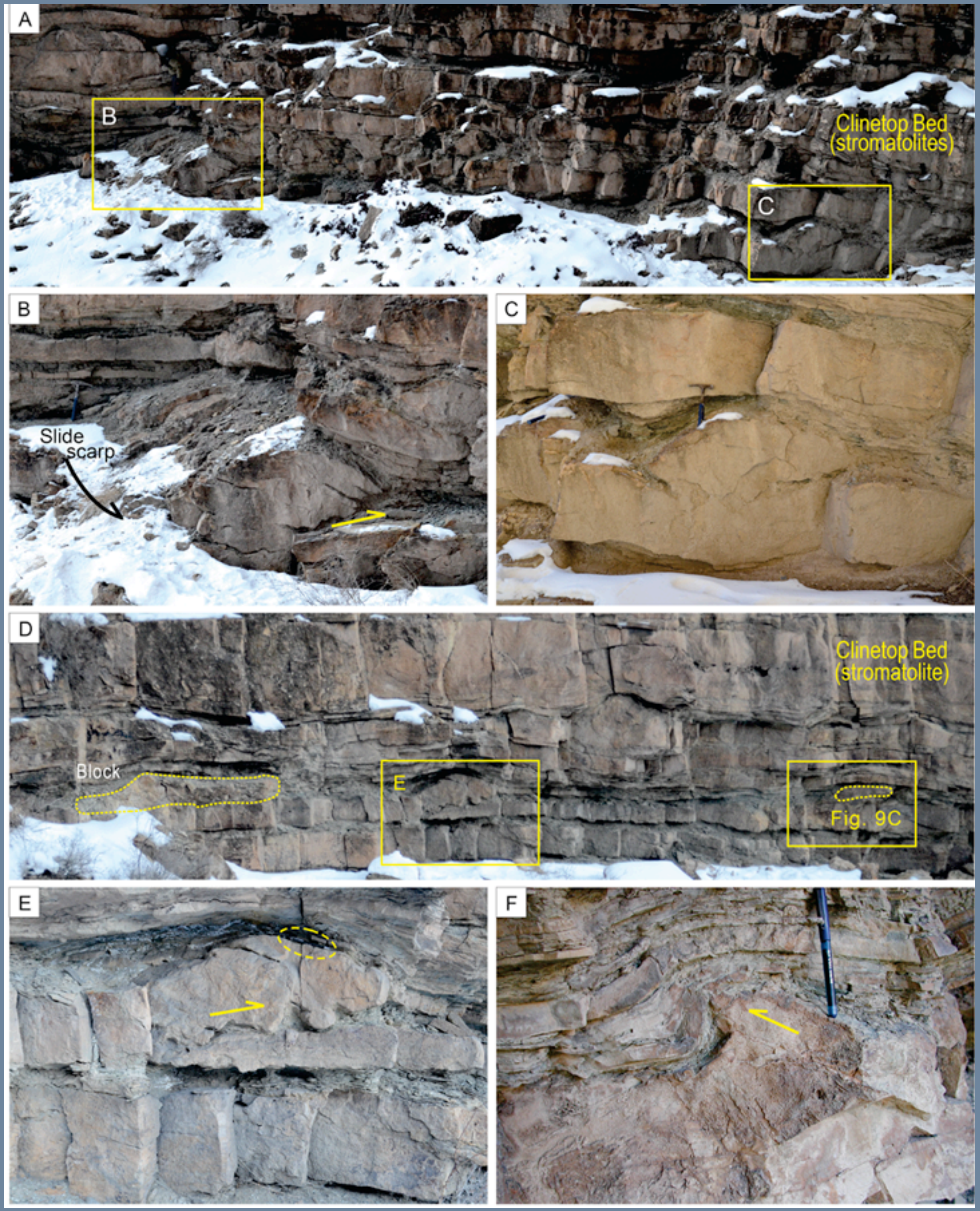


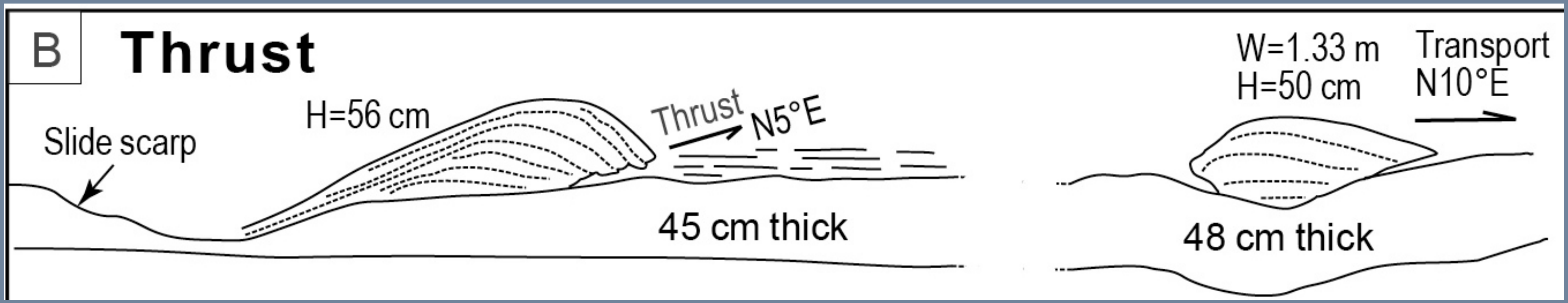



Oppositely Oriented Thrusts at Nearly Same Stratigraphic Level

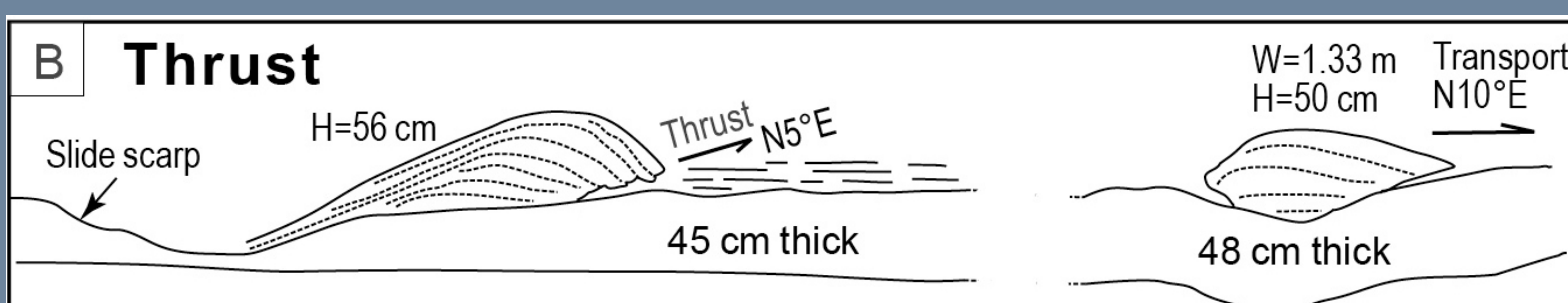
# Thrusted Beds

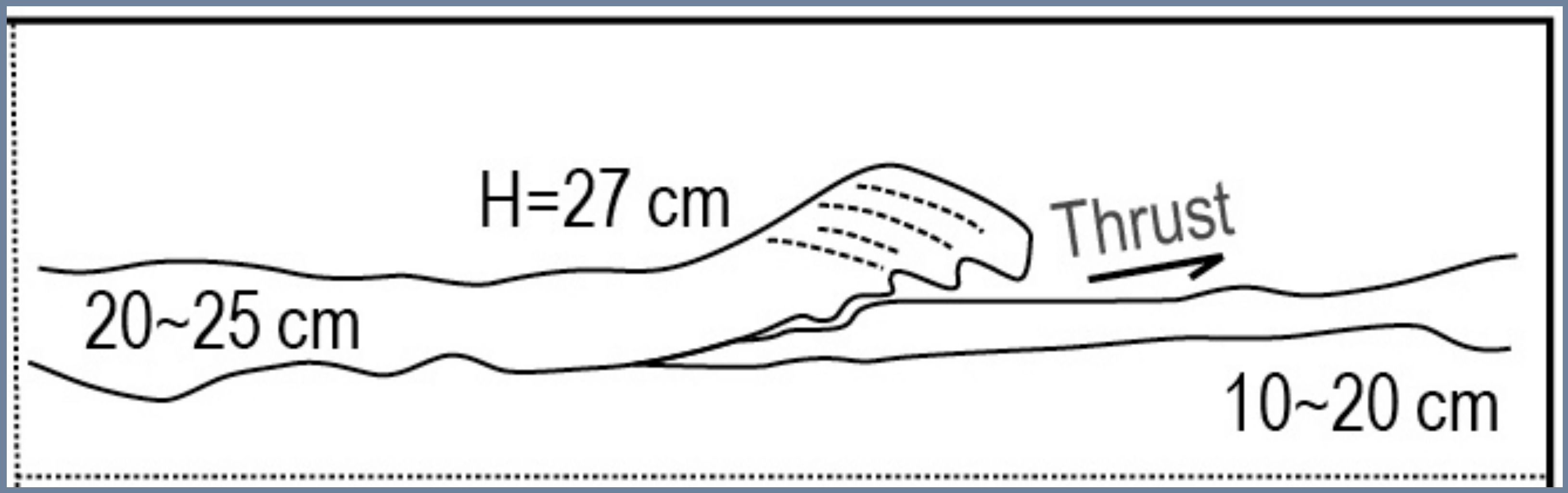



B
Thrusted
Lens


B
Thrust
Slide scarp
H=56 cm
Thrust
N5°E
45 cm thick
W=1.33 m
H=50 cm
Transport
N10°E
48 cm thick


Thrusted
Lens


B
Thrust
Slide scarp
H=56 cm
Thrust
N5°E
45 cm thick
W=1.33 m
H=50 cm
Transport
N10°E
48 cm thick

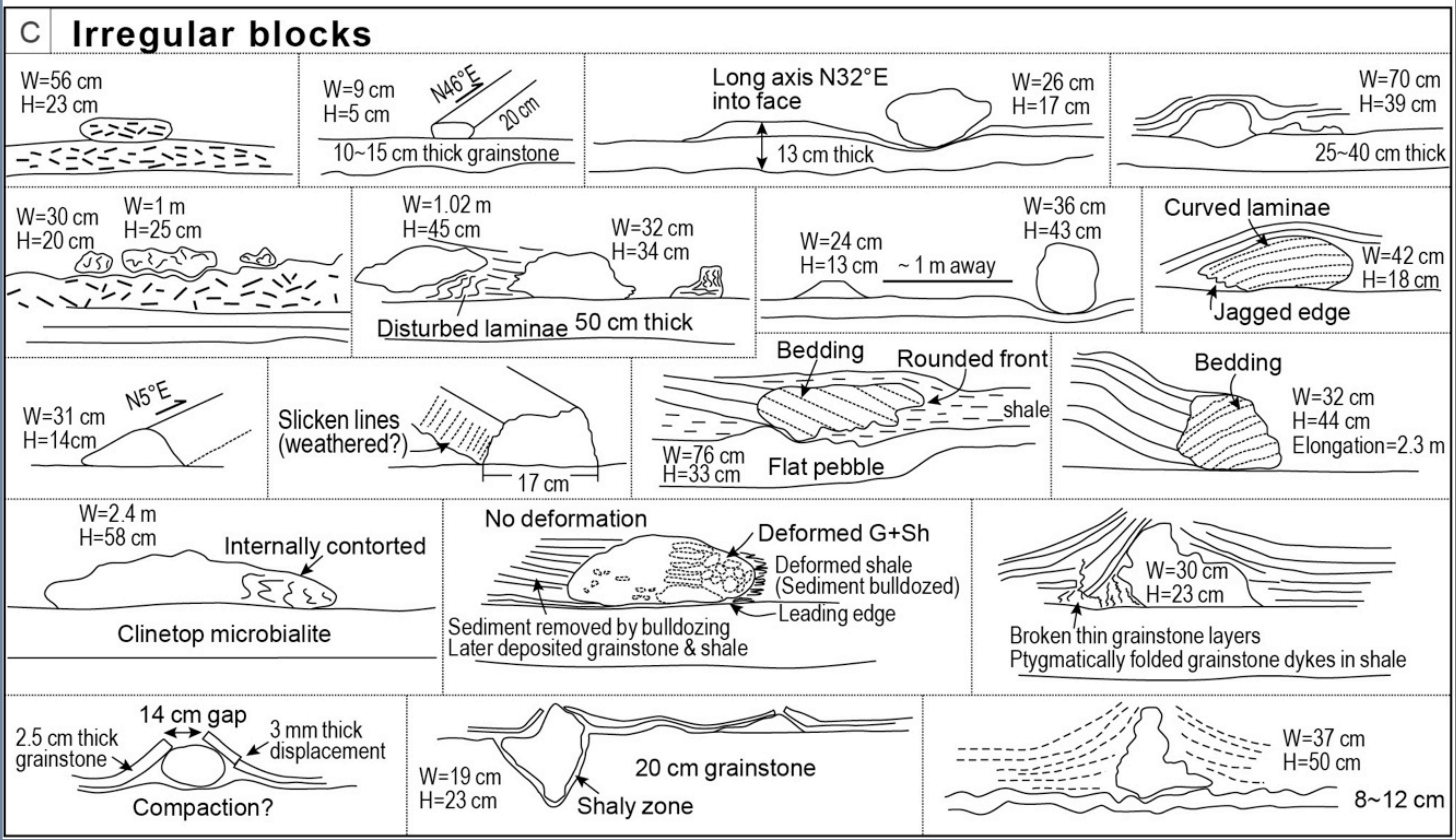


H=27 cm
Thrust
20~25 cm
10~20 cm

# BLOCKS

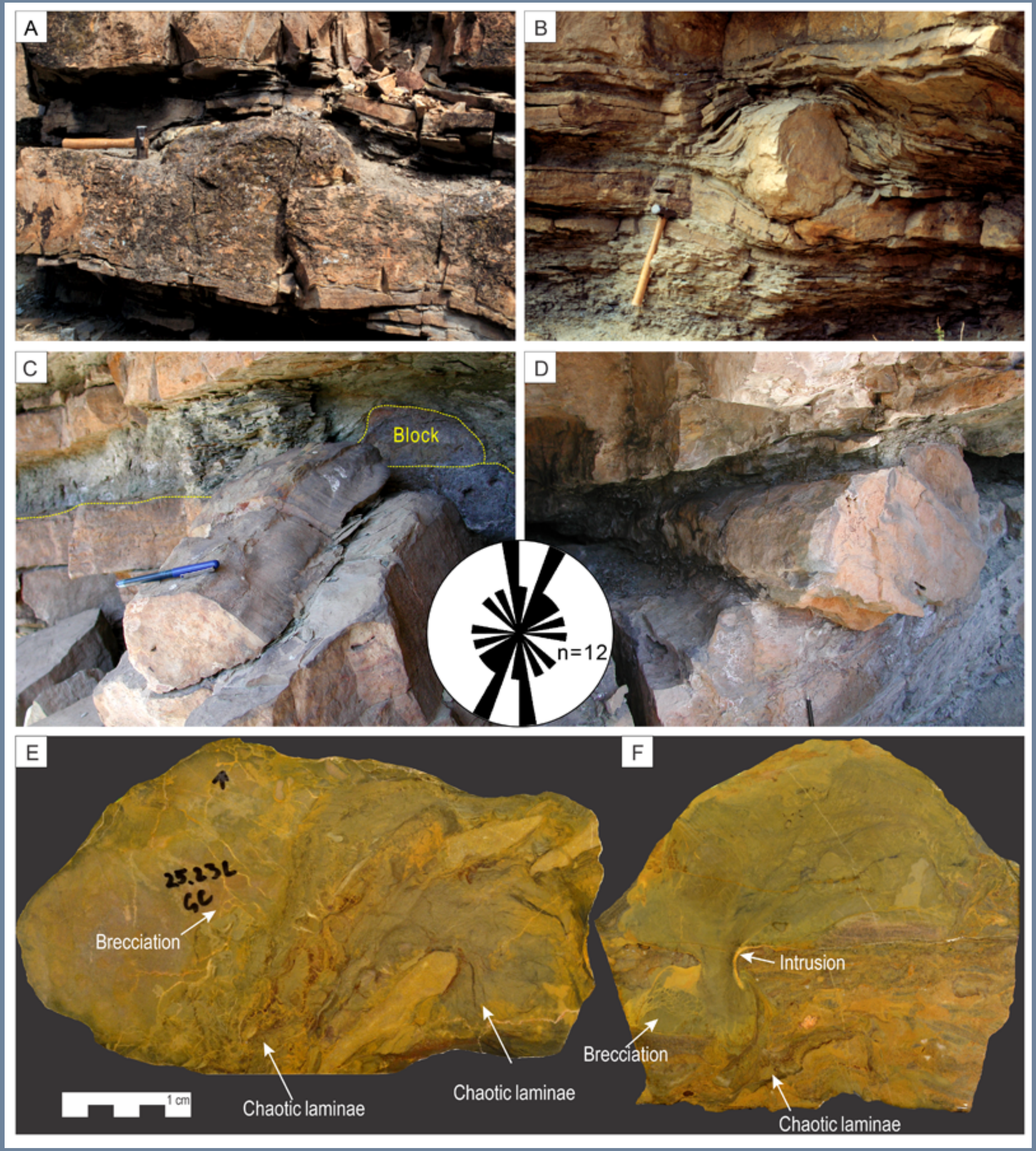
- Isolated irregular blocks on flat bedding surfaces. Similar in composition to the underlying beds.
- Parts of beds detached, moved onto and across laterally adjacent bed surfaces.
- Blocks moved at the sediment-water interface and intrastratally at shallow depths within overlying muddy deposits.

# Blocks



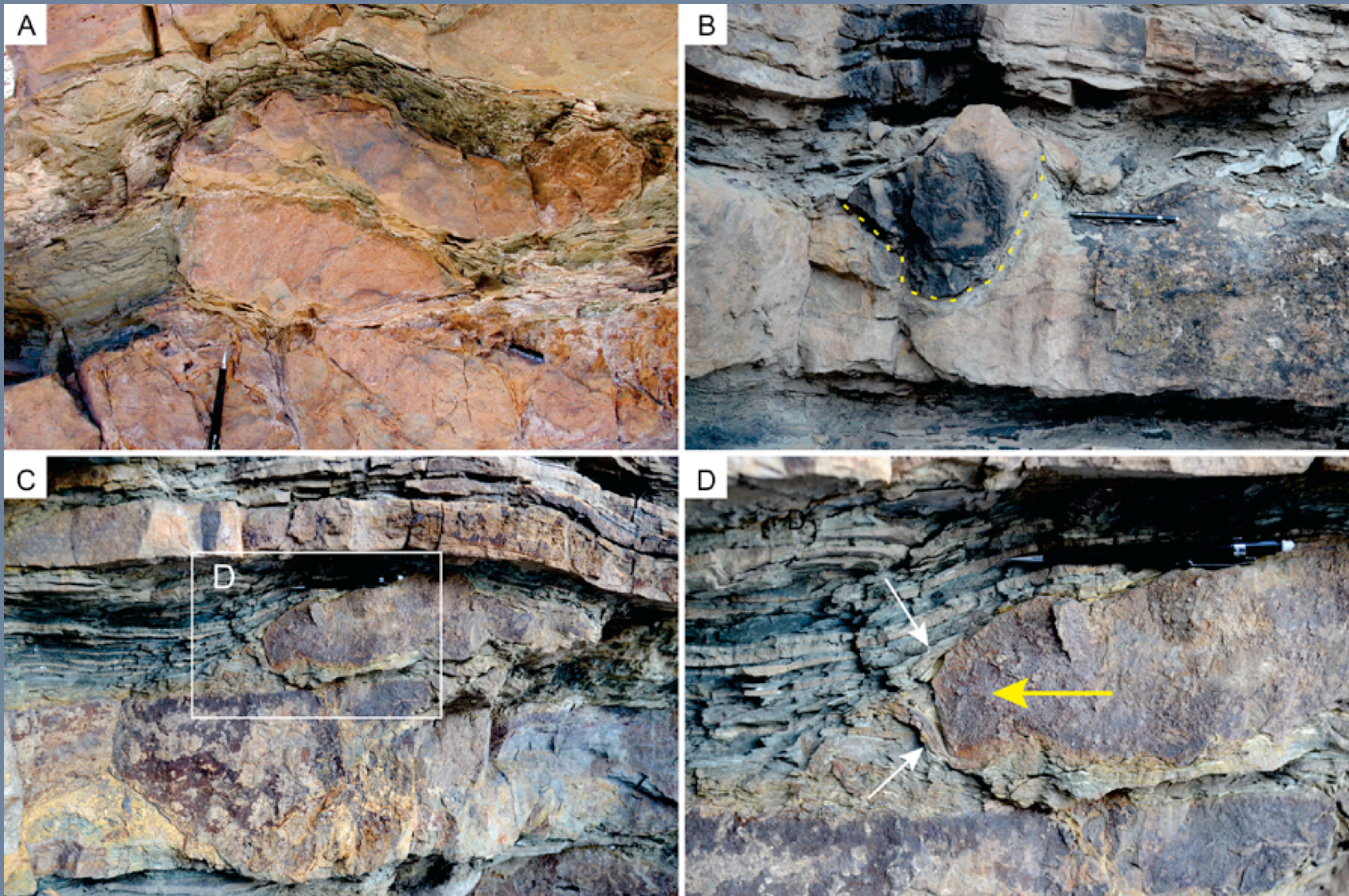
C
Irregular blocks
W=56 cm
H=23 cm
W=9 cm
H=5 cm
N46°E
20 cm
10~15 cm thick grainstone
Long axis N32°E
into face
W=26 cm
H=17 cm
13 cm thick
W=70 cm
H=39 cm
25~40 cm thick
W=30 cm
H=20 cm
W=1 m
H=25 cm
W=1.02 m
H=45 cm
W=32 cm
H=34 cm
Disturbed laminae
50 cm thick
W=24 cm
H=13 cm
~ 1 m away
W=36 cm
H=43 cm
Curved laminae
W=42 cm
H=18 cm
Jagged edge
W=31 cm
H=14cm
N5°E
Slicken lines
(weathered?)
17 cm
Bedding
Rounded front
shale
W=76 cm
H=33 cm
Flat pebble
Bedding
W=32 cm
H=44 cm
Elongation=2.3 m
W=2.4 m
H=58 cm
Internally contorted
Clinetop microbialite
No deformation
Deformed G+Sh
Deformed shale
(Sediment bulldozed)
Leading edge
Sediment removed by bulldozing
Later deposited grainstone & shale
W=30 cm
H=23 cm
Broken thin grainstone layers
Ptygmatically folded grainstone dykes in shale
14 cm gap
2.5 cm thick
grainstone
3 mm thick
displacement
Compaction?
W=19 cm
H=23 cm
20 cm grainstone
Shaly zone
W=37 cm
H=50 cm
8~12 cm

# Blocks

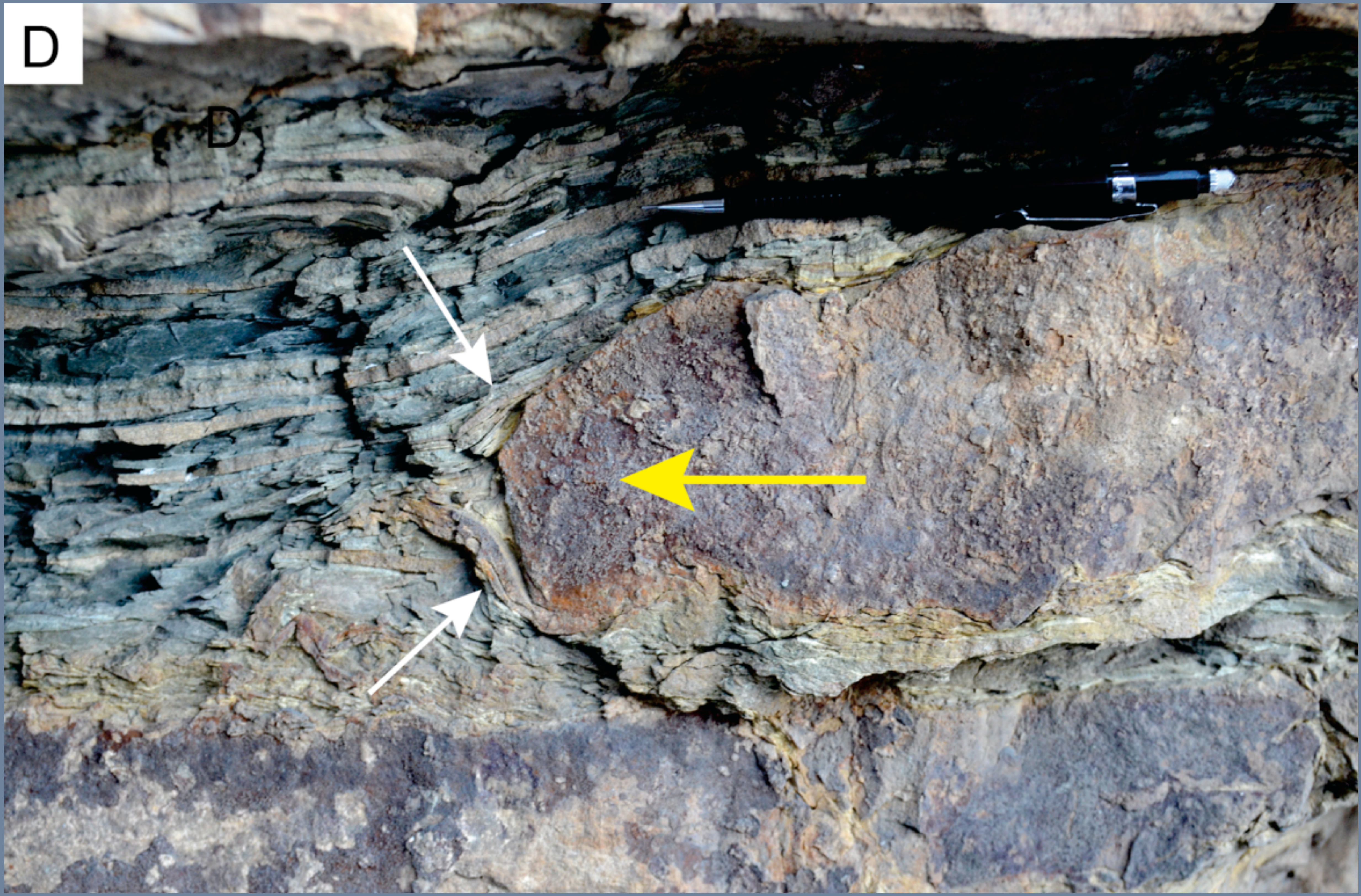


A
B
C
Block
D
n=12
E
25.23L
GC
Brecciation
Chaotic laminae
Chaotic laminae
1 cm
F
Intrusion
Brecciation
Chaotic laminae

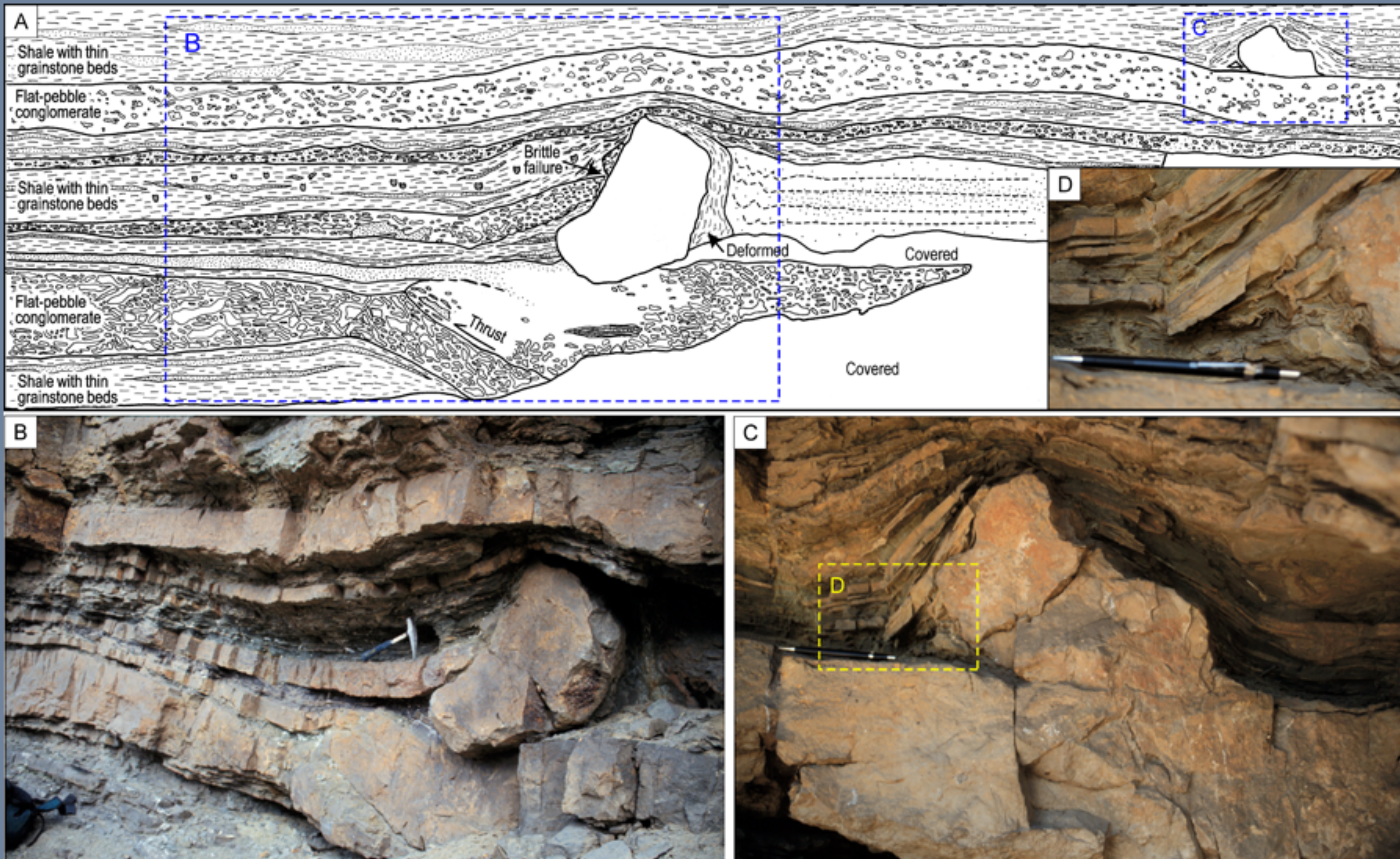
# Blocks



# Intrastratal Insertion of Block into overlying strata



# Blocks

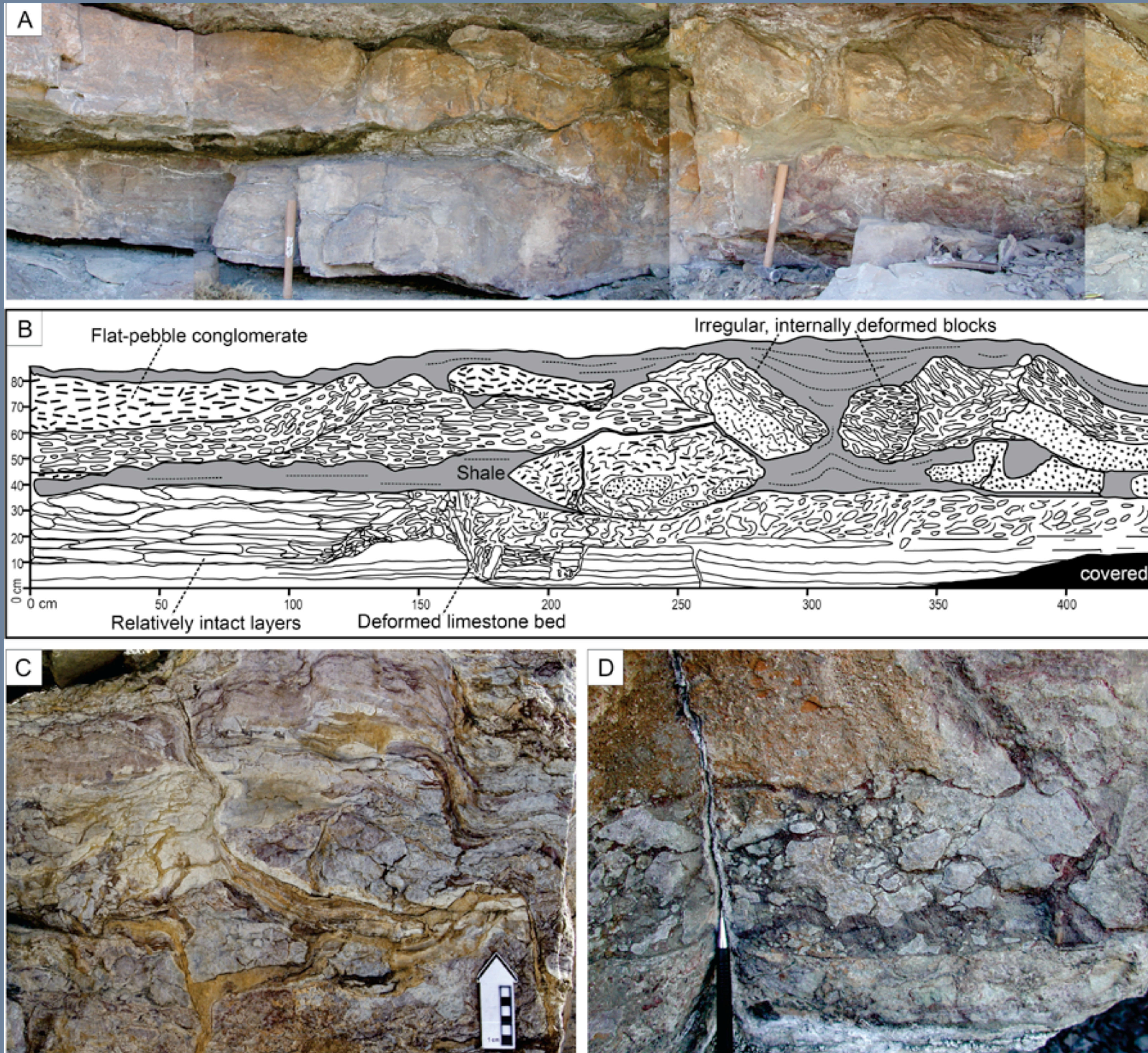


A
B
C
Shale with thin grainstone beds
Flat-pebble conglomerate
Shale with thin grainstone beds
Flat-pebble conglomerate
Shale with thin grainstone beds
Brittle failure
Deformed
Covered
Thrust
Covered
D
B
C
D

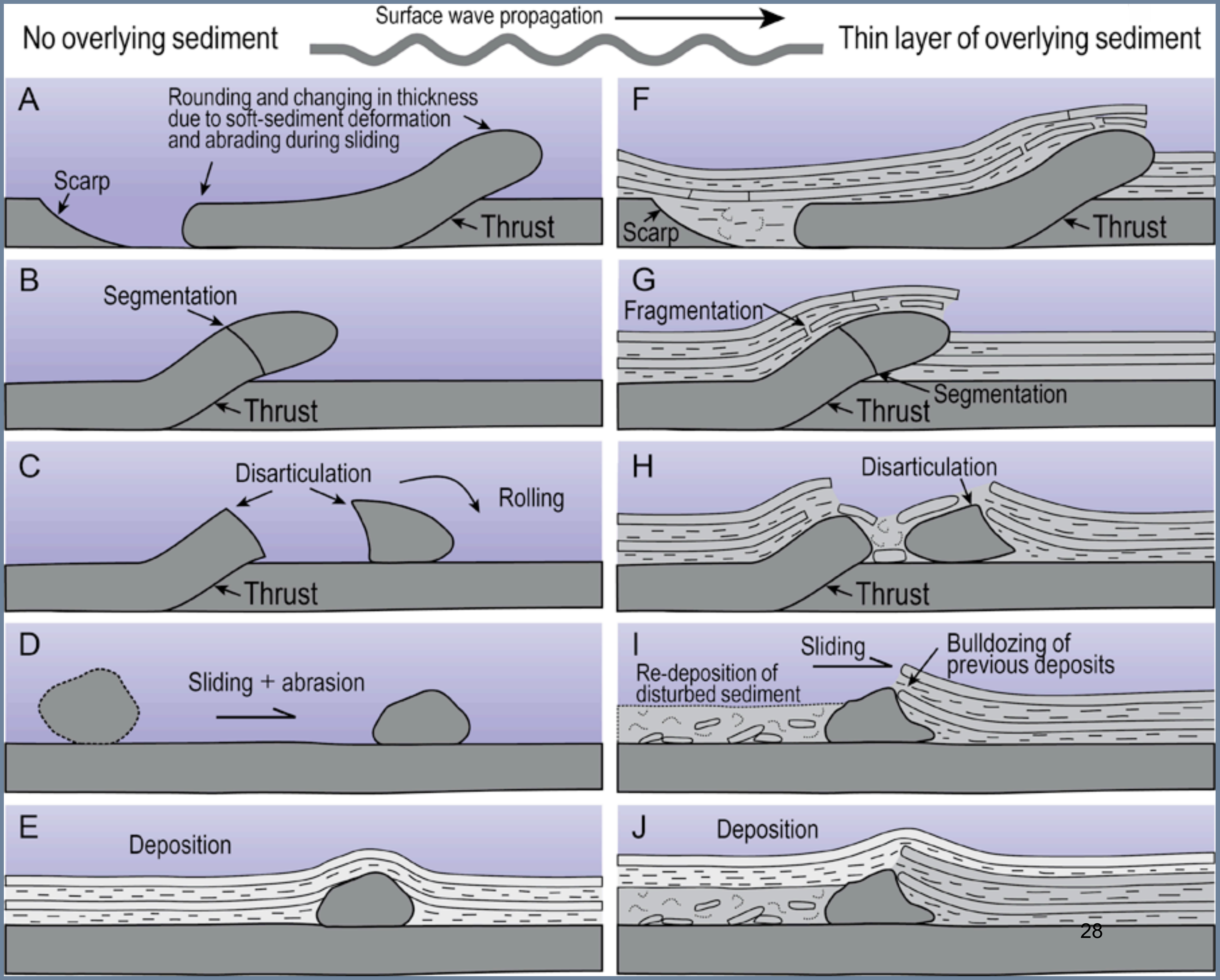
# Internally Deformed (Liquefied) Beds

- Internally deformed beds
- Large blocks, fitted fabrics of highly irregular fragments, and contorted lamination.
- Heterogeneous deformation: brecciation and liquefaction

# Internally Deformed Beds



# Model



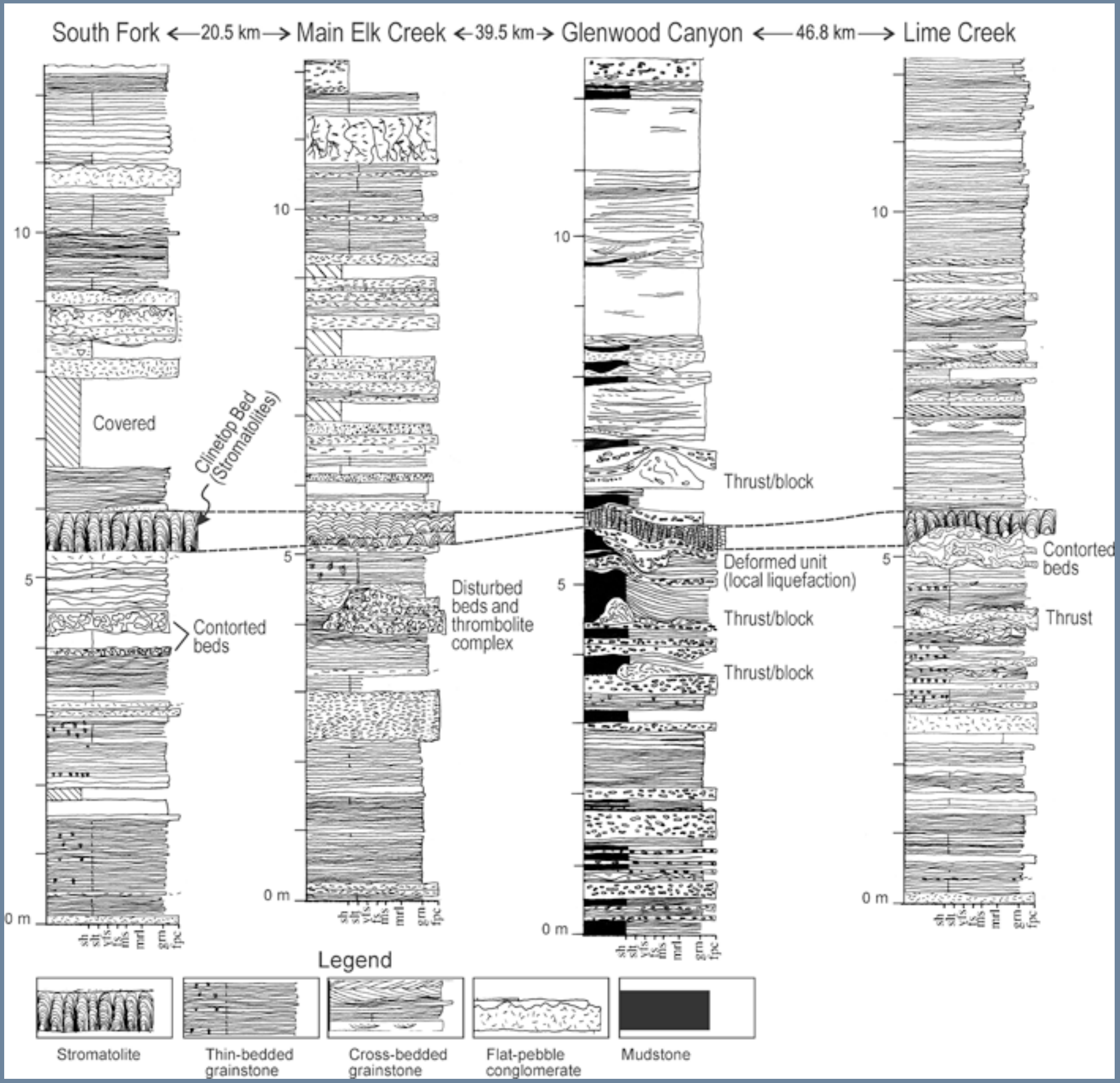
No overlying sediment
Surface wave propagation
Thin layer of overlying sediment
A
Rounding and changing in thickness due to soft-sediment deformation and abrading during sliding
Scarp
Thrust
B
Segmentation
Thrust
C
Disarticulation
Rolling
Thrust
D
Sliding + abrasion
E
Deposition
F
Scarp
Thrust
G
Fragmentation
Segmentation
Thrust
H
Disarticulation
Thrust
I
Sliding
Bulldozing of previous deposits
Re-deposition of disturbed sediment
J
Deposition

# Paleoseismic Analysis

- Block 56 cm thick resting on bed from which it was derived.
- Change in potential energy: mg(dh) where m= mass, g= acceleration due to gravity, dh= change in height (56 cm)
- Equals kinetic energy= $0{\cdot}5mv^2$
- Velocity= 3·28 m/s; relative velocity = 1.64 m/s (assuming no friction.
- Calculated velocity of 1·64 m/s corresponds to Mercalli Intensity of X+ (Wald et al., 1999)
- Similar velocities in large earthquakes: Northridge, CA 1994; Taiwan 1999; Christchurch 2011.

# Empirical data on the spatial distribution of liquefied strata

Maximum epicentral distances to liquefied sites versus moment Magnitude: empirical relationship of m=0.499 lnX/(3x1.62x10-5) where M is moment magnitude and X is the distance in kilometres (Allen, 1986; Obermeier, 1998; Manga & Brodsky, 2006)



# Paleoseismic Analysis II

- Galli (2000): vast majority of earthquakes produce liquefaction within 50 km of the epicenter. The nearby Grizzly Creek Shear Zone in Glenwood Canyon is the likely source of the earthquake
- Maximum distance with liquefaction structures: 38·5 km (South Fork) and 56 km (Lime Creek). Moment magnitude of 7·0 and 7·2, respectively.
- First documented example of large-intensity earthquakes for the (pre-Quaternary) Phanerozoic of the entire Rocky Mountain region

# Conclusions

- Seismites: Penecontemporaneous deformation features: slide scarps, thrusted beds, irregular blocks and liquefied beds
- Earthquakes linked to the reactivation of Mesoproterozoic, crustal-scale shear zones in the central Rockies during the Late Cambrian

- Large body forces, and calculated earthquake-generated ground motion velocities of ~1.6 m/s
- Moment magnitudes of ~7.0 or more and a Mercalli Intensity of X+
- Only known magnitude estimates of Phanerozoic (other than Quaternary) large-intensity earthquakes for the Rocky Mountain region