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.
References Cited


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Late Cambrian  514 Ma

PANTHALASSIC OCEAN

IAPETUS OCEAN

North China

Laurentia

Alaska

Mexico

Siberia

Baltica

Florida

Africa

South America

New England and Nova Scotia

GONDWANA

Pan-African Mts.

England and Wales

Ancient Landmass

Modern Landmass

Subduction Zone (triangles point in the direction of subduction)

Sea Floor Spreading Ridge
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

A. Close-up of a slide scarp with a pen for scale.
B. Clinoform Bed (Stromatolite) with visible thrusts.
C. Stratigraphic section showing layers of shale, dolomitic marlstone, flat-pebble conglomerate, and thin-bedded grainstone.

Slide scarp annotations:
- Shale
- Dolomitic marlstone
- Downward injection of marlstone
- Flat-pebble conglomerate
- Thin-bedded grainstone

Diagram showing dimensions of slide scars:
- Slide scarp: W=23 cm, H=14 cm
- Slide scarp: W=8 cm
- Slide scarp: H=36 cm
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.
Thrust Bed (stromatolite)

**A**

**B**

**C**

**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 deform overlying sediment

- H=37 cm
- Thrust: 36-15 cm thick
- 20 cm
Oppositely Oriented Thrusts at Nearly Same Stratigraphic Level
Thrusted Beds
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
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

Irregular blocks

- W=56 cm H=23 cm
- W=9 cm H=5 cm
- 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
- W=24 cm H=13 cm ~ 1 m away
- W=36 cm H=43 cm
- W=2.4 m H=58 cm
- W=2.5 cm thick grainstone
- W=37 cm H=50 cm

Disturbed laminae 50 cm thick

- Slicken lines (weathered?)
- Internally contorted
- Clinetop microbialite

Long axis N32°E

- 10-15 cm thick grainstone
- 13 cm thick
- Flat pebble
- 17 cm

Bedding

- Rounded front
- Deformed G+Sh
- Sediment removed by bulldozing
- Leading edge

No deformation

- Deformed shale (Sediment bulldozed)

Bedding

- Jagged edge

Broken thin grainstone layers

Ptygmatically folded grainstone dykes in shale

Compaction?

- 20 cm grainstone
- Shaly zone

Compaction?

2.5 cm thick grainstone

2.5 mm thick displacement

14 cm gap
Blocks

[A: Image of a rock formation with a block highlighted.]
[B: Close-up view of the rock formation showing layers.]
[C: Detailed view of a block with 'Block' labeled.]
[D: Another angle of the rock formation with a focus on a specific block labeled with a direction ('n=12').]
[E: Macro view of a rock showing 'Brecciation', 'Chaotic laminae', and 'Intrusion'.]
[F: Close-up of a rock showing 'Brecciation', 'Chaotic laminae', and 'Intrusion'.]
Blocks

[A] [B] [C] [D]
Intrastratal Insertion of Block into overlying strata
Blocks

A. Shale with thin grainstone beds
B. Flat-pebble conglomerate
C. Deformed area
D. Covered area

B. Photograph of a block structure
C. Close-up of a block
D. Detailed view of the deformed area
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

B. Segmentation

C. Disarticulation, rolling

D. Sliding + abrasion

E. Deposition

F. Scarp, thrust

G. Fragmentation, segmentation

H. Disarticulation

I. Re-deposition of disturbed sediment, sliding, bulldozing of previous deposits

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 = $0.5mv^2$
- 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 $m = 0.499 \ln X / (3 \times 1.62 \times 10^{-5})$ where $M$ is moment magnitude and $X$ is the distance in kilometres (Allen, 1986; Obermeier, 1998; Manga & Brodsky, 2006)
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