TIMING OF LATE QUATERNARY EARTHQUAKES ON THE HEBGEN LAKE FAULT BY COSMOGENIC CHLORINE-36 DATING OF BEDROCK FAULT SCARP

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![Graph showing cosmogenic 36Cl age vs. displacement](image_url)

cosmogenic-36Cl, exposure-dating, paleoearthquakes, fault-scarps, Hebgen-Lake

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Production and accumulation of $^{36}$Cl

neutron activation:
$^{35}$Cl (n,γ) $^{36}$Cl

spallation:
$^{39}$K (n, 2n2p) $^{36}$Cl
$^{40}$Ca (n, 2n3p) $^{36}$Cl

negative muon capture:
$^{40}$Ca (μ⁻, α) $^{36}$Cl

$$\frac{P}{\lambda}(1 - e^{-\lambda t})$$

Time

36 Cl/Cl

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Corrections

Global:

Latitude

Elevation

Local:

Topographic shielding

Subsurface production

Apparent \(^{36}\text{Cl}\) ages

Corrected \(^{36}\text{Cl}\) ages

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Subsurface distribution of cosmic rays

- Slow muons
- Thermal neutrons
- Fast neutrons

Relative production rate vs. Depth, g cm\(^{-2}\)
Episodic exposure of scarp

Prior to faulting
Slow buildup of cosmogenic
36Cl below the surface

t = 0

First faulting episode
Face AB exposed
Cosmogenic buildup in AB
Slower buildup in BC and CD

t = t1

Second faulting episode
Face BC exposed
Buildup continues in AB
Buildup starts in BC
Slower buildup in CD

t = t2

Third faulting episode
Face CD exposed
Buildup continues in AB, BC
Buildup starts in CD

t = t3

AB exposed from t1 till now
BC exposed from t2 till now
CD exposed from t3 till now

t = t\text{now}
Episodic exposure of fault scarp

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Hebgen Lake area

Explanation:
- **Q**: Quaternary
- **M**: Mezoic
- **P**: Paleozoic
- **pC**: Precambrian
- **Red Canyon Fault**: 1959 surface rupture
- **SCARP**: surface rupture

**Montana**

*Marek Zreda, 1999*
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Scarp - side view

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Apparent $^{36}$Cl ages

Scarp height (m)

Apparent $^{36}$Cl age (10$^3$ years)

Marek Zreda, 1999
# Surface exposure ages

<table>
<thead>
<tr>
<th>Height [m]</th>
<th>Age [ky]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 - 11.4</td>
<td>23.8 ± 1.1</td>
</tr>
<tr>
<td>7.2 - 9.1</td>
<td>20.3 ± 1.0</td>
</tr>
<tr>
<td>5.1 - 7.2</td>
<td>7.0 ± 1.5</td>
</tr>
<tr>
<td>3.8 - 5.1</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>2.6 - 3.8</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>0.5 - 2.6</td>
<td>0.4 ± 0.5</td>
</tr>
</tbody>
</table>

*Marek Zreda, 1999*
Corrected $^{36}\text{Cl}$ ages

Model age ($10^3$ years) vs. Scarp height (m)
Temporal clustering of earthquakes

![Graph showing temporal clustering of earthquakes with measured data, average rate, and piecewise average.](Marek Zreda, 1999)
<table>
<thead>
<tr>
<th>Time [ky]</th>
<th>Slip rate [m/ky]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>0 - 7.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0 - 20</td>
<td>0.45</td>
</tr>
<tr>
<td>0 - 24</td>
<td>0.5</td>
</tr>
<tr>
<td>0 - 37</td>
<td>0.33</td>
</tr>
<tr>
<td>7.0 - 20</td>
<td>0</td>
</tr>
<tr>
<td>20 - 24</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*Vertical slip rates*

*Marek Zreda, 1999*
Validity of $^{36}$Cl approach

- **Good chronology**
  - $^{36}$Cl ages follow predicted pattern
  - they are compatible with scarp degradation data

- **Reasonable displacement rates**
  - comparable to recent measurements

- **Clearly-defined clusters**
Advantages of $^{36}$Cl approach

- Can date previously undatable bedrock fault scarps
- Can obtain complete record of multiple earthquakes at single site
- Dating range: $10^3 - 10^{5.5}$ years
- Dating precision and accuracy: 10-20%
Conclusions

Cosmogenic $^{36}$Cl dating of bedrock fault scarps is feasible

At Hebgen Lake, earthquakes are clustered in two time intervals: 0-7 ky and 20-24 ky

During active periods vertical slip rate is 1-2 m/ky

Long-term vertical slip rate is 0.5 m/ky