Deltas provide a multifaceted record of past environmental conditions

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Geological and Geobiological value of ancient deltas

1. **Sedimentology & Stratigraphy**
   - paleoenvironmental reconstruction
   - water and sediment fluxes and their time variation

2. **Sediment Provenance & Composition**
   - weathering and erosion
   - “Noachian” shale composite (Taylor & McLennan 1985)

3. **Organic Carbon Preservation**
   - fine-grained sediment, rapid sedimentation

4. **Authigenic Phases**
   - redox chemistry and element cycling (e.g. iron formation)
   - climate (e.g. carbonates, isotopes)
Fluvial deltaic sedimentary rocks provide an unambiguous measure of the activity and work done by ancient water and the atmosphere at the planet’s surface.

Architecture of the delta stratigraphy informs: accommodation, lake level, water & sediment supply.

The resulting deposits provide a geological archive of denudation and mass flux into any given sedimentary basin.
Organic matter is naturally well-preserved in deltas.
- molecular association with fine-grained particles
- sedimentary removal from surface radiation and oxidants
Delta lobe-switching and deposition of authigenic phases

Mississippi River, USA

Yellow River, China

Coleman, 1988; Nasa Earth Observatory
Late Archean - early Paleoproterozoic Transvaal Supergroup
Paleoproterozoic deltaic iron formation - Western Australia

Figure 2. Stratigraphic section through Sydney Heads Pass (Australia) region. Hematitic iron formation occurs only where deep, clastic-starved environments were developed. Grain size categories include: cly—clay; slt—silt; fg—fine sand size; mg—medium sand size; cg—coarse sand size; peb—pebble; cob—cobble. Abbreviations: o/c—outcrop; no o/c—no outcrop.

Deposition of the overlying Miningarra Group in the Sydney Heads Pass region of the Stanley Fold Belt (Fig. 1) is interpreted to have occurred in a foreland basin that developed during the Capricorn orogeny. U-Pb ages from tuffaceous horizons in the Frere Formation (2027 ± 23 Ma) and unconformable between the Yelma and Chiall formations (2000 Ma) constrain the age development of the Miningarra Group to ca. 1890 Ma. A detrital zircon age of 1850 ± 19 Ma from the Chiall Formation (Akin et al., 2013) constrains the age of deposition of which was presumably triggered by movement of advancing thrust sheets.

Iron formation in the penecontemporaneous Miningarra Group is interpreted to have occurred in a foreland basin that developed during the Capricorn orogeny. Deposition of the overlying Miningarra Group is interpreted to have occurred in a foreland basin that developed during the Capricorn orogeny. Deposition of the overlying Miningarra Group is interpreted to have occurred in a foreland basin that developed during the Capricorn orogeny.
Post-depositional reduction of Fe & Mn-oxides is common in deposits.
Authigenic sedimentary minerals that accumulated in deltaic environments provide an important archive of ancient redox processes, water chemistry, and element cycling.
**Redox-sensitive detrital grains**

oxic

anoxic

Pyrite

\[
\text{FeS}_2 + \frac{7}{2} \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+
\]

Uraninite

\[
\text{UO}_2 + \frac{1}{2} \text{O}_2 + 2\text{HCO}_3^- \rightarrow \text{UO}_2(\text{CO}_3)_2^{2-} + \text{H}_2\text{O}
\]
Detrital pyrite and uraninite found throughout these sandstones

Johnson et al. 2014
Paleozoic and Archean conditions; $p\text{CO}_2 = 0.1\text{atm}$

- Short Rivers:
  - $r_c = 300$: no uraninite but some pyrite preserved
  - $r_c = 150$: some uraninite and some pyrite preserved
  - $r_c = 1$: all pyrite, some uraninite preserved
  - $r_c = 1$: all pyrite and uraninite grains preserved

- Long Rivers:
  - $r_c = 50$: all pyrite and uraninite grains preserved
  - $r_c = 50$: no pyrite but some uraninite preserved

B. Modern and Archean conditions; $p\text{CO}_2 = 0.1\text{atm}$

- Short Rivers:
  - $r_c = 150$: no pyrite but some uraninite preserved
  - $r_c = 1$: some uraninite and some pyrite preserved
  - $r_c = 1$: no pyrite but some uraninite preserved

- Long Rivers:
  - $r_c = 50$: no pyrite but all uraninite preserved
  - $r_c = 50$: no pyrite but some uraninite preserved

Johnson et al. 2014
Carbonates provide a material of uniquely high geological value

1. O isotopes
   - water budget, climate, temperature.
2. C isotopes
   - carbon cycling and burial, escape, FYS paradox
3. Geochronology
   - U/Pb, Pb/Pb, Sm/Nd
4. Clumped isotopes
   - precipitation temperature, mechanics, taphonomy
5. Body fossils, Trace fossils (microbial laminae)
   - direct record of ancient life
Carbonate isotopes and Mars carbon cycle and climate history

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**Figure a:** Evolution of the atmospheric $\delta^{13}$C (Atm.) for the Noachian, Hesperian, and Amazonian periods. The blue lines indicate carbonate deposition in shallow subsurface aquifers, the red lines show carbonate deposition that persisted through the Hesperian period, and the broken lines represent scenarios with carbonate deposition in the Amazonian period. The black dot at the top left indicates the present-day $\delta^{13}$C value.

**Figure b:** Escape rate (total loss = 232 mbar) showing a temperature of $18 \pm 4 ^\circ C$ (Halevy et al. 2011).

**Figure c:** CF rate (bar Gyr$^{-1}$) for carbonate deposition in open-water systems and shallow subsurface aquifers. The bars indicate the initial pressure range of 0.08–0.4 bar.

**Figure d:** Equivalent pressure of free carbon including the atmosphere, the absorbed carbon in the regolith, and the polar caps. Initial pressure ranges from 0.32–0.50 bar and 0.25–0.29 bar.

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<table>
<thead>
<tr>
<th>Time before present (Ga)</th>
<th>Escape rate (bar Gyr$^{-1}$)</th>
<th>Photochemical escape rate (total loss = 8.2 mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td>0.11</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>0.29</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Time before present (Ga)</th>
<th>CF rate (bar Gyr$^{-1}$)</th>
<th>Carbonate deposition in open-water systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>-</td>
<td>Carbonate deposition in shallow subsurface aquifers</td>
</tr>
<tr>
<td>0.11</td>
<td>-</td>
<td>Carbonate deposition in shallow subsurface aquifers</td>
</tr>
<tr>
<td>0.29</td>
<td>-</td>
<td>Carbonate deposition in shallow subsurface aquifers</td>
</tr>
</tbody>
</table>

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The evolution of the surface pressure (Surf.) and the escape rate (SP) is shown in the following table:

<table>
<thead>
<tr>
<th>Time before present (Ga)</th>
<th>Escape rate (SP)</th>
<th>Photochemical escape (PH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>0.11</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>0.29</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

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The evolution of the carbon isotopic ratio ($\delta^{13}$C) is shown in the following table:

<table>
<thead>
<tr>
<th>Time before present (Ga)</th>
<th>$\delta^{13}$C (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007</td>
<td>-20</td>
</tr>
<tr>
<td>0.11</td>
<td>-15</td>
</tr>
<tr>
<td>0.29</td>
<td>-10</td>
</tr>
</tbody>
</table>

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**Table 1:** Jacobian values for how the amount of sputtering escape ($M$) and volcanic outgassing ($VO$) affect the final $\delta^{13}$C.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Jacobian</th>
<th>Effect on $\delta^{13}$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>$VO$</td>
<td>0.007</td>
<td>3.5</td>
</tr>
<tr>
<td>$\delta^{13}$C</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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The evolution of the escape rate and the carbonate deposition at different time points is shown in the following graph:

**Figure a:** The evolution of the escape rate and the carbonate deposition at different time points. The graph shows the escape rate in bar Gyr$^{-1}$ and the carbonate deposition in mmol C Gyr$^{-1}$.

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The study determined that carbonate deposition only occurred during the Noachian Era. The blue lines are the scenarios where carbonate deposition occurred in shallow subsurface aquifers and the red lines are the scenarios where carbonate deposition persisted through the Hesperian Era and the broken lines are the scenarios where carbonate deposition occurred in the Amazonian period.

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The table below shows the Jacobian values of each parameter by calculating the effect of the amount of sputtering escape ($M$) and volcanic outgassing ($VO$) on the final $\delta^{13}$C.

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The carbon cycle and climate history of Mars are discussed in the context of carbonate deposition in open-water systems. The amount of carbonate deposition in the Noachian and Hesperian is indicated by the blue and red lines, respectively. The required total amount of carbonates in the Amazonian period is shown by the broken lines.

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The carbon isotopic ratio ($\delta^{13}$C) is compared with the MSL measurement shown by the error bar. The initial pressure range for sputtering escape is 0.32–0.50 bar and 0.25–0.29 bar.

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The carbon cycle and climate history of Mars are further discussed in the context of carbonate deposition in shallow subsurface aquifers. The amount of carbonate formation has a greater impact on the final $\delta^{13}$C value if it occurs later in the Hesperian period compared to the Noachian period. This is because a unit mass of carbonate formation has a greater impact on the final $\delta^{13}$C value if it occurs later in the Hesperian period compared to the Noachian period.
An example from the Black Sea
An empirical sea level curve from coral reefs

Post-Glacial Sea Level Rise

Meltwater Pulse 1A

Last Glacial Maximum

Bosporus sill depth

Sea Level Change (m)

Thousands of Years Ago
Cores from the western Black Sea sediments

Ryan et al. 1997
Glacial freshwater fluxes create a “New Euxine Lake”
Sedimentology and stratigraphy allow reconstruction of lake levels

Yanchilina et al. 2017
Sedimentology and stratigraphy allow reconstruction of lake levels.
“Lake Jezero” may have been able to get rid of its salt. (e.g. sulfate, chloride)
Deltaic sedimentary deposits provide a rich opportunity to observe and quantify the interactions of fluid Mars (water and atmosphere) with the ancient crust. This is not limited to study of clastic materials, sedimentology and strata architecture, but also extends to authigenic phases that record diverse aspects of the paleoenvironmental chemistry, element cycling, and climate.

On Earth, these environments are replete with “biosignatures” and constitute much of our record of the history of life.