GEOTHERMAL ALTERATION

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Sustainable Development Goals Short Course IV on Exploration and Development of Geothermal Resources
OUTLINE

Introduction

The concept of Hydrothermal alteration

Sampling and analytical methods

Alteration types

Factors affecting hydrothermal alteration

Significance of hydrothermal alteration
LEARNING OBJECTIVES

• Understand basic terminologies.
• Mention the common rock forming minerals.
• The concept of hydrothermal alteration.
• Understand the main components of a hydrothermal system.
• Sampling and analytical methods.
• Understand and discuss the concept of alteration intensity.
• Styles of hydrothermal alteration.
• Factors affecting hydrothermal alteration.
• Application of hydrothermal alteration minerals.
DEFINITION OF A ROCK

• An aggregate of one or more mineral particles forming part of the Earth’s crust.
• Main types- Igneous, Sedimentary and Metamorphic.
A MINERAL

• A naturally occurring inorganic solid which possesses a characteristic internal atomic structure and a definite chemical composition.

• Minerals must occur naturally—man made substances e.g. steel are not minerals.

• Inorganic substances—non-living.
COMMON ROCK FORMING MINERALS

- > 3500 known minerals
- Rock forming minerals-
  - quartz,
  - feldspars,
  - Mica,
  - Pyroxene,
  - Amphibole
  - Olivine
- Others include- oxides, sulfides, carbonates, native elements.
HYDROTHERMAL ALTERATION

• Hydo-water, thermal-heat.

• A change in mineralogy as a result of interaction of pre-existing solid phases (rock) with hot fluids (hydrothermal fluids).

• New minerals formed are stable/metastable at specific temperature, pressure and fluid composition range.
EXISTENCE OF A HYDROTHERMAL SYSTEM
SAMPLING METHODS

• In the field, representative sample collection.
• In geothermal drilling:
  ✓ Cuttings - 2 m interval.
  ✓ Cores - during exploration wells or when need arise.
ANALYTICAL METHODS

• Binocular microscope

• Preliminary analysis done at the rig site by use of binocular microscope.

• Aim - texture, color, alteration minerals, alteration intensity.

• Useful in understanding the sub-surface reservoir conditions.
ANALYTICAL METHODS CONT'D

• Petrographic microscope
  ✓ Representative samples selected and thin sections prepared for petrographic studies.
  ✓ Based on optical properties of minerals.
  ✓ Confirm the rock types.
  ✓ Confirm the alteration minerals.
  ✓ Mineralogical evolution of the alteration minerals.
• X-ray Diffractometer

✓ Used to identify individual minerals particularly clays and zeolites.
ANALYTICAL METHODS CONT'D

• Fluid inclusion analysis
  ✓ Trapped geothermal fluids.
  ✓ Reveals chemical composition and thermal histories of the fluids.
  ✓ Quartz and calcite crystals prepared for fluid inclusion analysis.
  ✓ Th- homogenization temperature of the fluids.
  ✓ Tm- melting temperature of the fluids.
ALTERATION INTENSITY

• A measure of how completely the rock has reacted to produce new minerals (i.e. hydrothermal).
• A measure of the percentage of the rock that has been altered.
• Critical to mapping and understanding alteration patterns.
• Described using the following terminologies;
  ✓ Non-pervasive/incipient- Weak/slight
  ✓ Selectively pervasive- Moderate
  ✓ Pervasive- High/strong
ALTERATION INTENSITY CONT'D

• Depends on the components of the rock + porosity and permeability.

Volcanic glass

Coarse grained syenite
STYLES OF HYDROTHERMAL ALTERATION

- **Direct deposition** - secondary mineral precipitation in open space fillings (fractures and cavities).
- Precipitation from saturated solution.
STYLES OF HYDROTHERMAL ALTERATION CONT'D

• **Replacement** - substitution of the primary components in the rocks by alteration minerals.
• Involves mass exchanges between the primary phases & the fluid.

<table>
<thead>
<tr>
<th>Primary Phases</th>
<th>Alteration Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic glass</td>
<td>Zeolites, clays, calcite, sec. quartz</td>
</tr>
<tr>
<td>Olivine</td>
<td>Chlorite, actinolite, hematite, clay minerals</td>
</tr>
<tr>
<td>Pyroxenes, Amphiboles</td>
<td>Chlorite, illite, sec. quartz, pyrite, calcite</td>
</tr>
<tr>
<td>Ca-plagioclase</td>
<td>Calcite, albite, adularia, epidote, titanite</td>
</tr>
<tr>
<td>Sanidine, Orthoclase, Microcline</td>
<td>Adularia</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Pyrite, titanite, haematite</td>
</tr>
<tr>
<td>Quartz</td>
<td>No alteration</td>
</tr>
</tbody>
</table>
STYLES OF HYDROTHERMAL ALTERATION CONT'D

- Leaching/dissolution - obvious in the surface rocks in steam heated thermal areas.
- Acidified steam condensate dissolves primary minerals without replacing hence formation of voids.
- Occurs at margins of geothermal fields.
# Temperature stability range of common hydrothermal alteration minerals

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Min. temp. °C</th>
<th>Max. temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>zeolites</td>
<td>40</td>
<td>120</td>
</tr>
<tr>
<td>*laumontite</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>quartz</td>
<td>180</td>
<td>&gt;300</td>
</tr>
<tr>
<td>*wairakite</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>smectite</td>
<td></td>
<td>&lt;200</td>
</tr>
<tr>
<td>**MLC</td>
<td>200</td>
<td>230</td>
</tr>
<tr>
<td>chlorite</td>
<td>230</td>
<td>&gt;300</td>
</tr>
<tr>
<td>calcite</td>
<td>50-100</td>
<td>280-300</td>
</tr>
<tr>
<td>prehnite</td>
<td>240</td>
<td>&gt;300</td>
</tr>
<tr>
<td>epidote</td>
<td>230-250</td>
<td>&gt;300</td>
</tr>
<tr>
<td>wollastonite</td>
<td>260</td>
<td>&gt;300</td>
</tr>
<tr>
<td>actinolite</td>
<td>280</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

*Belong to the zeolite group.
**Mixed layer clay.
HYDROTHERMAL THERMAL ALTERATION ZONATION PATTERNS
FACTORS AFFECTING HYDROTHERMAL ALTERATION

• Temperature
• Permeability
• Fluid composition
• Rock type
• Pressure
• Duration of activity
FACTORS AFFECTING HYDROTHERMAL ALTERATION CONT'D

• **Temperature**
  - Most critical factor in hydrothermal alteration.
  - Controls the composition of secondary alteration mineral assemblages.
  - Chemical reactions requires elevated temperature.
  - Minerals are thermodynamically stable at high temperatures.
FACTORS AFFECTING HYDROTHERMAL ALTERATION CONT'D

- Permeability
  - Controls access of thermal fluids.
  - Cause hydrothermal alteration of rocks & precipitation of secondary minerals in open spaces.
  - High permeability & porosity – pervasive alteration.
  - Restricted permeability & porosity - Limited alteration.
FACTORS AFFECTING HYDROTHERMAL ALTERATION CONT'D

• Fluid composition
  ✓ Controlled by the interaction between the fluids and geothermal minerals.
  ✓ pH and composition of fluid greatly determine rate and types of hydrothermal minerals to be formed in a geothermal system.
  ✓ Acidic fluids - Kaolinite; sulphate bearing fluids - anhydrite.
  ✓ Haematite coexisting with pyrite -> fluid with relatively more oxygen.

• Rock type
  ✓ Chemical composition of host rock determines the availability of primary components to form alteration minerals.
  ✓ Volcanic glass susceptible to alteration than crystalline rock.
  ✓ Andesite regions - illite dominant clay type, basaltic regions - chlorite dominates.
FACTORS AFFECTING HYDROTHERMAL ALTERATION CONT'D

- Pressure

✓ Compared to metamorphic environments pressure in geothermal systems is low -> 200 bars.
✓ Has insignificant effect on hydrothermal alteration.
✓ Indirectly: Controls depth at which boiling occurs.
✓ Boiling results in removal of high proportion of dissolved gases (H$_2$S and CO$_2$).
✓ Remaining liquid becomes more alkaline (pH increases).
✓ Calcite with bladed morphology -> loss of CO$_2$. 
FACTORS AFFECTING HYDROTHERMAL ALTERATION CONT'D

• Duration of activity

✓ Lifetime of a thermal area is difficult to assess- assumed to correlate with the age of the magmatic activity.
✓ Within every thermal area- many thermal episodes of different intensities.
✓ Associated with differential magmatism, self sealing, tectonic movements.
✓ Significant in understanding the system history.
✓ Heating, Cooling, Equilibrium & Episodic.
Application of hydrothermal minerals in geothermal systems

• 1. Mineral Geothermometers

✓ Alteration minerals e.g. zeolites, clays, prehnite, epidote are useful temperature indicators.

<table>
<thead>
<tr>
<th>MINERALS</th>
<th>TEMPERATURE °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalcedony</td>
<td></td>
</tr>
<tr>
<td>Mordenite</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td></td>
</tr>
<tr>
<td>Illite</td>
<td></td>
</tr>
<tr>
<td>Albite</td>
<td></td>
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<tr>
<td>Adularia</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
</tr>
<tr>
<td>Sphene</td>
<td></td>
</tr>
<tr>
<td>Wairakite</td>
<td></td>
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<tr>
<td>Prehnite</td>
<td></td>
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<tr>
<td>Epidote</td>
<td></td>
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<tr>
<td>Biotite</td>
<td></td>
</tr>
<tr>
<td>Actinolite</td>
<td></td>
</tr>
<tr>
<td>Garnet</td>
<td></td>
</tr>
</tbody>
</table>

- Alteration minerals e.g. zeolites, clays, prehnite, epidote are useful temperature indicators.
Application of hydrothermal minerals in geothermal systems cont’d

• 2. Permeability indicators
  ✓ Hydrothermal minerals e.g. quartz, pyrite and adularia are used as indicators of high permeability.
  ✓ Hydrothermal minerals e.g. albite implies zones of limited permeability.

• 3. Setting production casing depths
  ✓ Temperature ranges of minerals e.g. phyllosilicates and calc-silicates are useful in estimating sub-surface temperatures hence setting of production casing depth.
  ✓ E.g. Epidote, chlorite.
Application of hydrothermal minerals in geothermal systems cont'd

• 4. Reconstructing the historical evolution of the geothermal system
  ✓ Integration of alteration, formation and fluid inclusion studies.
  ✓ Realistic model of the geothermal system.
  ✓ Heating, cooling and equilibrium.
  ✓ Up-flow, out-flow and marginal zones.
  ✓ Predicting possible boiling-bladed calcite
Application of hydrothermal minerals in geothermal systems cont'd

5. Predicting scaling and corrosion tendencies

- Bladed calcite indicate boiling hence possibility of calcite scaling and corrosion.
- Formation of certain hydrothermal minerals depend on the pH of hydrothermal fluids.
PROBLEMS WITH HYDROTHERMAL ALTERATION MINERALS

• Corrosion and scaling problems in geothermal systems.
Thank you
INFORMATION

Name of course: SDG Short Course IV on Exploration and Development of Geothermal Resources
Location: Lake Bogoria and Lake Naivasha, Kenya
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Organized by: United Nations University Geothermal Training Programme (UNU-GTP) and Kenya Electricity Generating Company PLC (KenGen)

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