HYDROTHERMAL ALTERATION AND FLUID INCLUSION
GEOTHERMOMETRY IN ACTIVE GEOTHERMAL SYSTEMS: THE
CASE OF ALUTO-LANGANO GEOTHERMAL SYSTEM, ETHIOPIA

MESERET T. ZEMEDKUN
UN ENVIRONMENT
The discovery, assessment and development of geothermal resources require an extraordinarily wide range of science and technology.

Anyone preparing for a career in geothermics should expect to work as a member of broadly disciplinary team and have a basic working knowledge of, at least, the rudiments of geology, geophysics, geochemistry, reservoir engineering, drilling, and of electricity production and direct use of geothermal energy.
Phases of Geothermal Development
## Phases of Geothermal Development & Role of Geologist

<table>
<thead>
<tr>
<th>Phases</th>
<th>Type</th>
<th>Role of BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary Study</td>
<td>Reconnaissance Study, Prospect Investigation, Exploration Drilling</td>
<td>Very Active, Very Active, Active</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appraisal Study</td>
<td>Appraisal Drilling, Reservoir Evaluation, Feasibility Study</td>
<td>Very Active, Very Active, Active</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project Planning</td>
<td>Production Drilling, Well Testing, Preliminary Project Design</td>
<td>Very Active</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contract Document</td>
<td>Project Design</td>
<td></td>
</tr>
</tbody>
</table>
• Identify nature, age and history of surface rocks, e.g. hydrothermal discharge zones, etc.

• Mapping the geological Structures that affect the flow of fluids within the Reservoirs

• Relate geothermal alteration to the past and present condition of the hydrothermal system
• Collect cuttings/cores penetrated and alteration (deposition, leaching, replacement).

• Nature, age, and history of rocks and correlations between wells.

• Investigate reservoir characteristics, e.g. (Information can be available while drilling, and before wells come to thermal equilibrium).
USES OF CORES

• Identify reservoir rocks – assist in determining stratigraphy, structure and hydrology of the field

• Examine hydrothermal alteration produced by fluid rock interaction

• Analyze for major and trace elements and so learn about mass transfer processes taking place in the reservoir
USES OF CUTTINGS

- Identify **subsurface formations** when this can be done
- Locate formation boundaries
- Recognise **Permeable zones**
- Provide material for **fluid inclusion** and stable isotope studies
Study Ejecta, work-over and scaling products.

Make inferences about, “What is likely to happen if we inject fluid of a particular composition in a specific location?”
WHAT CAN PETROLOGY (HA/FI) CONTRIBUTE?
(AS A SUPPLEMENT TO EG, BG, GEOCHEMISTRY etc.)

- Lithological Correlations between Multiple Wells
- Physical Characteristics of Reservoir Rocks
- Geothermometry and Direction of Temperature Change
- Patterns of Fluid Flow
- Shape, Size, and Boundaries of the Reservoir
- Inferences about the Location and Nature of the Heat Source
WHAT SPECIFICALLY CAN AMS CAN TELL US?

- Nature of permeability – primary or secondary porosity; fractures and their history.
- Prograde or retrograde alteration
- Recharge zone, heating volume, discharge zone.
- Boiling and vapor dominated zones.
- Water/rock ratios.
- Thermal history – mineral sequences, cross-cutting relationships of fractures and veins, dating by various means.

PAST AND PREVAILING T, P, FC
OCCURRENCE AND SIGNIFICANCE OF HYDROTHERMAL ALTERATION MINERALS IN ACTIVE GEOTHERMAL FIELDS
• The Minerals

• Sampling Methods

• Methods of Study

• Intensity and Rank of hydrothermal alteration

• Application of Hydrothermal alteration to Geothermal investigation

• Case Study Examples

• Fluid inclusion Geothermometry and its application

• Summary
Melting of rocks in hot, deep crust and upper mantle

Weathering and erosion of rocks exposed at surface

Deposition, burial and lithification

Rocks under high PT in deep crust and upper mantle

Recrystallization in solid state of new minerals
HYDROTHERMAL ALTERATION

ORIGINAL ROCK

\[ \downarrow \]

REACTION WITH THERMAL FLUID AND/OR STEAM

\[ \downarrow \]

HYDROTHERMAL ALTERED ROCK

DEVITRIFICATION
RECRYSTALLIZATION
DEPOSITION

LITHOSPHERIC MANTLE
RAINFALL
RAINFALL

Rift Graben (50-70 km)

Early Pleistocene volcanics

“Recent” Volcanic Plume

Geothermal Well

Mau Ranges

Aberdare Ranges

Geothermal reservoir

Dikes

NOT TO SCALE

Geothermal
reservoir

Ptocene volcanics and Mozambican formation metamorphics

LITHOSPHERIC MANTLE
Sources of Hydrothermal Fluids

- Meteoric water/Near surface ground water
- Magmatic rocks exsolve water during final stage of cooling
- Metamorphic-Dehydration reaction
Fluids and Reservoir rocks in geothermal systems commonly react together with the result that both composition of fluid and rocks phases change that can be viewed as chemical reactions.

The identity and abundance of these hydrothermal minerals depends on several factors: particularly temperature, fluid composition (especially its pH), availability of fluid (permeability), whether or not boiling occurs in the system.
Main Rock Forming Minerals

Although any of hundreds of different minerals can group together to form a rock, only six are very common in rocks.

These common minerals are referred to as the “rock-forming minerals” and include:

“Quartz, Feldspars, Micas, Amphiboles, Pyroxenes and Olivine”.

Others include: Fe-Mg, oxides, sulphides, Carbonates, phosphates, halide and native elements.
• **Carbonates:** Calcite, Aragonite, Siderite
• **Sulfates:** Anhydrite, Alunite, Natro-alunite, Barite
• **Sulfides:** Pyrite, Pyrohtite, marcasite, Sphalerite, Galena, Chalcopyrite
• **Oxides:** Magnetite, Hematite, Leucoxene, Diaspore Ilmenite
• **Phosphates:** Apatite
• **Halides:** Fluorite
• **Silicates:** Sphene, Garnet, Epidote, Tremolite, Actinolite, Illite, Biotite, Montmorillonite, Pyrophyllite, Kaolin, Chlorite, Prehnite, Adularia, Albite, Quartz, Laumontite, Wairakite
Collecting samples from the field and wells
• Samples for petrographic, petrochemistry and dating require fresh samples.

• Altered samples are already obliterated and the alteration products are mainly clays, zeolites.

• Alteration samples for AM analysis are collected from surroundings of fumaroles, Hot springs, and altered grounds.
SAMPLING AT THE RIG

Lagat, 2006
METHODOLOGIES TO IDENTIFY VARIOUS TYPES OF MINERALS
BINOCULAR MICROSCOPE:

Preliminary Analysis is done by use of BM at well site.
PETROGRAPHIC MICROSCOPE:

Representatives cuttings and core samples are selected and examined by petrographic microscope.
X-Ray Diffractometer is used to identify individual minerals especially clays and zeolites.

Clays (OW-903, 1137-1135 masl)
• X-Ray Fluoresence – for major oxides and trace elements

• AAS- for major and trace elements

• DTA- capable of detecting thermal characteristics of clays, sulphides and carbonates

• IS- for detecting clays, zeolites and sulfide minerals

• Electron Microprobe-Detecting the chemical comp. of mineral

• SEM

• ICP-SEM
INTENSITY AND RANK OF ALTERATION
**INTENSITY OF ALTERATION**: a measure of how a rock is completely reacted to produce new secondary minerals.

**RANK OF ALTERATION**: depends on the identity of the new minerals.

**L R AND H.I =**
Cold and permeable zones

**HR AND LI =**
Hot and impermeable zones

**HIGH RANK AND HIGH INTENSITY** = Hot and Permeable zones
Types of Hydrothermal Alteration systems in terms of Fluid/rock ratio

**HYDROTHERMAL ALTERATION SYSTEMS**

**Rock Dominated**
- No reaction in impermeable system, rock unaltered
- Isochemical reaction in low permeability systems

**Fluid Dominated**
- Metasomatism in high permeability systems
- Rock dissolution in sufficiently aggressive environments

**Fluid/Rock Ratio**
OCCURRENCE OF HYDROTHERMAL ALTERATION MINERALS

- Direct Deposition
- Replacement
- Leaching
- Ejecta
DIRECT DEPOSITION

• Most HM formed in geothermal fields can deposit directly from solution.

• This happens mainly when reservoir contains passages such as joints, Hydraulic fractures, voides, cavities and vesicles.

• Common Minerals = Quartz, Anhydrite, calcite, Chlorite
Most rocks contain some minerals which are unstable in a geothermal environment, and have a tendency to be replaced by stable, metastable under the new conditions. Rate of replacement depends on permeability of the reservoir rock.

<table>
<thead>
<tr>
<th>Primary phases</th>
<th>Alteration products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic glass</td>
<td>Zeolites, clays, quartz, calcite</td>
</tr>
<tr>
<td>Olivine</td>
<td>Chlorite, actinolite, hematite, clays</td>
</tr>
<tr>
<td>Pyroxenes, amphiboles</td>
<td>Chlorite, illite, quartz, pyrite, calcite</td>
</tr>
<tr>
<td>Ca-plagioclase</td>
<td>Calcite, albite, adularia, quartz, illite, epidote, sphene</td>
</tr>
<tr>
<td>Sanidine,orthoclase, microline</td>
<td>Adularia</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Pyrite, sphene, haematite</td>
</tr>
</tbody>
</table>
Ca-Al Silicate (Cerro-Prieto)

Montmorillonite zone (Cerro Prieto)

Biotite zone (CerroPrieto)

Ca- Al silicate zone (Aluto-Langano)
Factors that Affect the formation HM in Active Geothermal Fields

- Temperature
- Permeability
- Parent rock type
- Reservoir fluid composition
- Duration of activity
Temperature is the most significant factor in hydrothermal alteration because most of the chemical reactions require elevated temperatures and also minerals are thermodynamically stable at high temperatures.

Minerals that contain OH or n.H₂O provide information on their temperature.

Eg. Clays, Zeolites, Prehnite, Epidote, Garnet
ICELAND GEOTHERMAL FIELDS (H. Franzson)
Mineral Distribution in one of high temperature Icelandic Geothermal Fields (H. Franzson)
The Aluto-Langano Geothermal field, Ethiopia

Distribution of clay minerals vs temperature

- Mixed Layer Illite smectite
- Illite-chlorite
- Chlorite intergrade
- Illite
- Chlorite
THE OLKARIA GEOTHERMAL FIELD, KENYA
Permeability of the rocks controls the access of thermal fluids, which cause hydrothermal alteration of the rocks and precipitation of secondary minerals in open spaces.

Rocks which have very restricted permeability or are completely impervious to fluid will be only slightly altered.
Deduced Permeability Units (Mineralogical change)

0 = No Hydrothermal Minerals
1 = Traces of Calcite, Montmorillonite, Pyrite, Quartz
2 = Primary Feldspars Fresh, Ferromagnesian Partially Altered
3 = Primary Feldspars Fresh, Ferromagnesian Completely Altered
4 = Primary Feldspars partially Altered, Ferromagnesian Completely Altered
5 = Primary Feldspars Completely Altered, Minor hydrothermal albite
6 = Abundant Hydrothermal Albite, Matrix consists of Hydrothermal Minerals
7 = Abundant Hydrothermal Albite along with less adularia
8 = Adularia with less Albite
9 = Adularia the only Feldspar present
10 = Adularia Occurs throughout the rock in the matrix and as phenocrysts
The close relationship between fluid composition and alteration mineral may be seen in superficial alteration thus acid fluid deposit (pH <3) deposit kaolin, sulfur, alunite etc..

And near neutral alkali cholride water precipitates Silica Sinter.
ACTIVITY DIAGRAM

AD are useful tools for summarizing the relationship between the hydrothermal minerals and fluids.

Aluto-LAngano, Teklemariam, 1998

Waiaraki, NZ Browne, 1984
FLUID INCLUSION GEOTHERMOMETRY
✓ When hydrothermal minerals grow or recrystallize in a fluid envt. tiny growth irregularities trap small amounts of the depositing fluid within the solid crystal. PRIMARY INCLUSION

✓ When there are micro fractures after formation of Crystal and filled by fluid: SECONDARY INCLUSION
FLUID INCLUSION HEATING-FREEZING STAGE

CHAIXMECA H-F STAGE
Measurement of Th and Tm in a fluid inclusion
THE ALUTO-LANGANO GEOTHERMAL FIELD
THE ALUTO-LANGANO GEOTHERMAL FIELD
THE OLKARIA GEOTHERMAL FIELD

Lagat, 2006
THE OLKARIA GEOTHERMAL FIELD

Lagat, 2006
SUMMARY

DURING S. EXPLORATION & DRILLING:

• Rock Formations (Porosity and Permeability)
• Age of the system
• Heat Source
• Alteration Temperature
• Depths of Casing
• Condition of Well

GEOTHERMAL SYSTEM: RESERVOIR MODEL

• Subsurface and Structural Geology
• Relation of Geology and Permeability
• Hydrothermal Alteration (Shape of system, Evolution and Present state)
• Fluid inclusion (Thermal history and Composition fluid)
WATER-ROCK INTERACTION PROCESS
THANK YOU