Geothermal Reservoir Monitoring Using Multi-geophysical Survey Techniques

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Abstract

Prediction of the behavior of a geothermal reservoir under exploitation conditions is carried out based upon numerical models of the reservoir. Since the uncertainty in the predictions of numerical reservoir models is directly related to the amount of field data available against which the models can be tested, it is clear that the addition of repeat geophysical survey data to the list of pertinent field measurements is likely to improve the reliability of these forecasts.

The application of improved geophysical techniques to reservoir management was among the objectives of a geothermal R&D project which was carried out by NEDO from 1997 through 2002. GSJ has been carrying out supporting basic research in cooperation with NEDO: pursuing the development of improved field survey techniques and associated modeling studies involving various passive and active geophysical survey techniques and their application to reservoir performance monitoring.

In this project, the so-called mathematical postprocessors have been developed to calculate time-dependent earth-surface distributions of geophysical observables such as microgravity, self-potential, and apparent resistivity (from either DC or MT/CSMT surveys). The temporal changes are caused by changing underground conditions (pressure, temperature, salinity, gas saturation, etc.) as computed by numerical unsteady multidimensional thermohydraulic reservoir/aquifer simulations. The postprocessors enable us to incorporate repeat geophysical survey data into "history-matching" studies, which is especially useful for appraising the volumetric properties of any proposed mathematical reservoir model.

APEC seminar 2007 Dec 5

GEOTHERMAL RESERVOIR MONITORING USING MULTI-GEOPHYSICAL SURVEY TECHNIQUES

Institute for Geo-Resources and Environment

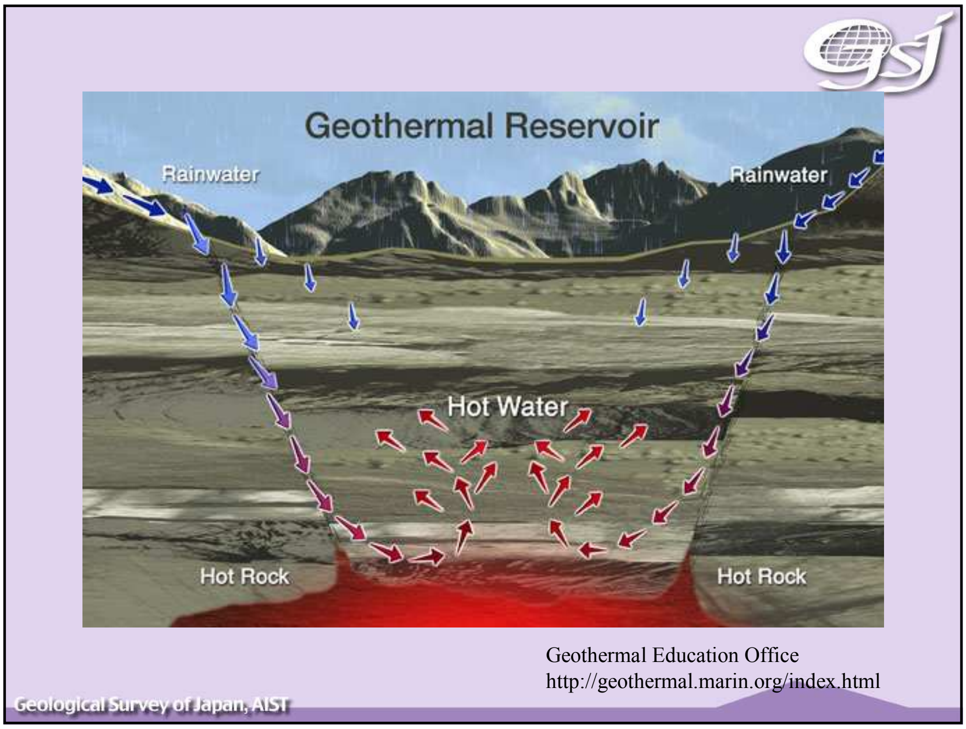
Principal Research Scientist

Tsuneo Ishido, Ph D.

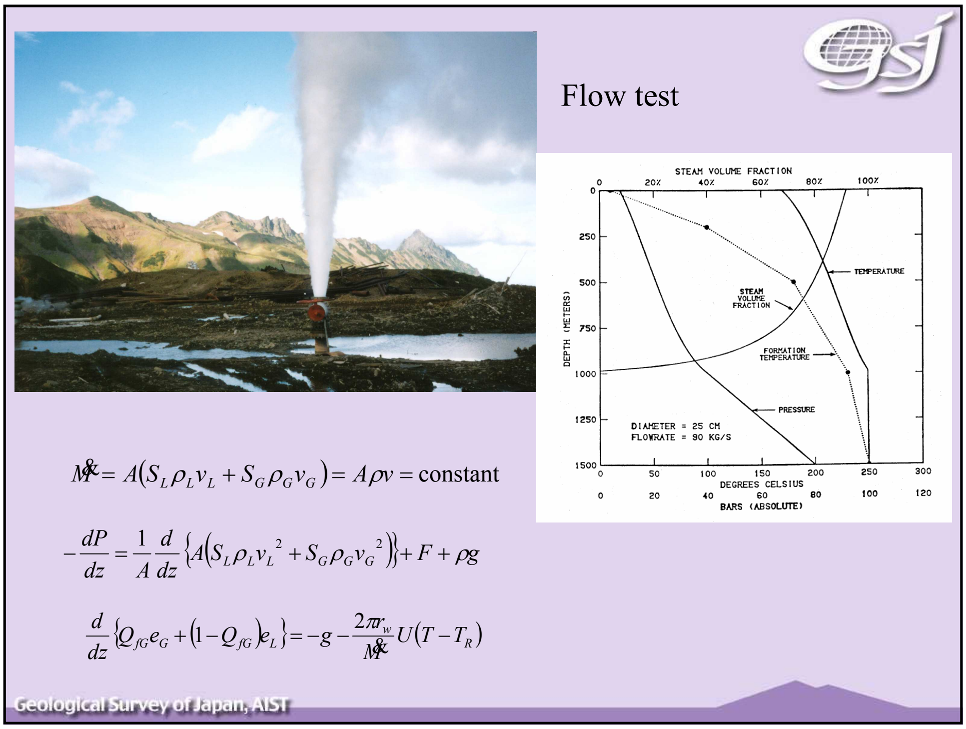
Outline:

- Geothermal reservoir
- Numerical reservoir modeling
- History matching
- Feasibility study of reservoir monitoring by various geophysical techniques

- Geothermal reservoir monitoring with a combination of absolute and relative gravimetry by M. Sugihara



Geothermal Education Office
http://geothermal.marin.org/index.html

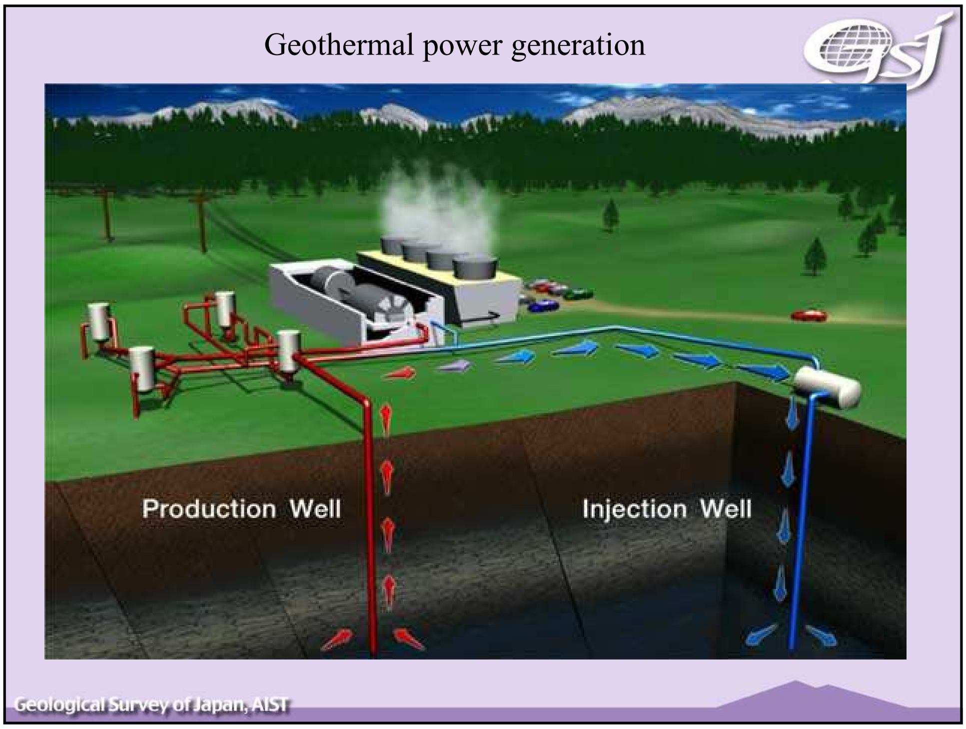


Flow test

$$\dot{M} = A\left(S_L \rho_L v_L + S_G \rho_G v_G\right) = A\rho v = \text{constant}$$

$$-\frac{dP}{dz} = \frac{1}{A}\frac{d}{dz}\left\{A\left(S_L \rho_L {v_L}^2 + S_G \rho_G {v_G}^2\right)\right\} + F + \rho g$$

$$\frac{d}{dz}\left\{Q_{fG} e_G + \left(1 - Q_{fG}\right) e_L\right\} = -g - \frac{2\pi r_w}{\dot{M}} U\left(T - T_R\right)$$



Geothermal power generation

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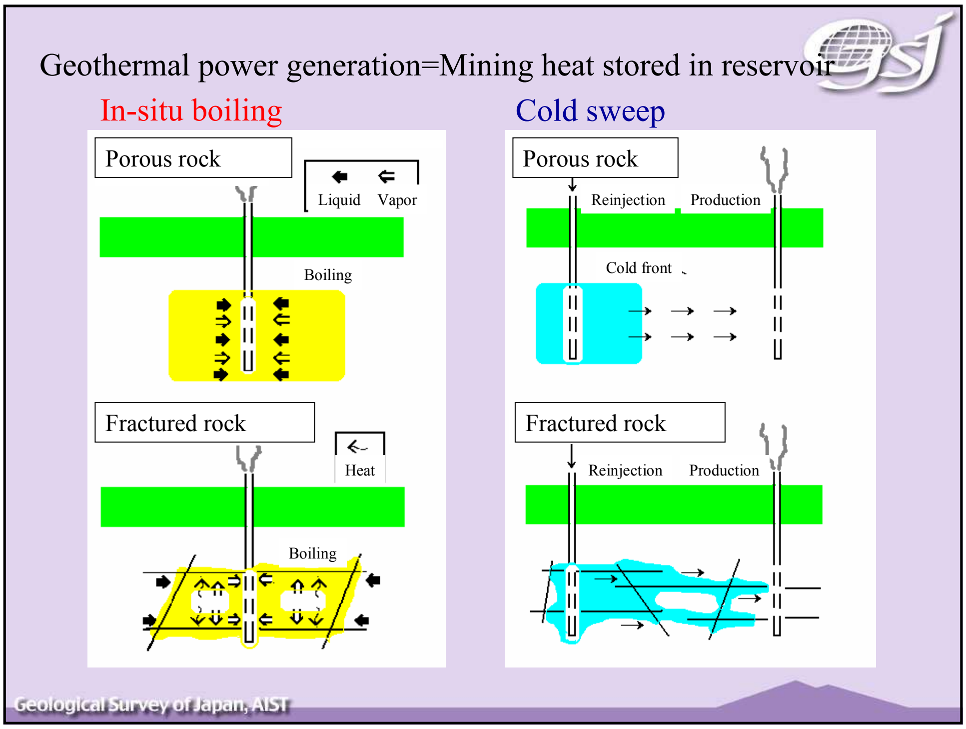


Geothermal power generation=Mining heat stored in reservoir

In-situ boiling

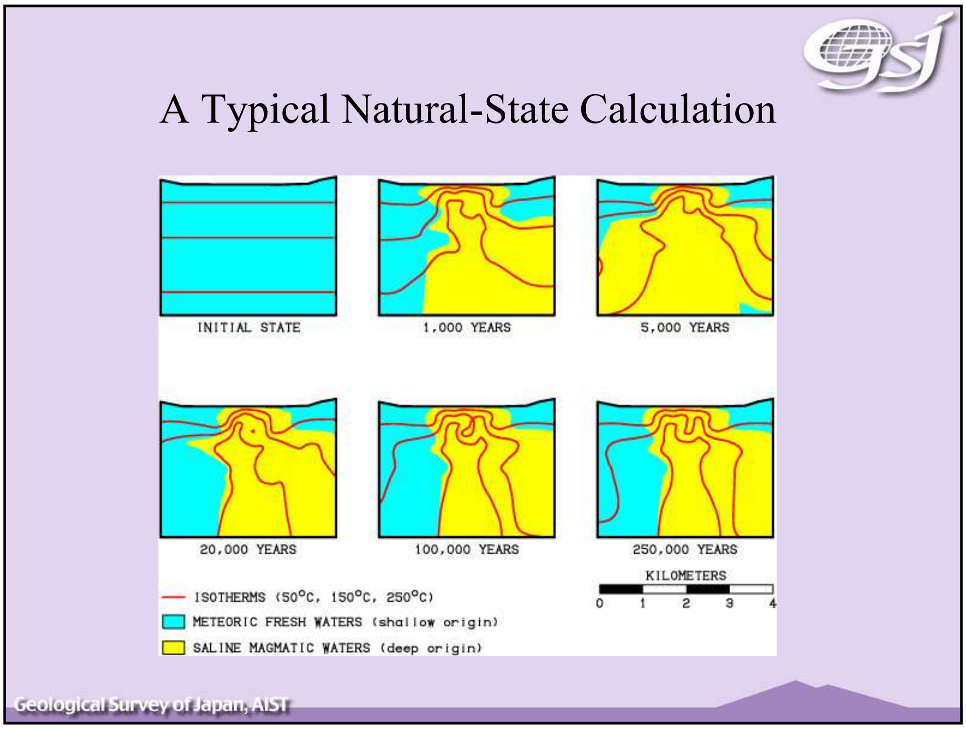
Cold sweep

Geological Survey of Japan, AIST

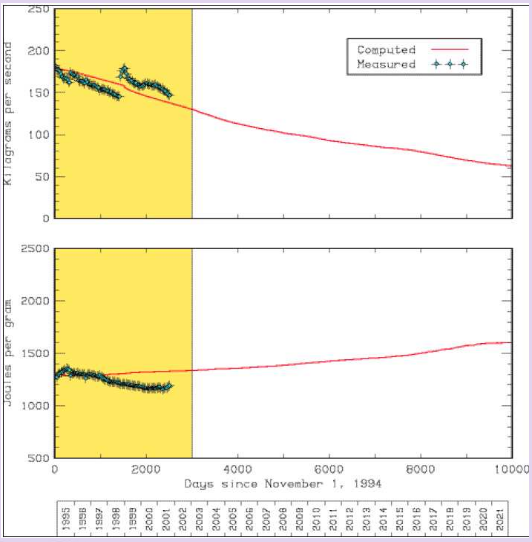
Numerical Reservoir Modeling

- Calculations using geothermal reservoir simulators usually are of three types:
  - Natural-state calculations,
  - History-matching calculations (if production history exists), and
  - Forecasts.

A Typical Natural-State Calculation



History-Matching

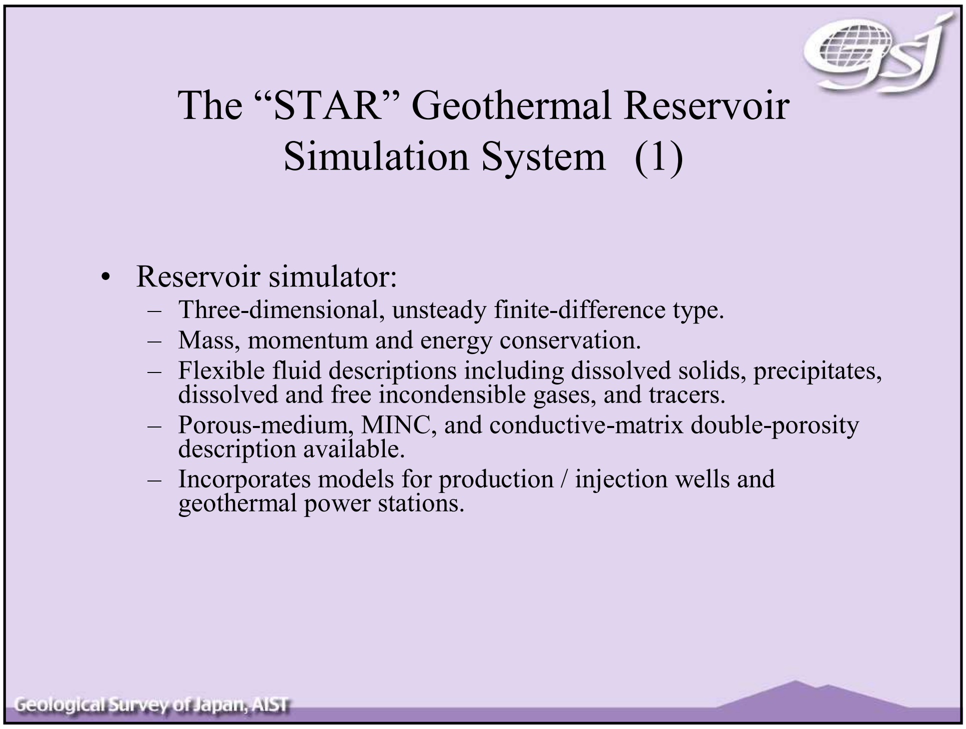


Solving the Inverse Problem

- Both natural-state and history-match calculations must usually be repeated numerous times, adjusting free parameters to optimize match with field observations.
- Typically, the observables used for matching include:
  - Natural-state (prior to plant startup):
    - Stable feedpoint pressures in shutin wells.
    - Stable long-term shutin well temperature profiles.
    - Observed surface discharges of mass and heat.
    - Hot-spring and test well discharge chemistry.
    - Drilling logs, cuttings, mud loss records.
    - Laboratory test results on core samples.
  - History-matching (after large-scale production/injection):
    - Records of wellhead flow rates and wellhead pressures.
    - Wellhead and separator water and steam flow rates.
    - Chemical analyses of discharged fluids.
    - Pressure/temperature/chemistry measurements in shut-in observation wells.

Degrees of Freedom

- Free parameters available to accomplish the match will usually include:
  - Permeabilities of the various rock formations.
  - Geological structure in undrilled areas.
  - Locations of lateral and lower reservoir boundaries.
  - Boundary conditions (mass and heat inflow distributions) on the bottom surface of the region considered.



The “STAR” Geothermal Reservoir Simulation System (1)

- Reservoir simulator:
  - Three-dimensional, unsteady finite-difference type.
  - Mass, momentum and energy conservation.
  - Flexible fluid descriptions including dissolved solids, precipitates, dissolved and free incondensible gases, and tracers.
  - Porous-medium, MINC, and conductive-matrix double-porosity description available.
  - Incorporates models for production / injection wells and geothermal power stations.

Basic equations

Mass conservation

$$\frac{\partial}{\partial t}\left[\phi\sum_j\left(S_j\rho_jC_{kj}\right)\right]+\sum_j\nabla\cdot\left(\vec{M}_jC_{kj}-L\left|\vec{M}_j\right|\nabla C_{kj}\right)=\dot{m}_{in}C_k^{in}-\dot{m}_{out}C_k^{flow}$$

Energy conservation

$$\frac{\partial}{\partial t}\left[\left(1-\phi\right)\rho_RC_{VR}T+\phi\sum_j\left(S_j\rho_jE_j\right)\right]+\sum_j\nabla\cdot\left(\vec{M}_jH_j-L\left|\vec{M}_j\right|\nabla H_j\right)$$

$$=\nabla\cdot\left(\kappa\nabla T\right)+\sum_j\vec{M}_j\cdot\vec{g}+\dot{m}_{in}H^{in}-\dot{m}_{out}H^{flow}+\&$$

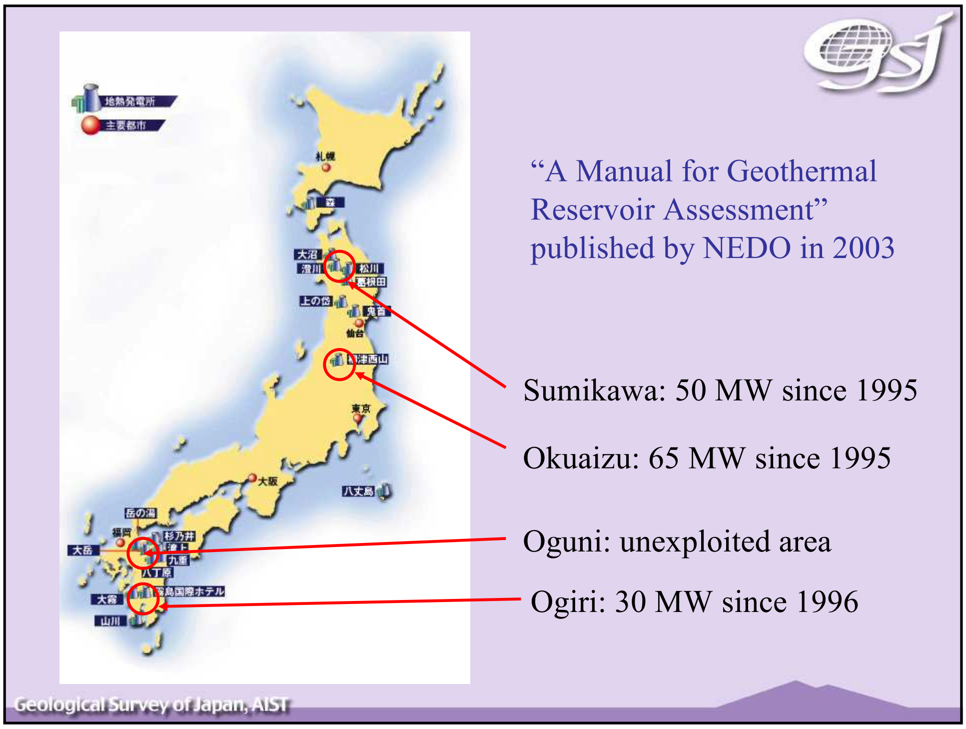
Momentum conservation

$$\vec{M}_j=\frac{KR_j}{\nu_j}\left(\rho_j\vec{g}-\nabla P_j\right)$$

The “STAR” Geothermal Reservoir Simulation System (2)

- Geophysical postprocessors:
  - Based on reservoir simulation results, calculate changes that would be observed over time in surface survey results. Techniques considered include:
    - Microgravity surveys.
    - DC resistivity surveys (i.e., Schlumberger type).
    - Conventional magnetotelluric (MT) surveys.
    - Self-potential (SP) surveys.
  - Additional techniques being developed for:
    - CSAMT magnetotelluric surveys.
    - Active seismic surveys.

Developed under a NEDO’s geothermal program
By GSJ/AIST, J-Power and SAIC



"A Manual for Geothermal Reservoir Assessment" published by NEDO in 2003

Sumikawa: 50 MW since 1995

Okuaizu: 65 MW since 1995

Oguni: unexploited area

Ogiri: 30 MW since 1996

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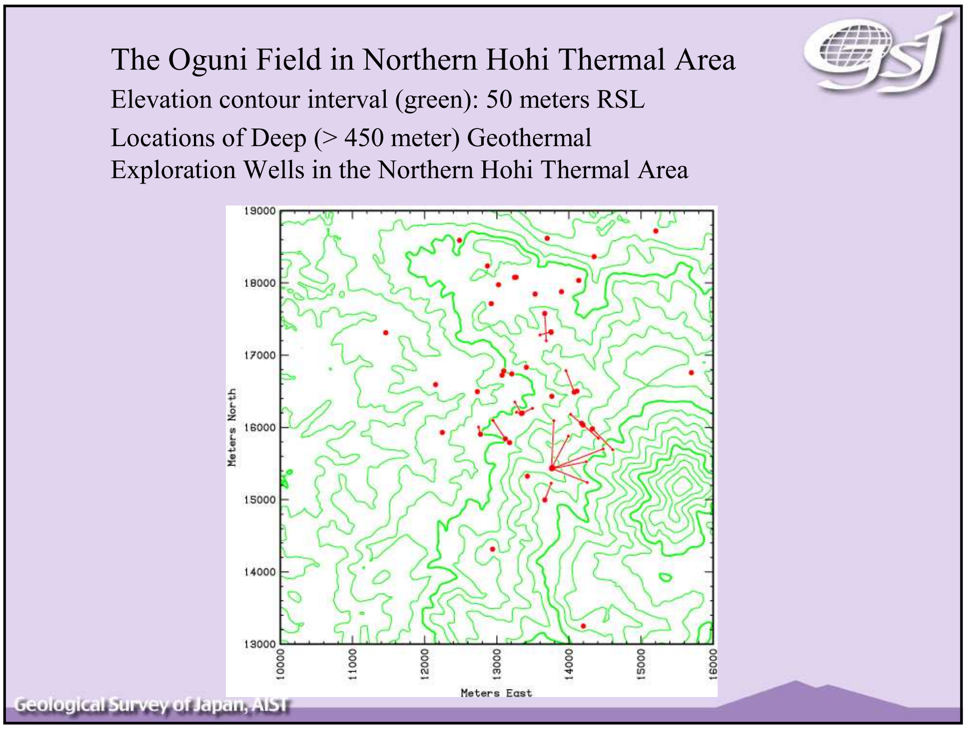

The Oguni Field in Northern Hohi Thermal Area

Elevation contour interval (green): 50 meters RSL

Locations of Deep (> 450 meter) Geothermal Exploration Wells in the Northern Hohi Thermal Area

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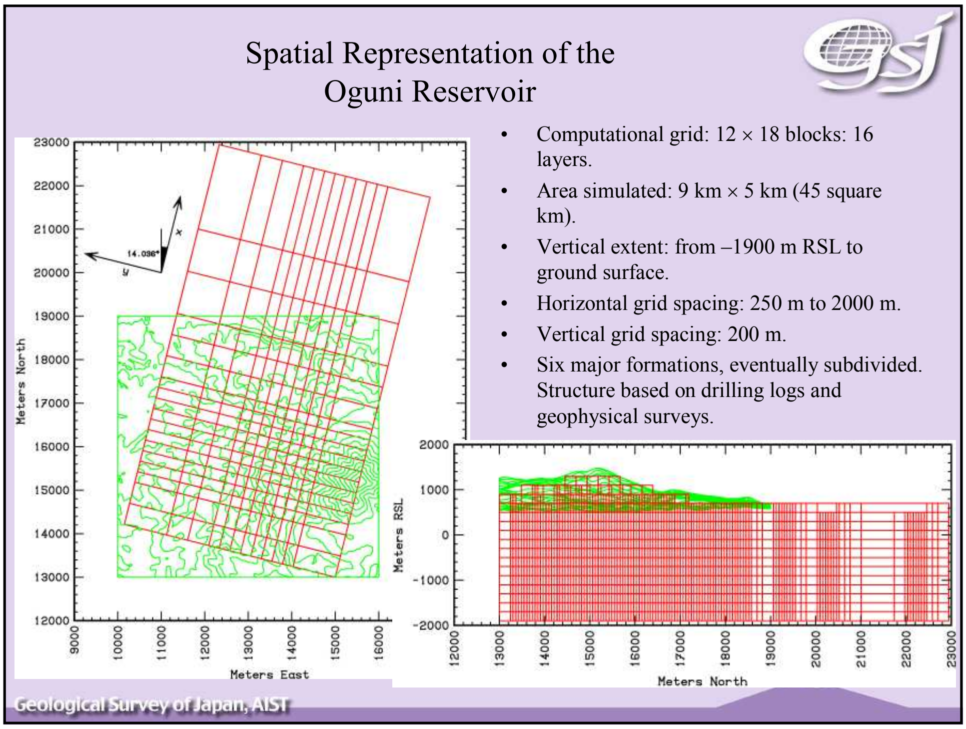

Spatial Representation of the Oguni Reservoir

- Computational grid: 12 × 18 blocks: 16 layers.
- Area simulated: 9 km × 5 km (45 square km).
- Vertical extent: from –1900 m RSL to ground surface.
- Horizontal grid spacing: 250 m to 2000 m.
- Vertical grid spacing: 200 m.
- Six major formations, eventually subdivided. Structure based on drilling logs and geophysical surveys.

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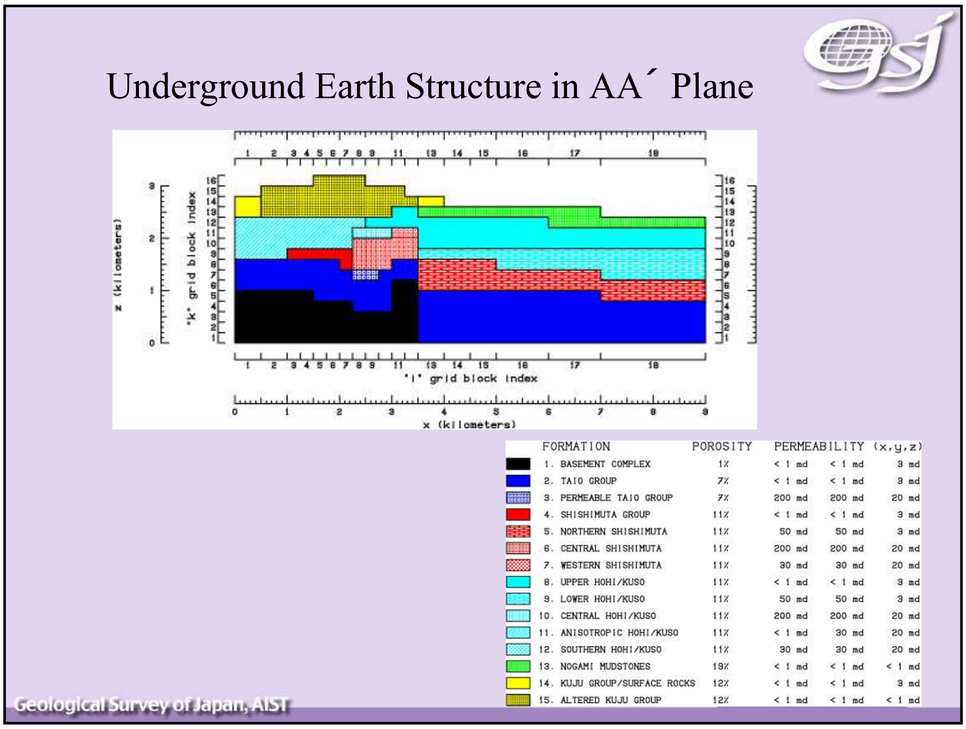

Underground Earth Structure in AA´ Plane

	FORMATION	POROSITY	PERMEABILITY (x,y,z)		
⬛	1. BASEMENT COMPLEX	1%	< 1 md	< 1 md	3 md
🟦	2. TAIO GROUP	7%	< 1 md	< 1 md	3 md
▦	3. PERMEABLE TAIO GROUP	7%	200 md	200 md	20 md
🟥	4. SHISHIMUTA GROUP	11%	< 1 md	< 1 md	3 md
▤	5. NORTHERN SHISHIMUTA	11%	50 md	50 md	3 md
▦	6. CENTRAL SHISHIMUTA	11%	200 md	200 md	20 md
▩	7. WESTERN SHISHIMUTA	11%	30 md	30 md	20 md
■	8. UPPER HOHI/KUSO	11%	< 1 md	< 1 md	3 md
▤	9. LOWER HOHI/KUSO	11%	50 md	50 md	3 md
▥	10. CENTRAL HOHI/KUSO	11%	200 md	200 md	20 md
▨	11. ANISOTROPIC HOHI/KUSO	11%	< 1 md	30 md	20 md
▩	12. SOUTHERN HOHI/KUSO	11%	30 md	30 md	20 md
🟩	13. NOGAMI MUDSTONES	19%	< 1 md	< 1 md	< 1 md
🟨	14. KUJU GROUP/SURFACE ROCKS	12%	< 1 md	< 1 md	3 md
▦	15. ALTERED KUJU GROUP	12%	< 1 md	< 1 md	< 1 md

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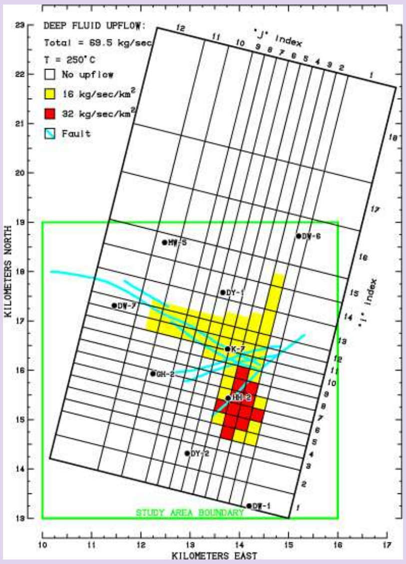
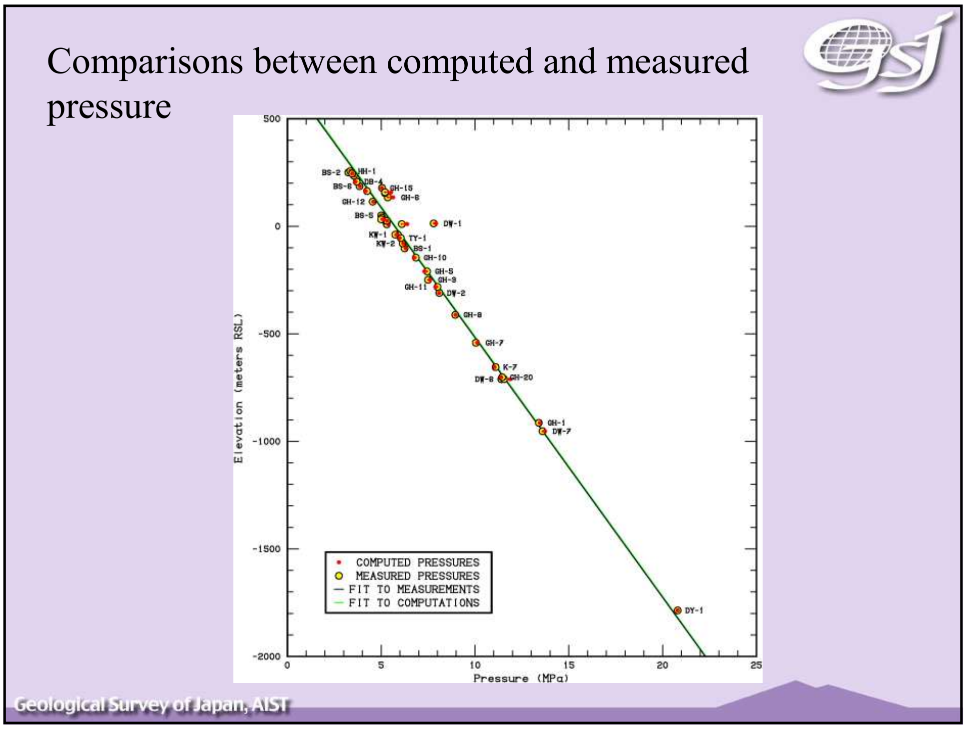
Modeling the "Natural State" at Oguni

- About 50 repetitive long-term calculations required.
- Duration: 250,000 years (steady solutions) starting from cold initial conditions.
- Main free parameters:
  - Permeability distribution.
  - Boundary conditions on grid bottom (–1900 m RLS).

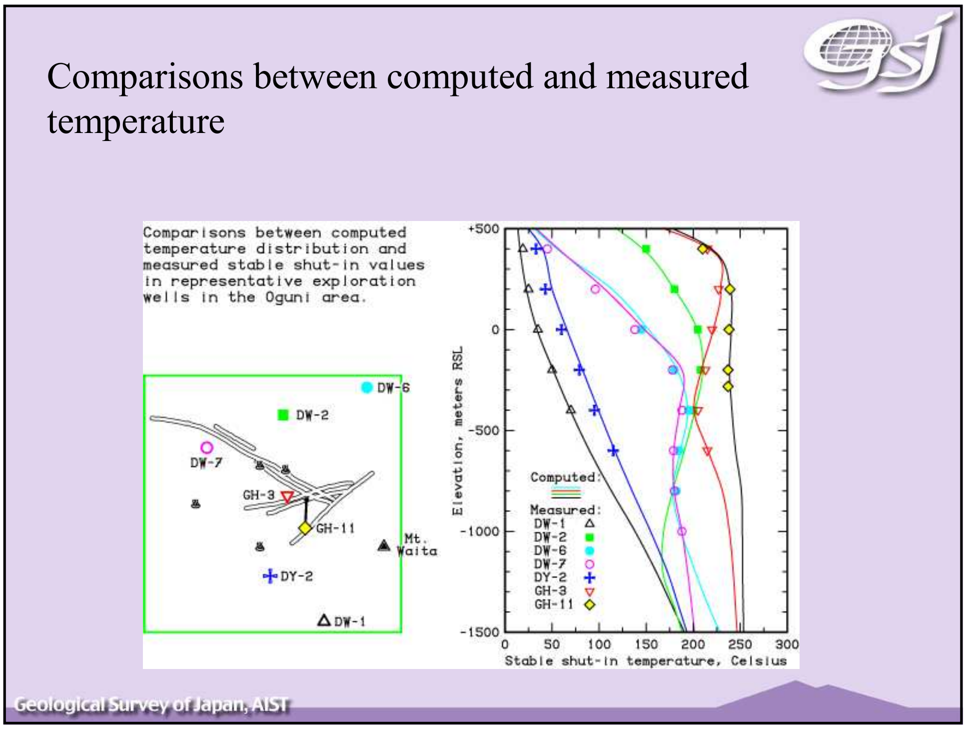
- Data available for comparison:
  - Shut-in stable feedpoint pressure in wells.
  - Long-term stable shut-in temperature profiles.
  - Natural surface mass and heat discharge rates and locations (hot springs and fumaroles).
  - A limited amount of pressure-transient (interference) test information (used to estimate permeabilities).

Boundary conditions on the bottom surface





Comparisons between computed and measured pressure



Comparisons between computed and measured temperature

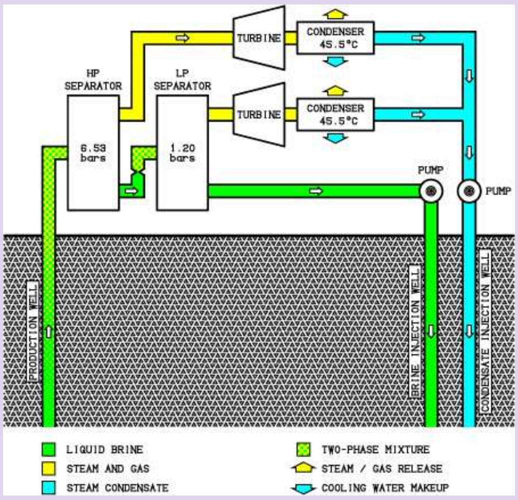
Comparisons between computed temperature distribution and measured stable shut-in values in representative exploration wells in the Oguni area.

Forecasting Power Production at Oguni

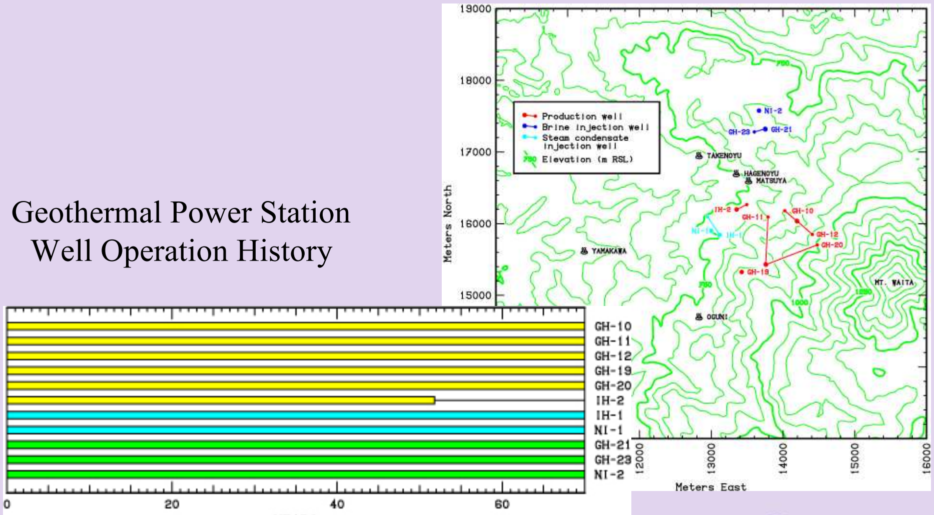
- Same spatial grid, formation properties, boundary conditions, as for natural state calculation.
- Initial conditions—final natural state.
- Dual-flash steam plant—capacity 20 MWe.
- Problem duration: 70 years. Power station starts up at *t* = 5 years. Total of 65 years of operation in forecast.

- Production from six wells (all exist). Brine injection into three wells (two exist) in Sugawara area to the north. Condensate injection into two wells (1 exists) adjacent to power station to the west of the production wellfield.
- No makeup drilling considered.

Geothermal Power Station
Fluid Flow Circuit Schematic Diagram

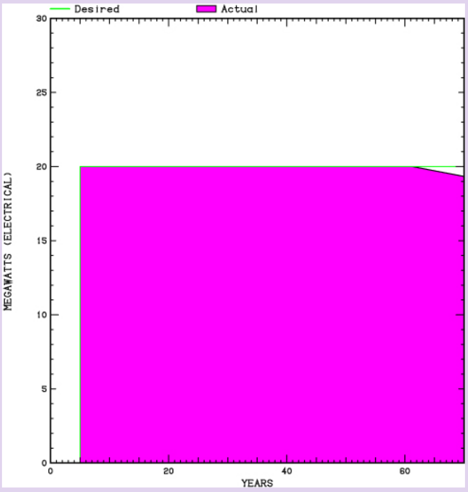


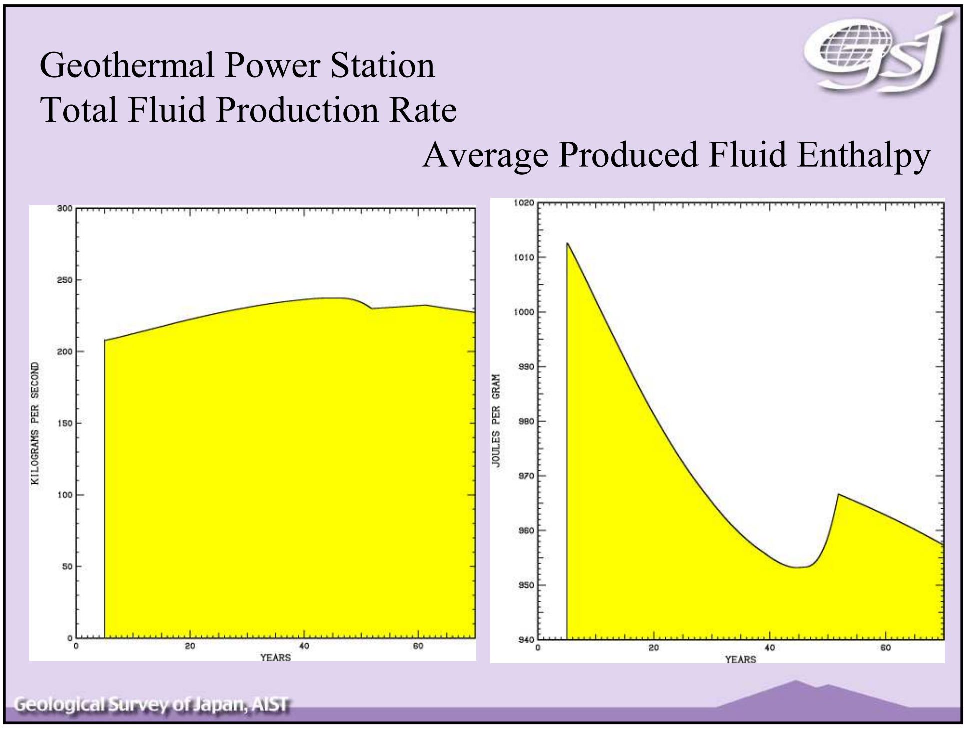
Locations of Wells Used for Electrical Power Production From the Oguni Geothermal Field



Geothermal Power Station
Well Operation History

Geothermal Power Station
Total Electrical Power Generation





Geothermal Power Station
Total Fluid Production Rate
Average Produced Fluid Enthalpy

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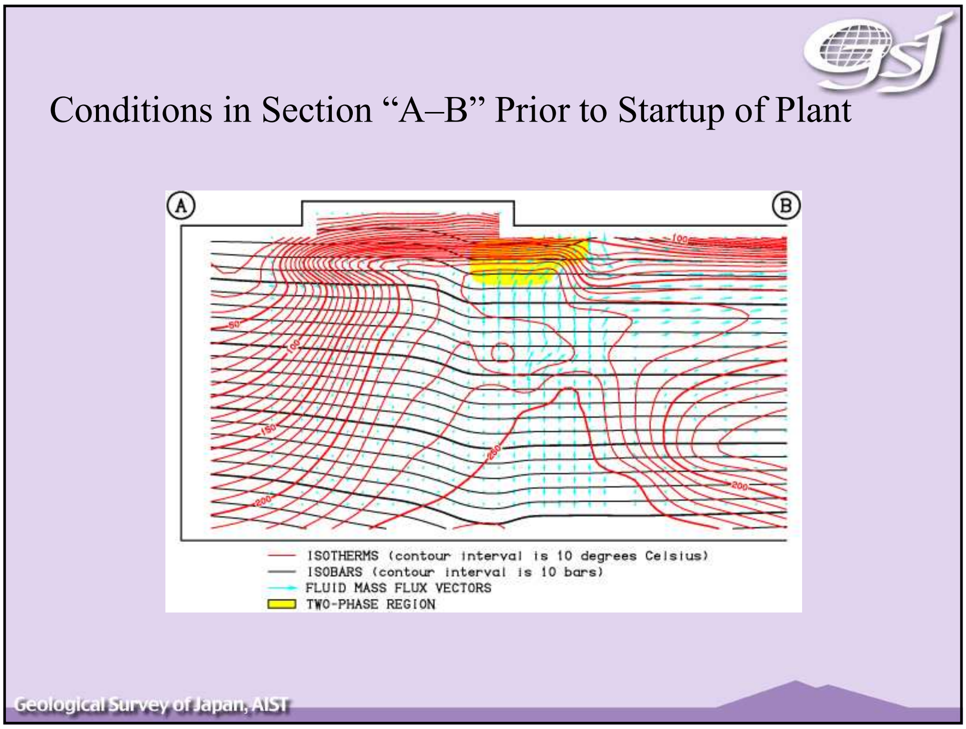

Conditions in Section "A–B" Prior to Startup of Plant

ISOTHERMS (contour interval is 10 degrees Celsius)
ISOBARS (contour interval is 10 bars)
FLUID MASS FLUX VECTORS
▨ TWO-PHASE REGION

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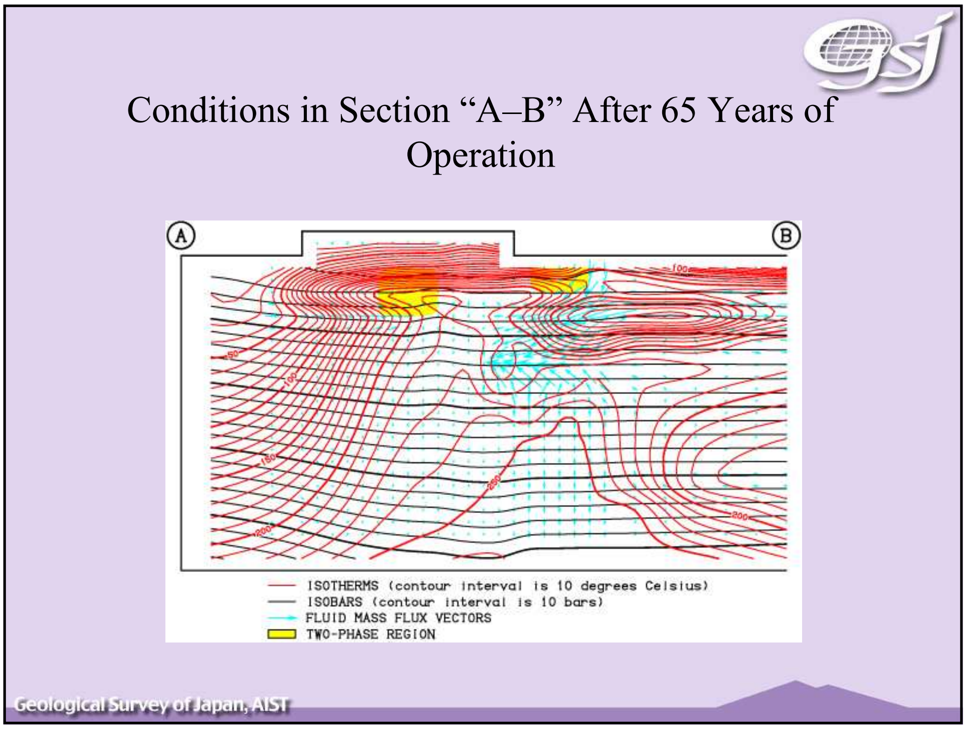
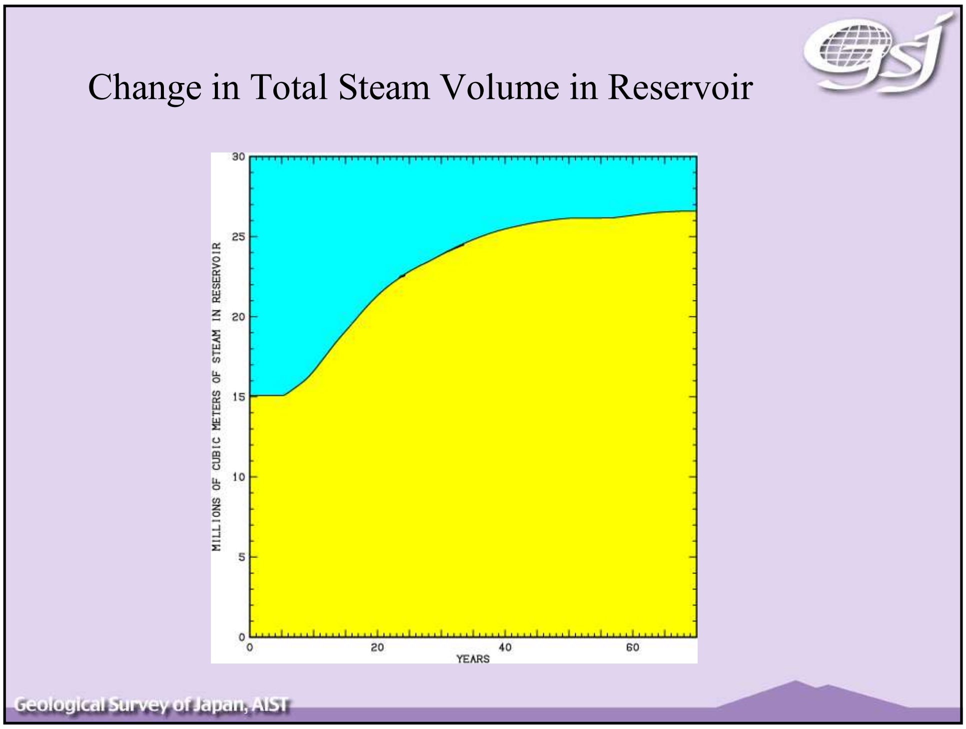
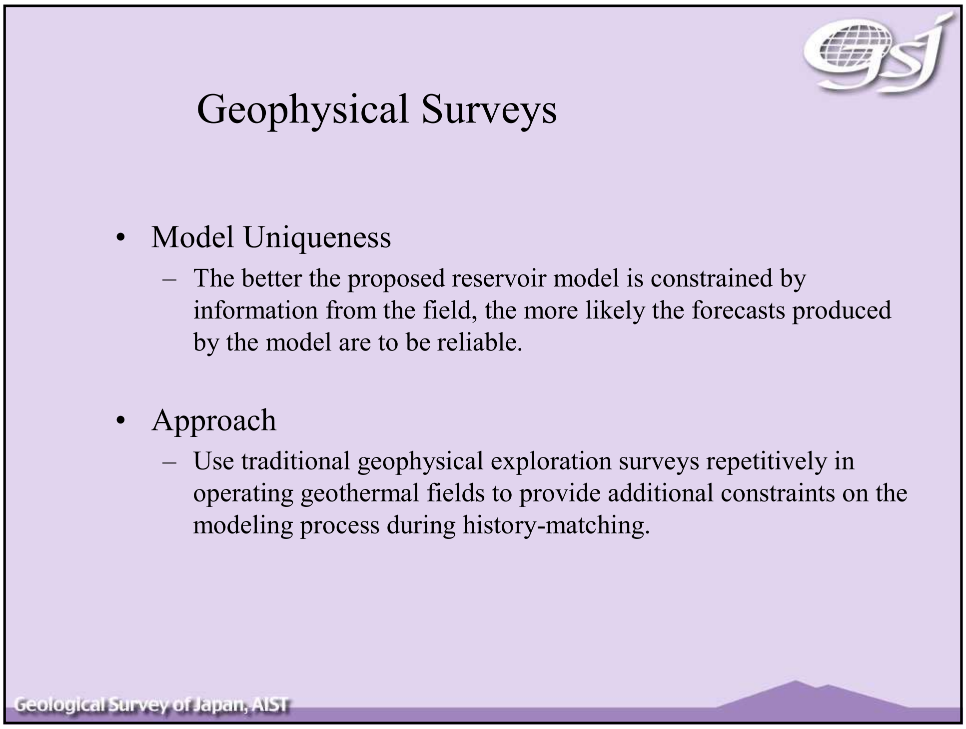


Conditions in Section “A–B” After 65 Years of Operation

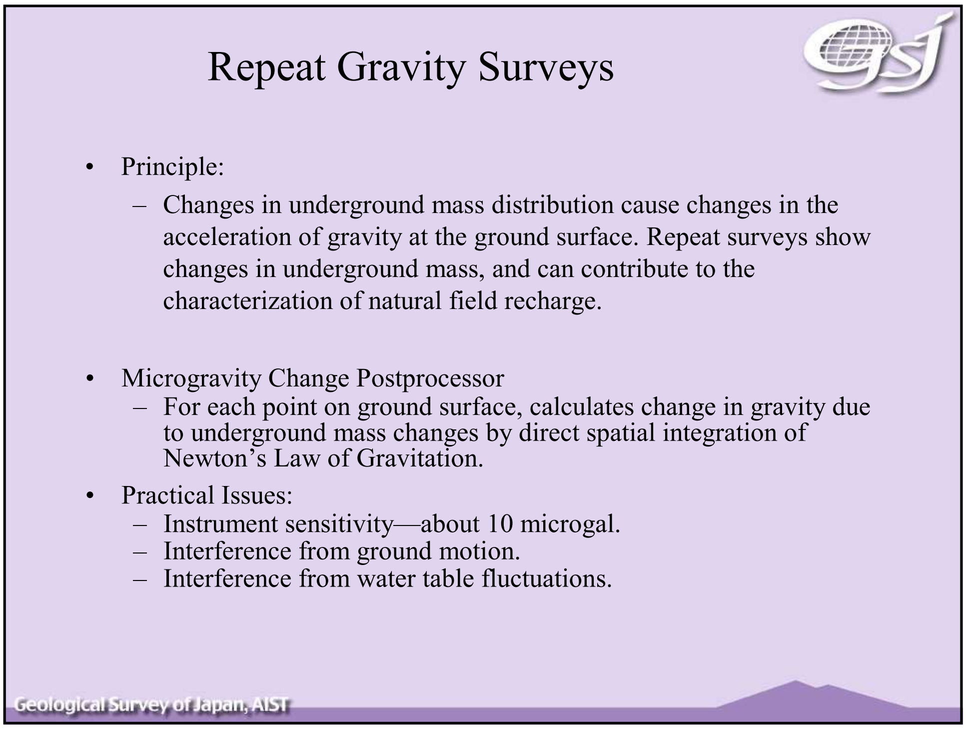


Change in Total Steam Volume in Reservoir



Geophysical Surveys

- Model Uniqueness
  - The better the proposed reservoir model is constrained by information from the field, the more likely the forecasts produced by the model are to be reliable.
- Approach
  - Use traditional geophysical exploration surveys repetitively in operating geothermal fields to provide additional constraints on the modeling process during history-matching.

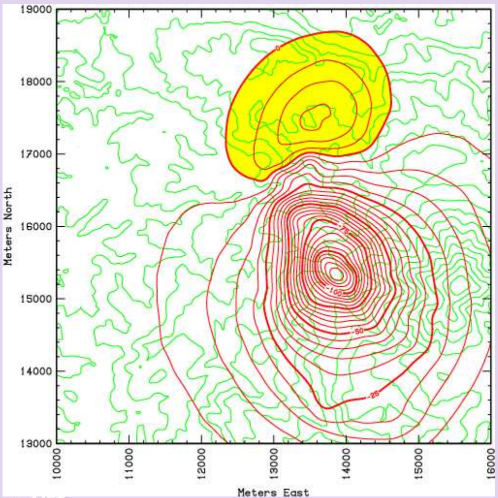


Repeat Gravity Surveys

- Principle:
  - Changes in underground mass distribution cause changes in the acceleration of gravity at the ground surface. Repeat surveys show changes in underground mass, and can contribute to the characterization of natural field recharge.
- Microgravity Change Postprocessor
  - For each point on ground surface, calculates change in gravity due to underground mass changes by direct spatial integration of Newton’s Law of Gravitation.
- Practical Issues:
  - Instrument sensitivity—about 10 microgal.
  - Interference from ground motion.
  - Interference from water table fluctuations.

Gravity Change After 20 Years of Field Operation

Contour interval is 5 microgals



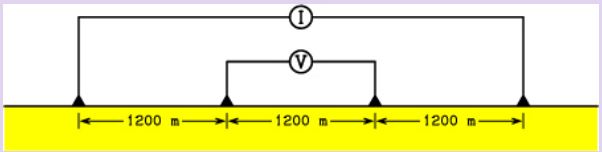
Electrical Postprocessors

- Currently available:
  - "DC (direct current) Resistivity" postprocessor.
  - "MT (magnetotelluric) Resistivity" postprocessor.
  - "CSAMT" (controlled-source audio-frequency magnetotelluric) postprocessor.
  - "SP (self-potential)" postprocessor.
- Common features:
  - Overlay "electrical" grid on STAR reservoir simulation grid.
  - Specify phenomonological models for pertinent quantities (electrical resistivities) for each formation and dependence on local conditions (temperature, salinity, steam saturation).
  - Interpolate pertinent quantities (resistivities, etc.) at selected times from STAR grid to electrical grid.
  - Calculate observables (voltages, apparent resistivities, etc.) using electrical grid.

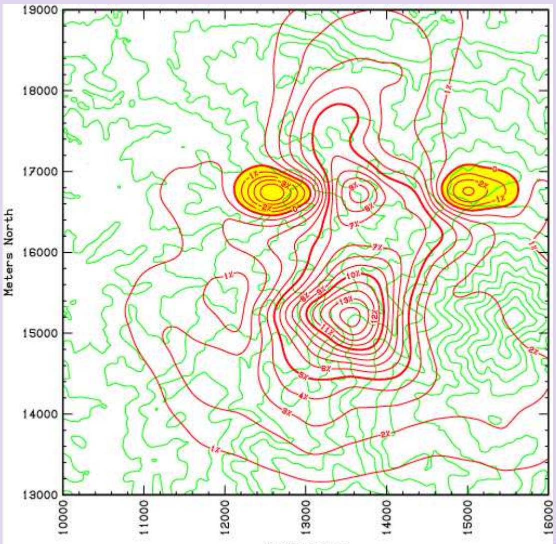
DC Resistivity Surveys

- Have been used in exploration to find and delineate geothermal prospects. Low resistivities often correlate with good permeability, high temperature, and/or alteration minerals.
- Principle: Install two well-separated “current” electrodes at the earth surface and impose known current. Measure potential difference thereby induced between two “voltage” electrodes located in the same general area.
- “Apparent DC Resistivity” is the electrical resistivity of a uniform flat-surface half-space that would yield the same ratio of voltage to current for the same geometrical arrangement of the electrodes.
- Note: Owing to underground heterogeneity and surface topography, the apparent resistivity of the reservoir at a point on the surface will depend upon the type of electrode arrangement selected, the electrode separation, and the orientation of the array (north-south? east-west?).
- Increasing the electrode separation increases penetration depth but degrades lateral spatial resolution.

DC Resistivity Survey Electrode Arrangement
Electrode array orientation: East-West

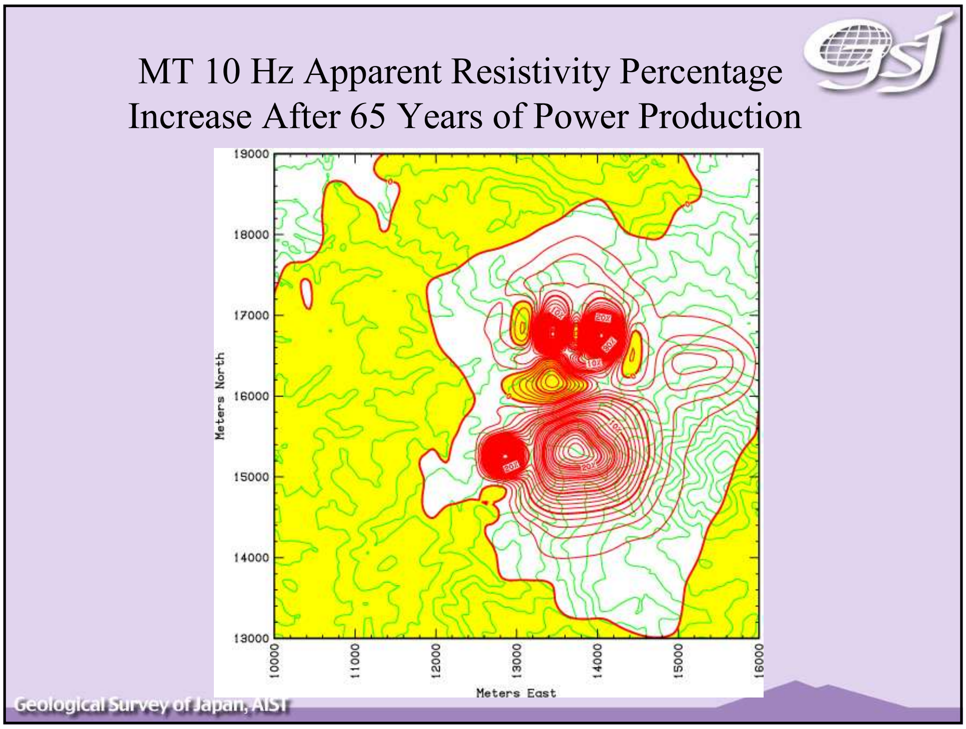


Apparent DC Resistivity Percentage Increase After 65 Years of Power Station Operations



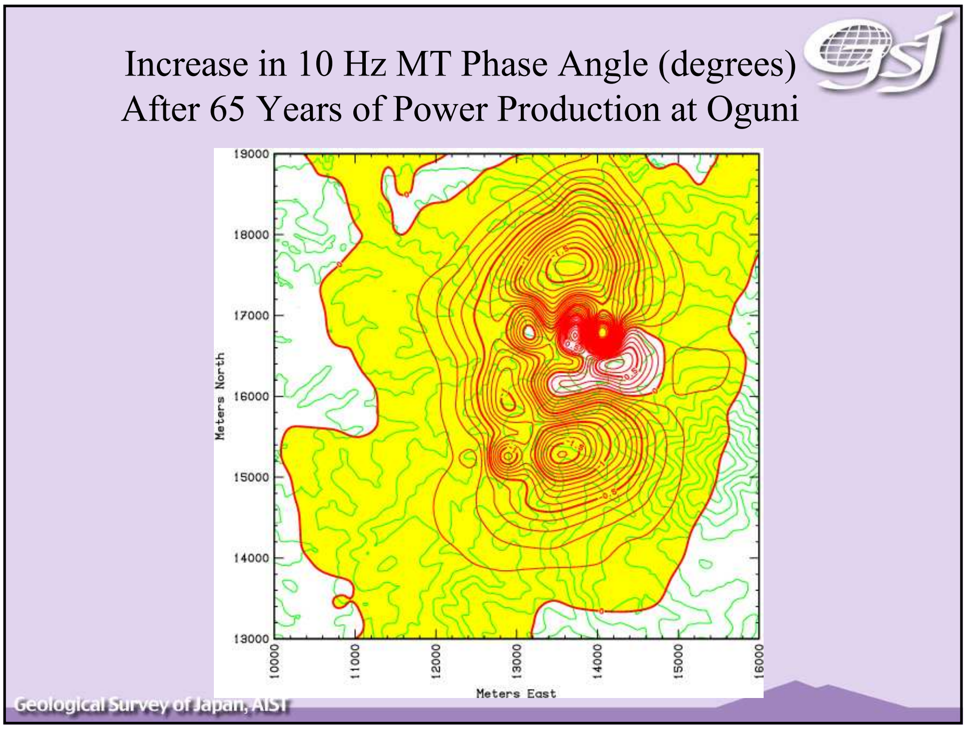
Magnetotelluric Surveys

- Magnetotelluric (MT) surveys also measure underground resistivity, but use the time-modulated electromagnetic signals that originate with solar fluence and worldwide atmospheric electrical activity, usually in the range 0.1 - 1000 Hz. Interpretation is therefore based on Maxwell's Equations rather than Ohm's Law.
- In geothermal field exploration projects, MT surveys are gradually supplanting traditional DC resistivity surveys.
- The "apparent MT resistivity" is analogous to the corresponding DC parameter. Examining response at lower frequencies provides results representative of deeper layers, analogous to the use of wider electrode spacings in DC surveys. The "phase angle" (between voltage and current) can also be used for diagnostic purposes, and will in general be a function of position, frequency, and time.



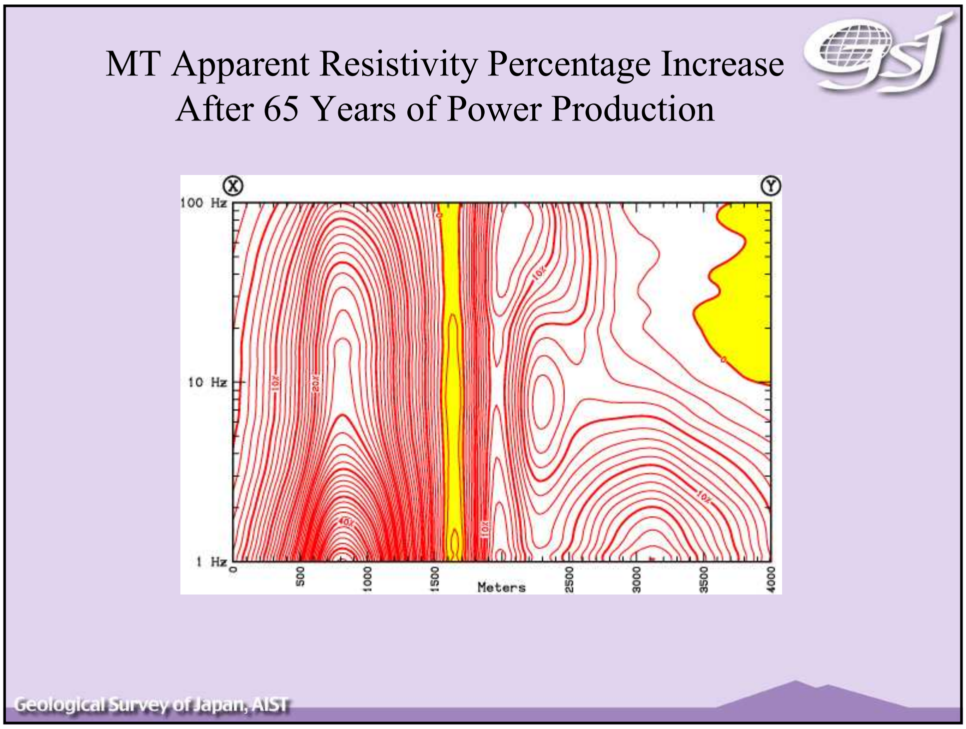
MT 10 Hz Apparent Resistivity Percentage Increase After 65 Years of Power Production

Geological Survey of Japan, AIST



Increase in 10 Hz MT Phase Angle (degrees) After 65 Years of Power Production at Oguni

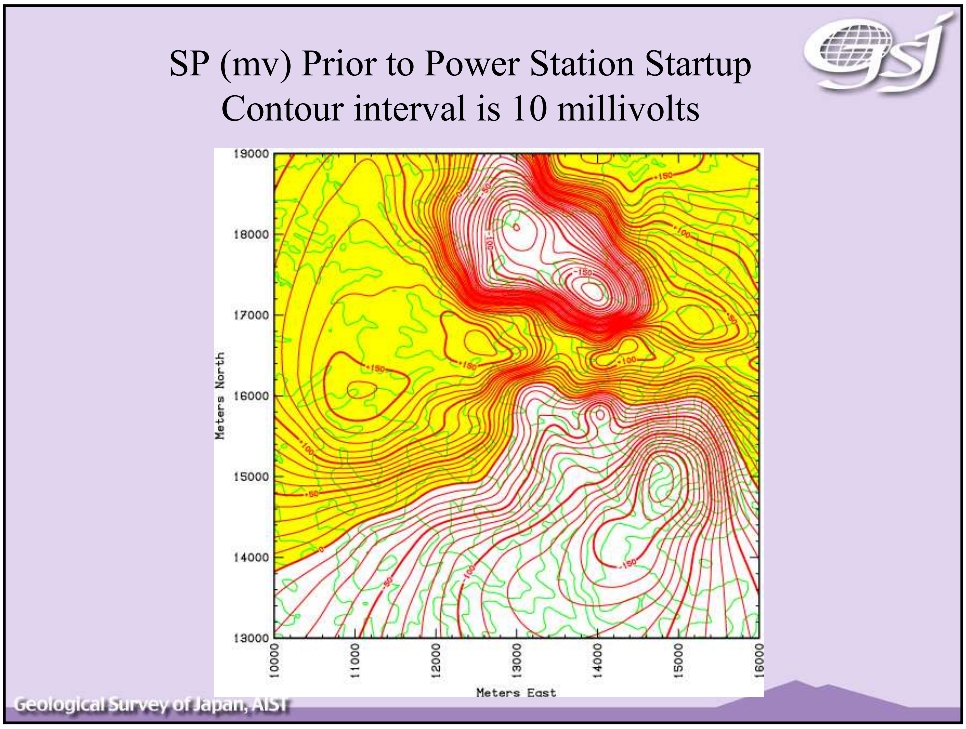
Geological Survey of Japan, AIST



MT Apparent Resistivity Percentage Increase After 65 Years of Power Production

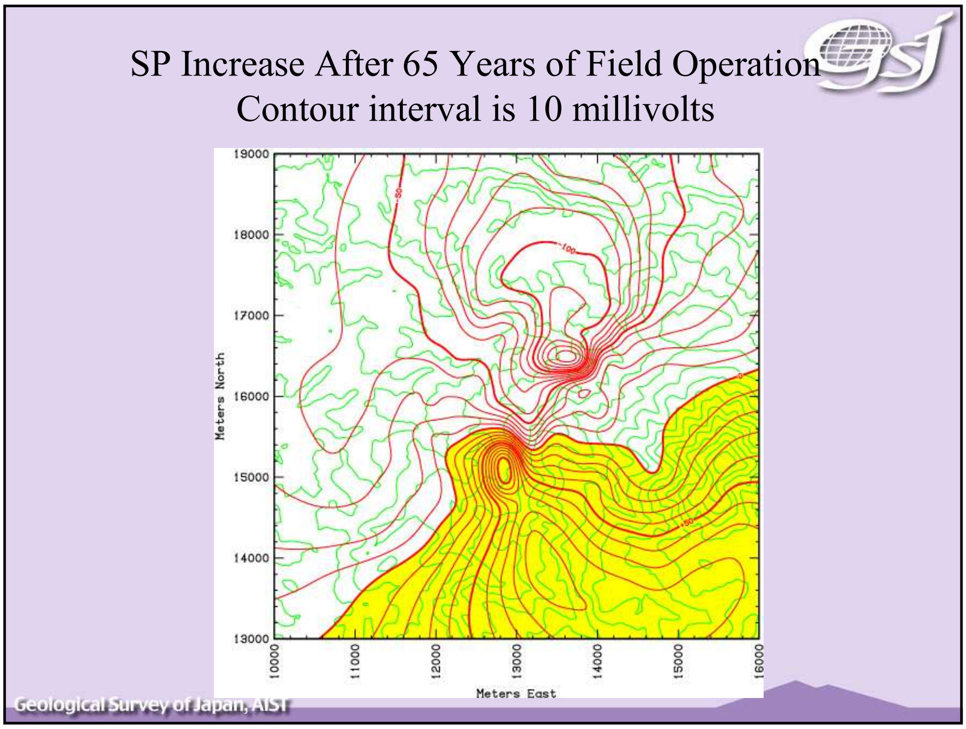
Self-Potential Surveys

- Distribution of electrical potential on the ground surface in geothermal areas is due to various causes:
  - Thermal gradients (“the earth as a thermocouple”)
  - Chemical gradients (“the earth as a battery”)
  - Electrokinetic effects (“the earth as a dynamo”)
- Of these, only the electrokinetic component is likely to exhibit rapid substantial changes due to power production operations.
- Changes in electrokinetic SP arise from:
  - Changes in underground electrical resistivity distribution due to changes in underground temperature, salinity, and steam saturation.
  - Changes in amplitude and direction of the “drag current” caused by underground fluid flow as well flow rates change.



SP (mv) Prior to Power Station Startup
Contour interval is 10 millivolts

Geological Survey of Japan, AIST



SP Increase After 65 Years of Field Operation
Contour interval is 10 millivolts

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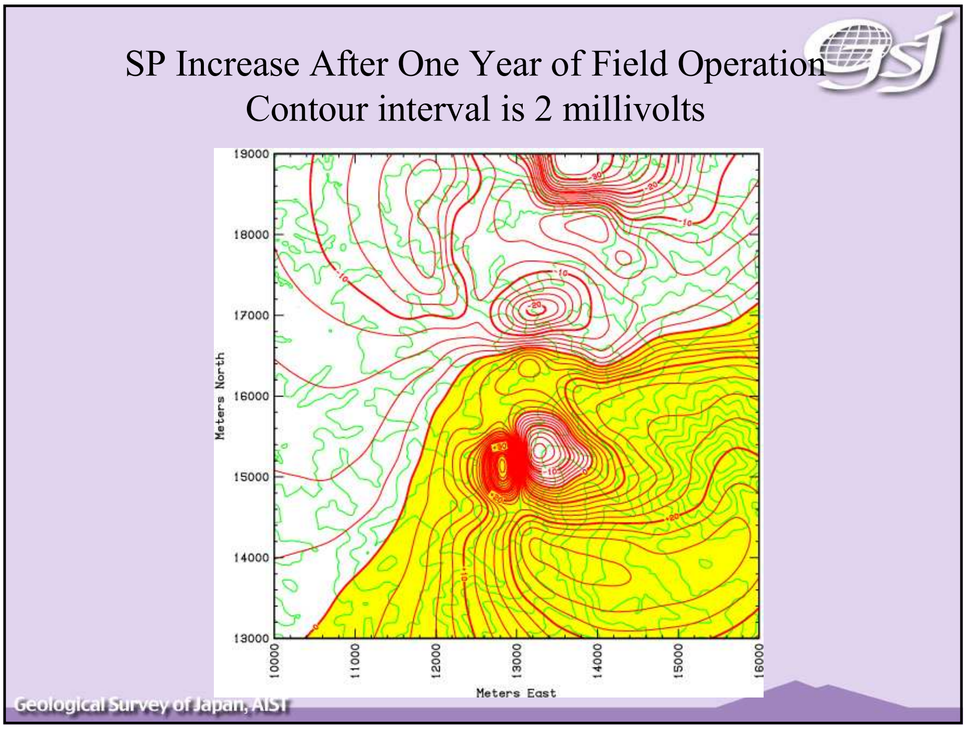

SP Increase After One Year of Field Operation
Contour interval is 2 millivolts

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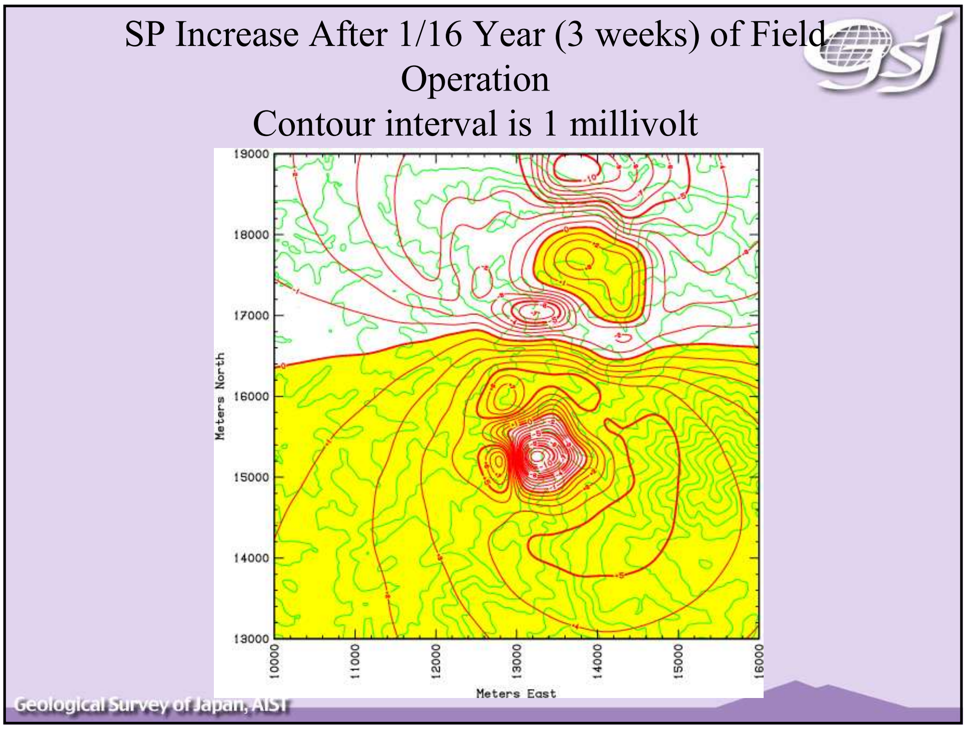


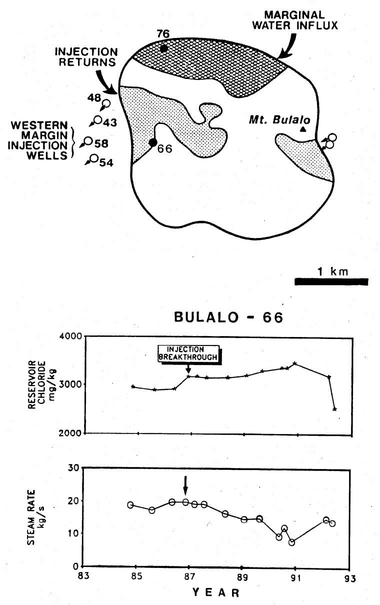
SP Increase After 1/16 Year (3 weeks) of Field Operation
Contour interval is 1 millivolt

Geological Survey of Japan, AIST

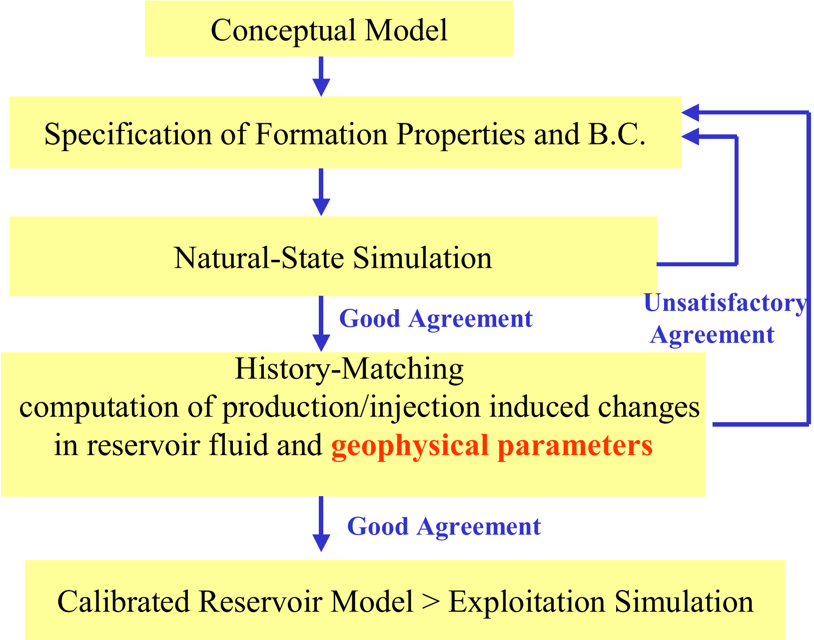
History Matching

Reservoir Management

A well documented production history and a history match is a must for making reliable forecasts of the performance of the geothermal field.



Clemente, W.C. and Villadolid-Abrigo, F.L. (1993): The Bulalo geothermal field, Philippines: reservoir characteristics and response to production. *Geothermics*, **22**, p.381-394.



Conceptual Model

Specification of Formation Properties and B.C.

Natural-State Simulation

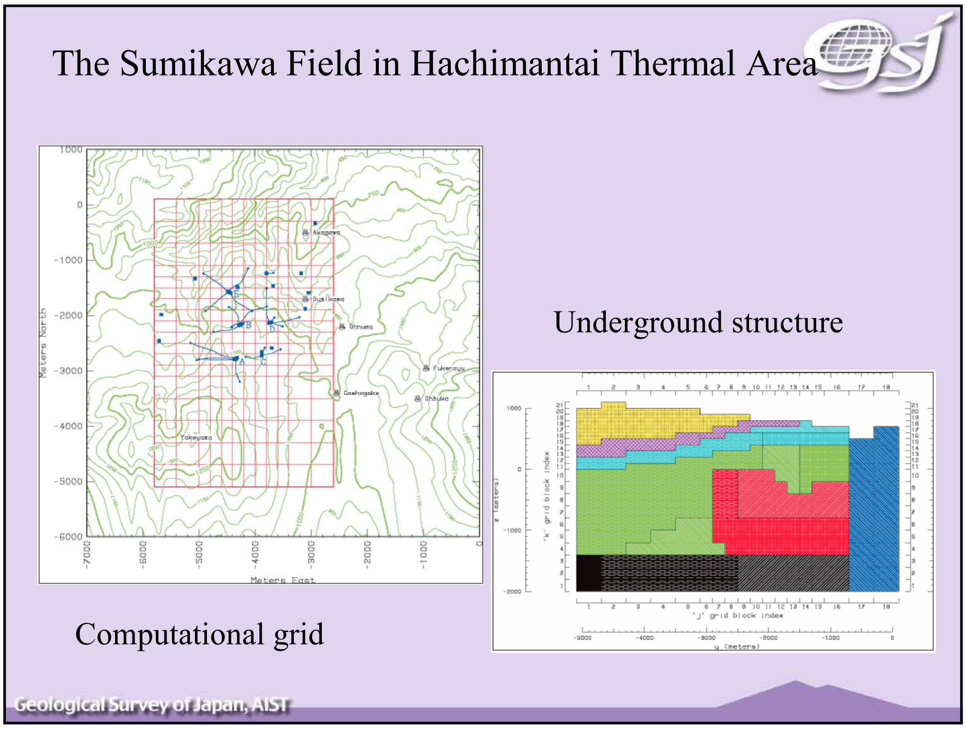
Good Agreement

Unsatisfactory Agreement

History-Matching
computation of production/injection induced changes in reservoir fluid and **geophysical parameters**

Good Agreement

Calibrated Reservoir Model > Exploitation Simulation

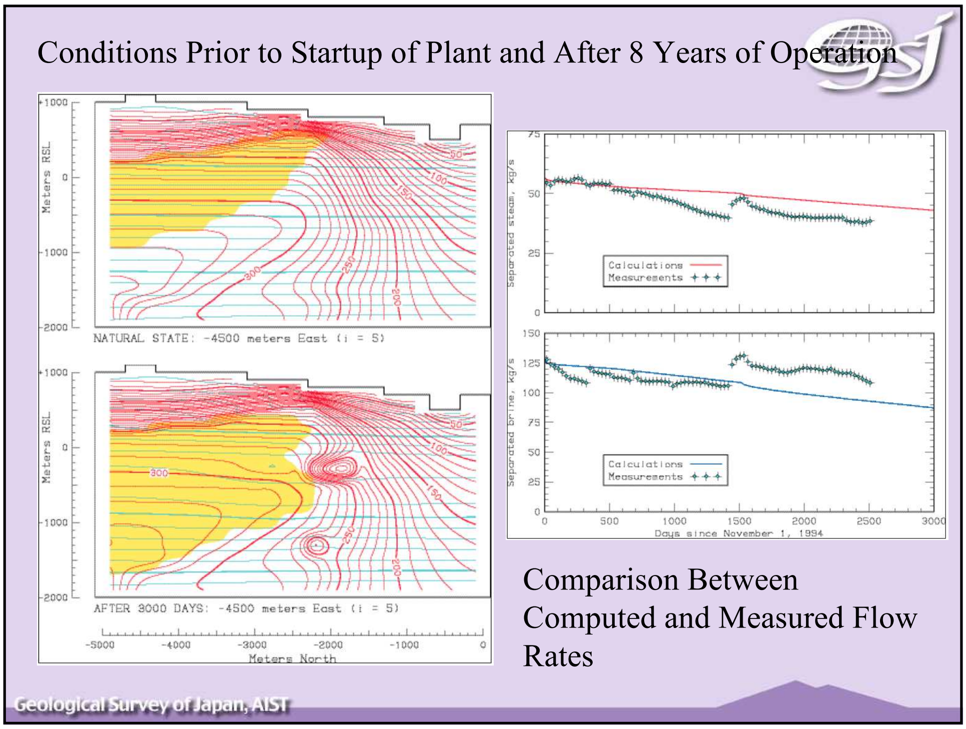


The Sumikawa Field in Hachimantai Thermal Area

Underground structure

Computational grid

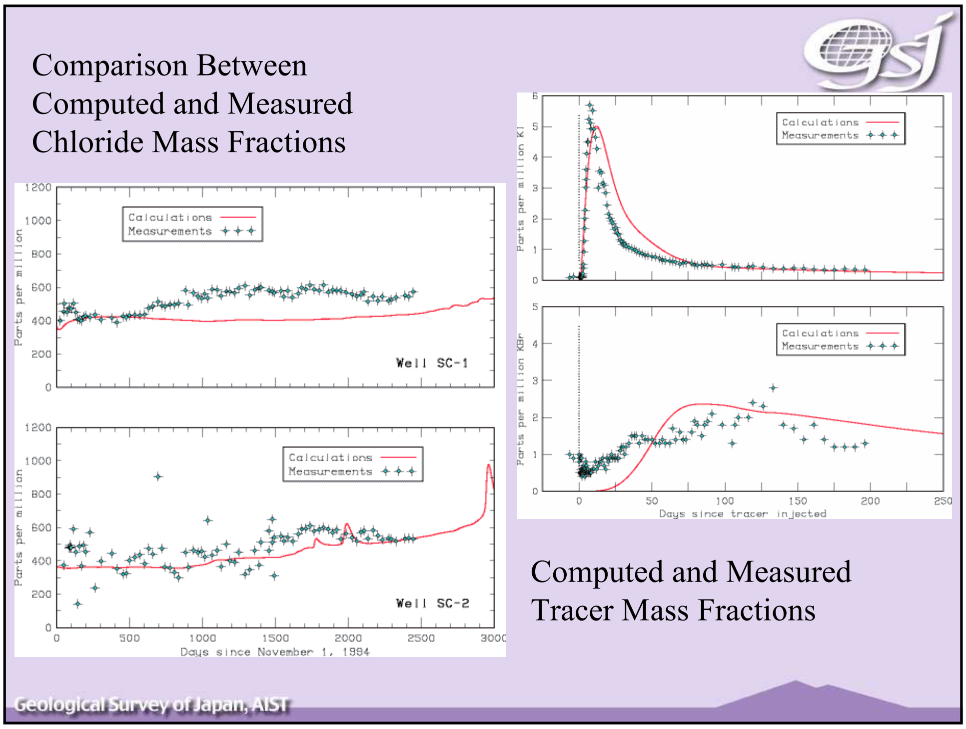
Geological Survey of Japan, AIST



Conditions Prior to Startup of Plant and After 8 Years of Operation

Comparison Between Computed and Measured Flow Rates

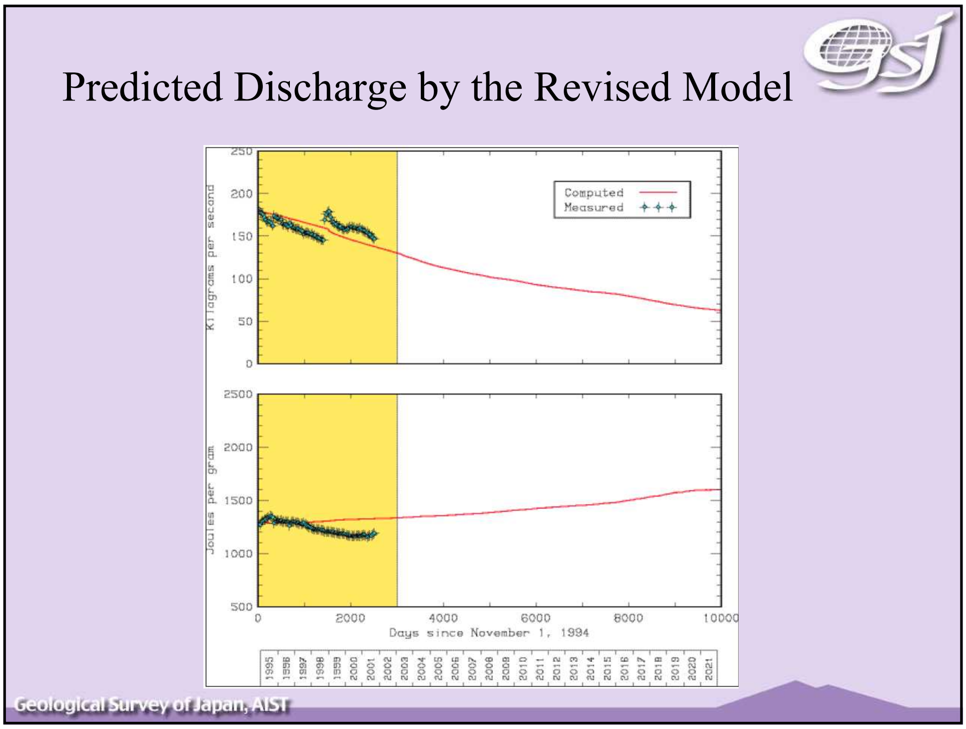
Geological Survey of Japan, AIST



Comparison Between Computed and Measured Chloride Mass Fractions

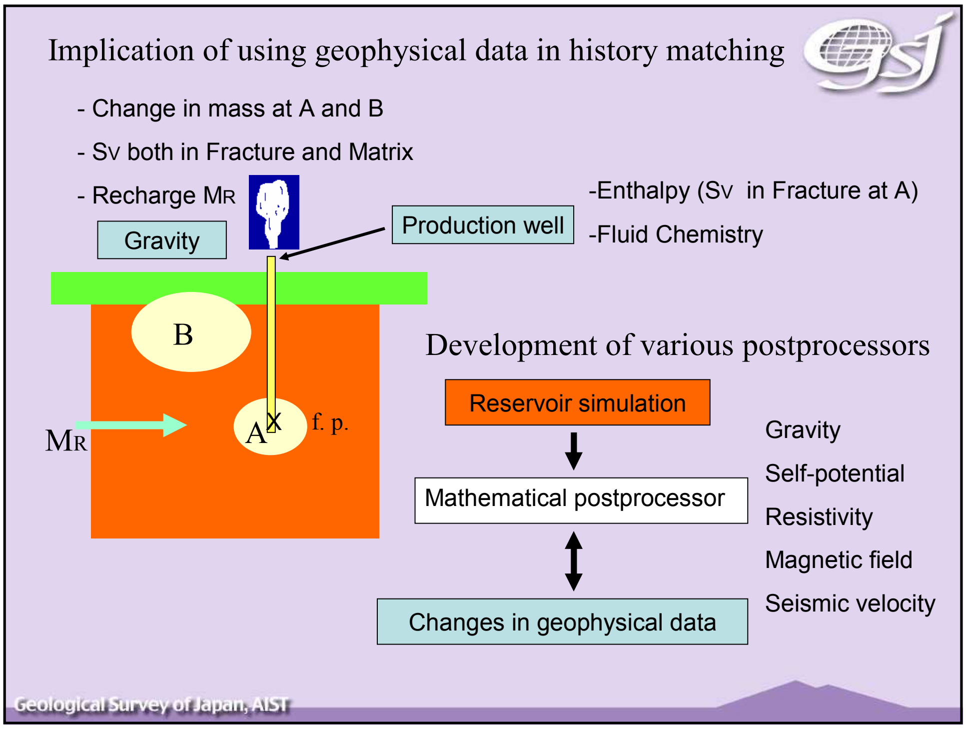
Computed and Measured Tracer Mass Fractions

Geological Survey of Japan, AIST



Predicted Discharge by the Revised Model

Geological Survey of Japan, AIST



Implication of using geophysical data in history matching

- Change in mass at A and B
- S_V both in Fracture and Matrix
- Recharge M_R

Gravity

Production well

-Enthalpy (S_V in Fracture at A)

-Fluid Chemistry

Development of various postprocessors

Reservoir simulation

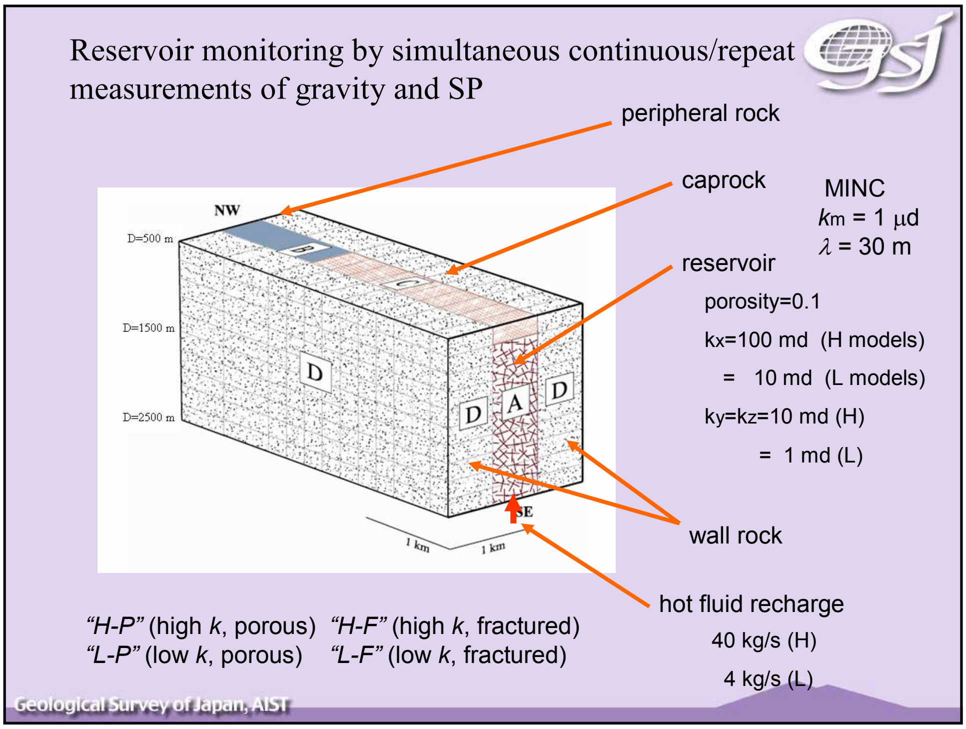
↓

Mathematical postprocessor

↕

Changes in geophysical data

- Gravity
- Self-potential
- Resistivity
- Magnetic field
- Seismic velocity



Reservoir monitoring by simultaneous continuous/repeat measurements of gravity and SP

peripheral rock

caprock

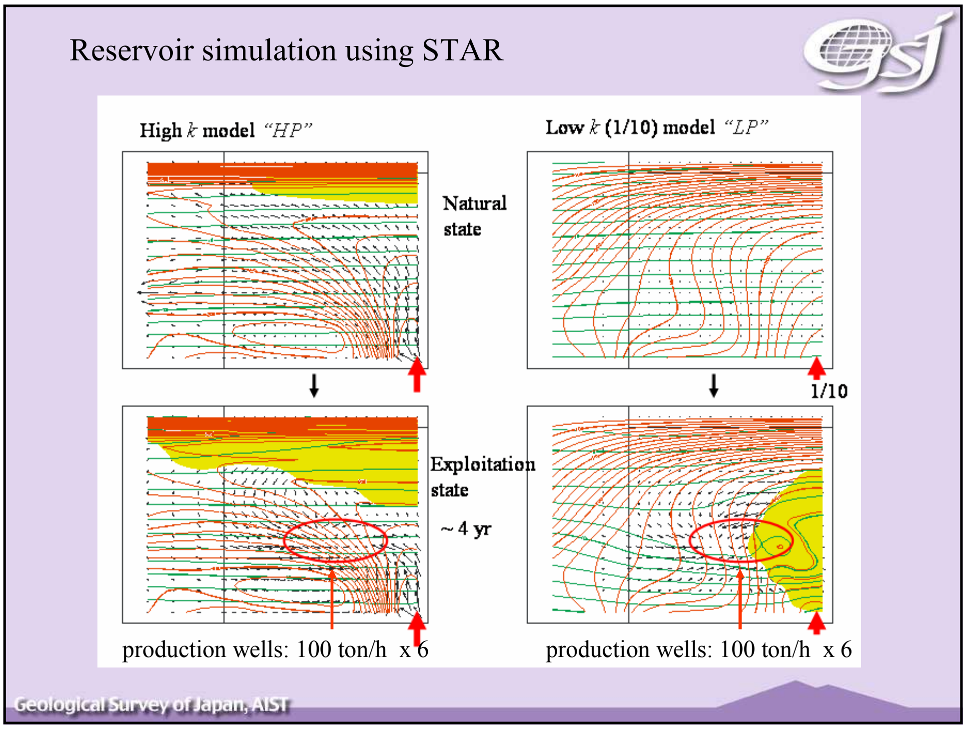
MINC
k_m = 1 μd
λ = 30 m

reservoir
porosity=0.1
kx=100 md (H models)
= 10 md (L models)
ky=kz=10 md (H)
= 1 md (L)

wall rock

hot fluid recharge
40 kg/s (H)
4 kg/s (L)

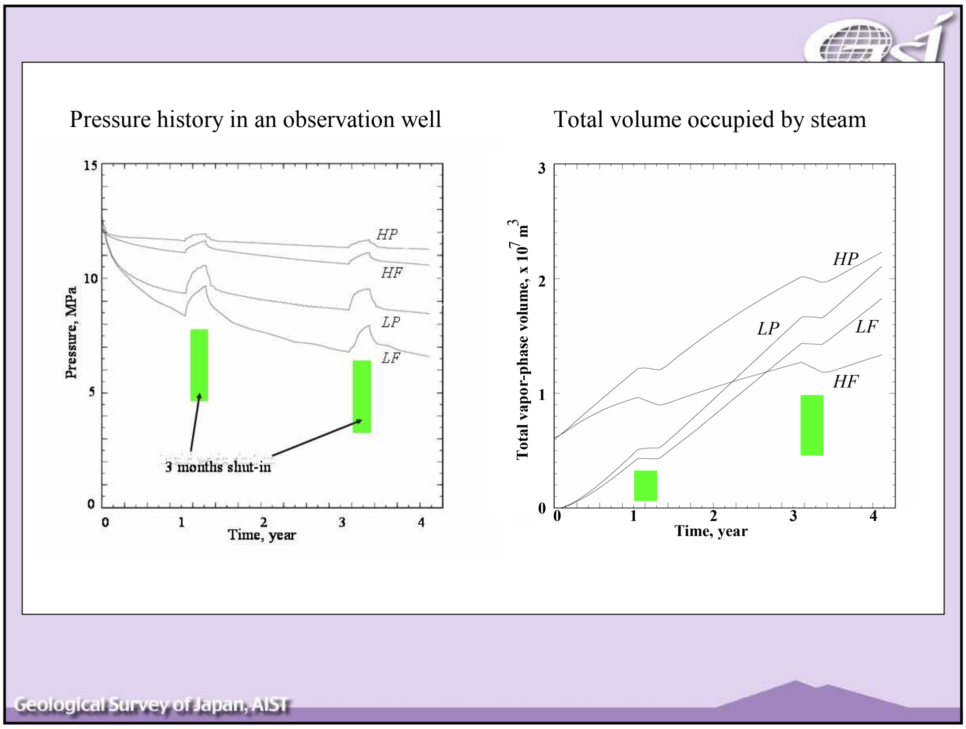
“H-P” (high *k*, porous) *“H-F”* (high *k*, fractured)
“L-P” (low *k*, porous) *“L-F”* (low *k*, fractured)



Reservoir simulation using STAR

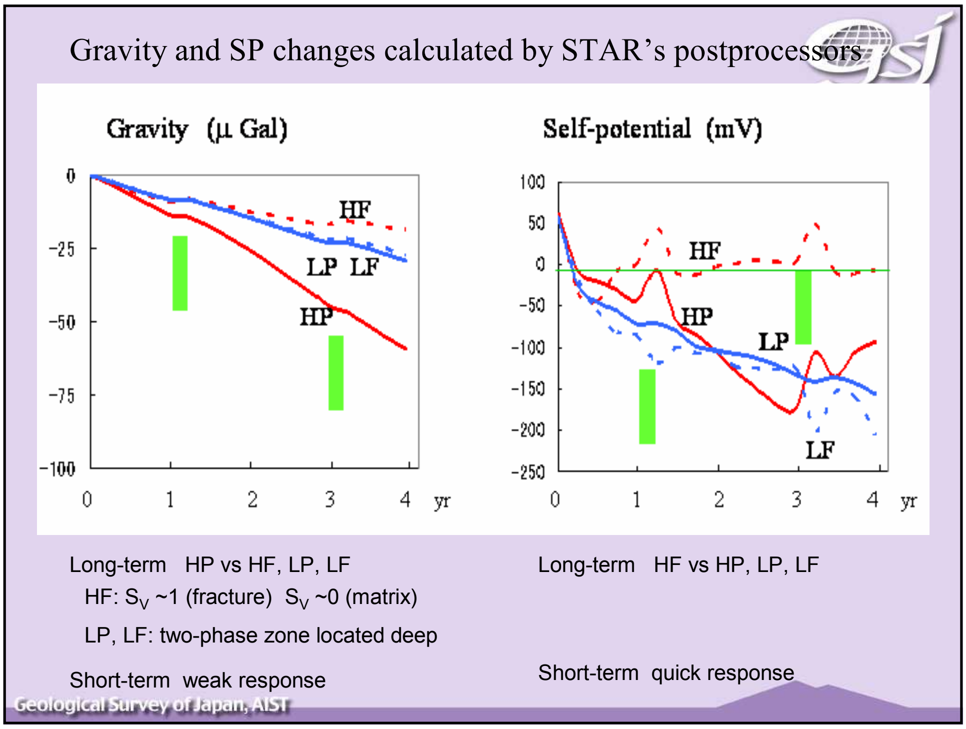
production wells: 100 ton/h x 6

production wells: 100 ton/h x 6



Pressure history in an observation well

Total volume occupied by steam



Gravity and SP changes calculated by STAR's postprocessors

Long-term HP vs HF, LP, LF

HF: S_V ~1 (fracture) S_V ~0 (matrix)

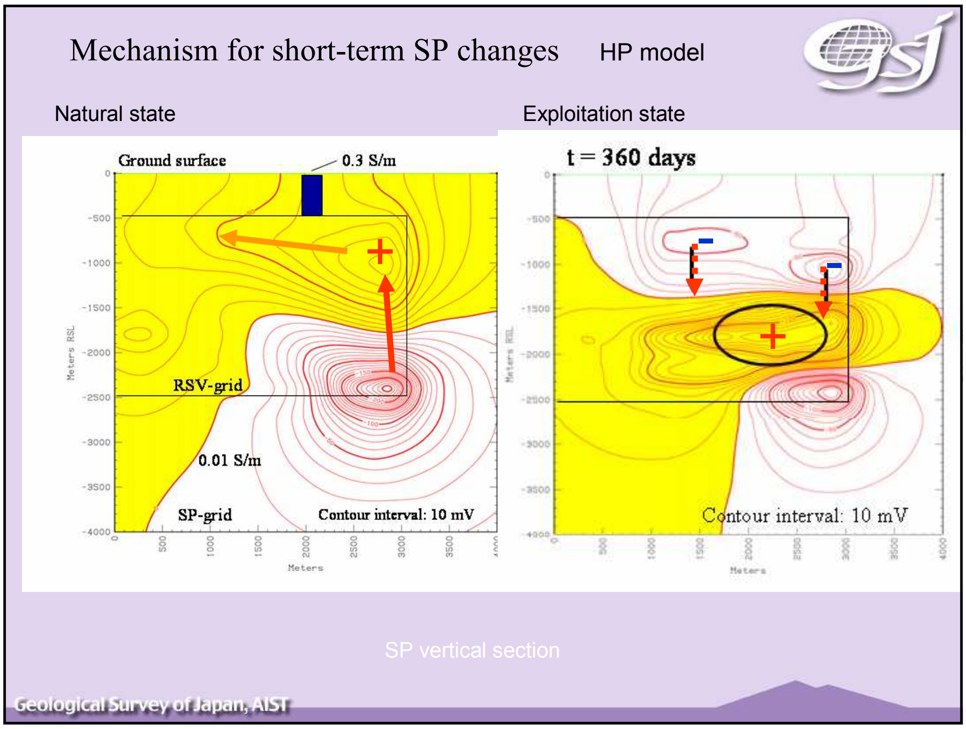
LP, LF: two-phase zone located deep

Short-term weak response

Long-term HF vs HP, LP, LF

Short-term quick response

Geological Survey of Japan, AIST



Mechanism for short-term SP changes HP model

Natural state

Exploitation state

SP vertical section

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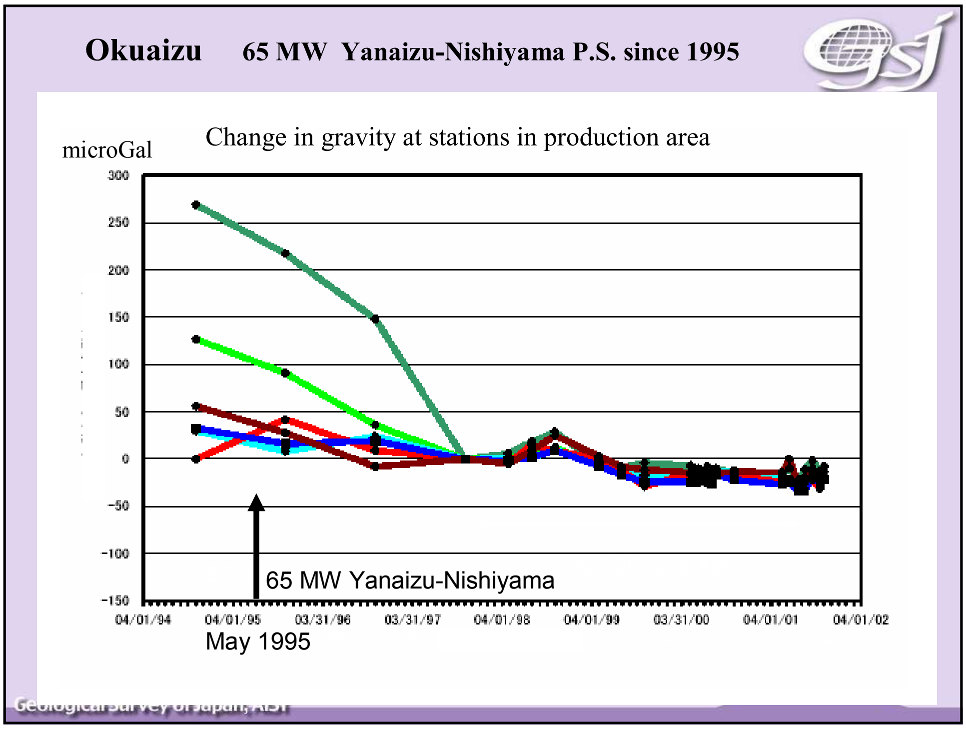
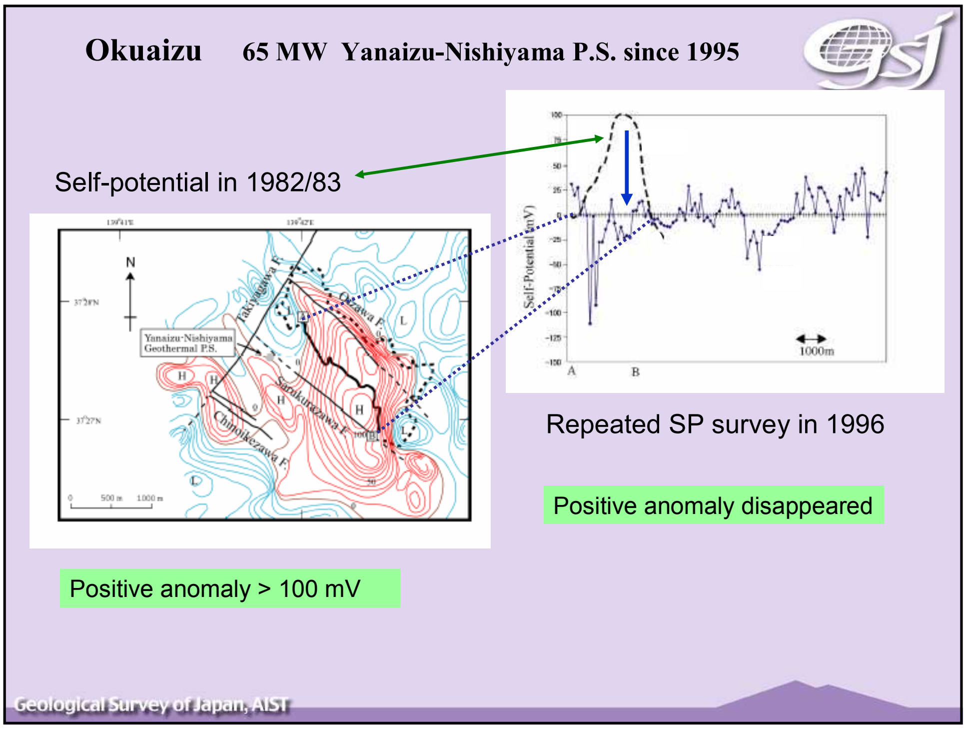


Okuaizu 65 MW Yanaizu-Nishiyama P.S. since 1995

Change in gravity at stations in production area



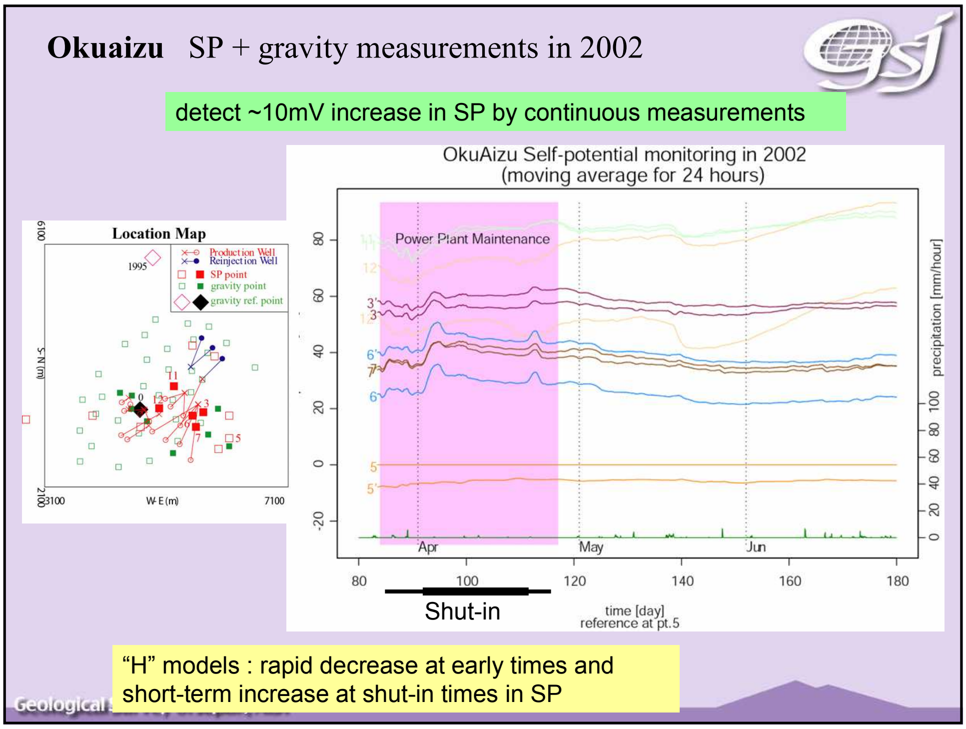
Okuaizu 65 MW Yanaizu-Nishiyama P.S. since 1995

Self-potential in 1982/83

Repeated SP survey in 1996

Positive anomaly disappeared

Positive anomaly > 100 mV



Okuaizu SP + gravity measurements in 2002

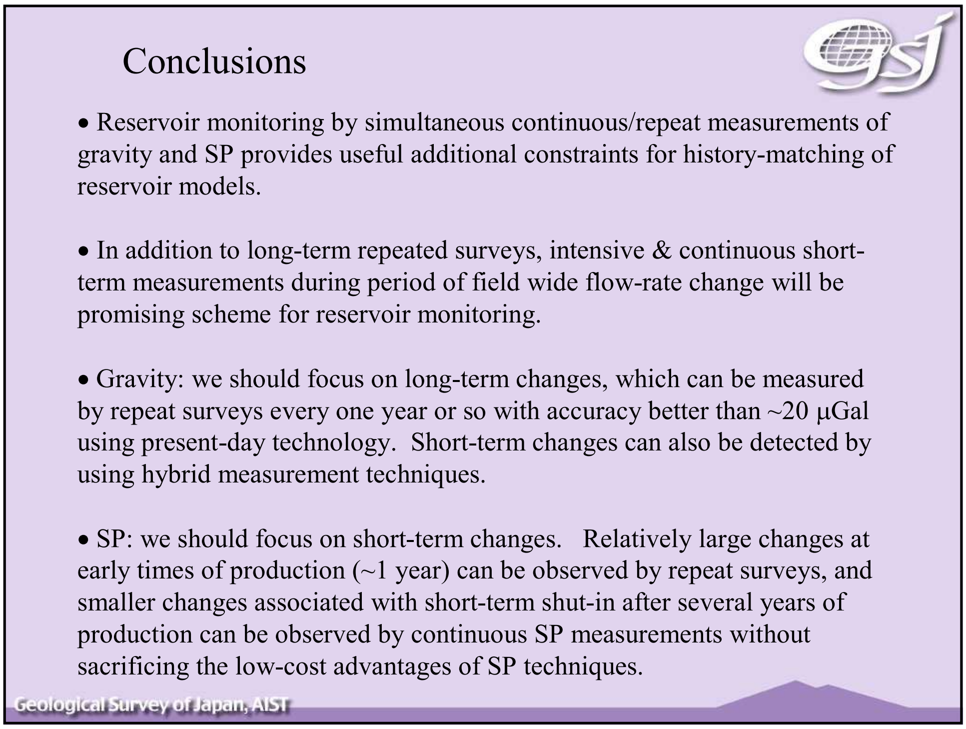
detect ~10mV increase in SP by continuous measurements

OkuAizu Self-potential monitoring in 2002
(moving average for 24 hours)

Shut-in

“H” models : rapid decrease at early times and short-term increase at shut-in times in SP

Geological Survey of Japan, AIST



Conclusions

- Reservoir monitoring by simultaneous continuous/repeat measurements of gravity and SP provides useful additional constraints for history-matching of reservoir models.

- In addition to long-term repeated surveys, intensive & continuous short-term measurements during period of field wide flow-rate change will be promising scheme for reservoir monitoring.

- Gravity: we should focus on long-term changes, which can be measured by repeat surveys every one year or so with accuracy better than ~20 μGal using present-day technology. Short-term changes can also be detected by using hybrid measurement techniques.

- SP: we should focus on short-term changes. Relatively large changes at early times of production (~1 year) can be observed by repeat surveys, and smaller changes associated with short-term shut-in after several years of production can be observed by continuous SP measurements without sacrificing the low-cost advantages of SP techniques.

Geological Survey of Japan, AIST