

Geothermal Reservoir Modeling

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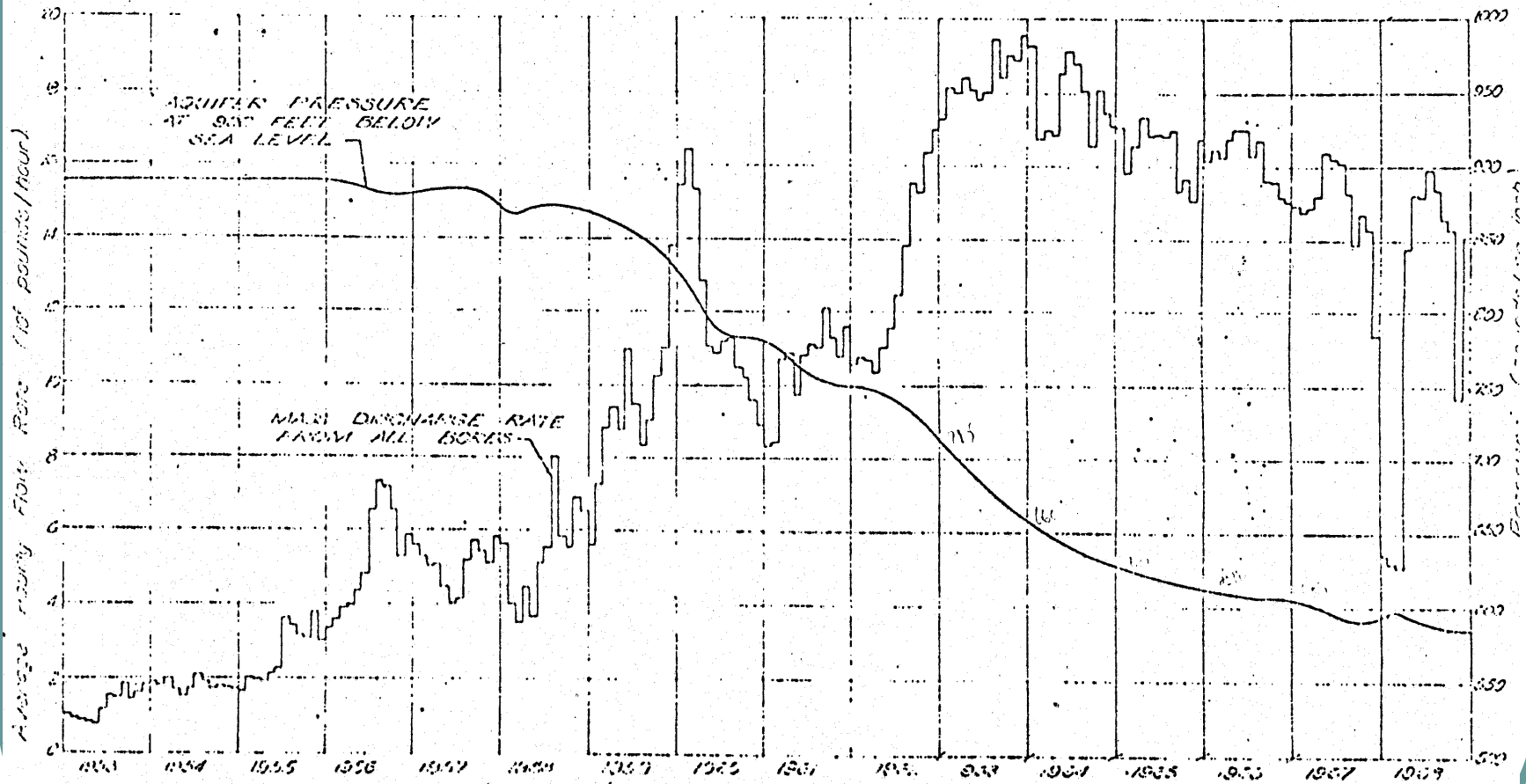


August 11, 2015

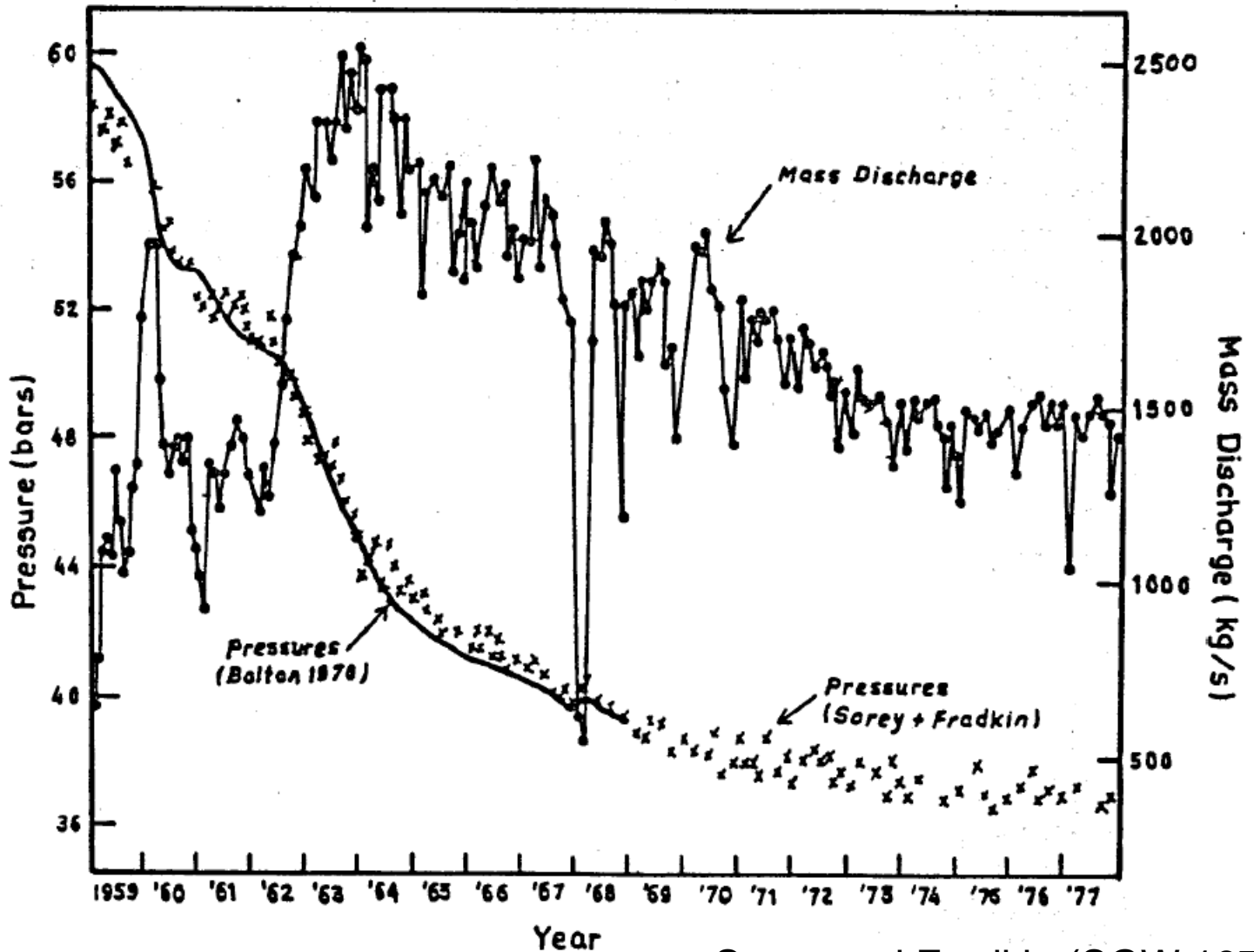
Reservoir Modeling

- The process of reservoir modeling is one of accumulating data and improving the model throughout the producing life of the reservoir.....
- so that on the day the production eventually ceases, we have a complete and perfect prediction of the past.

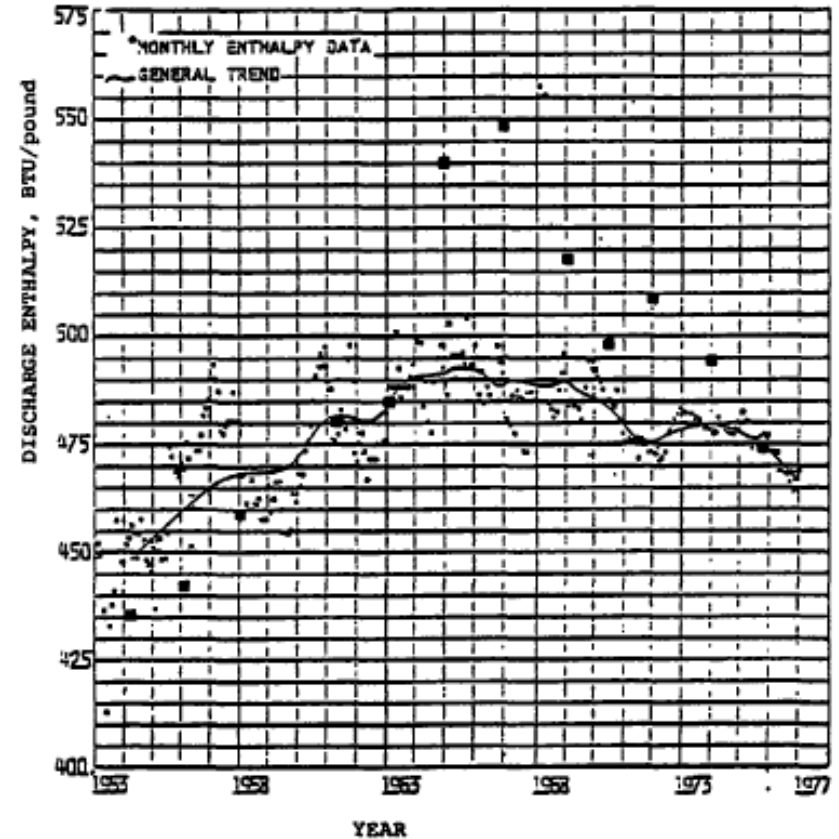
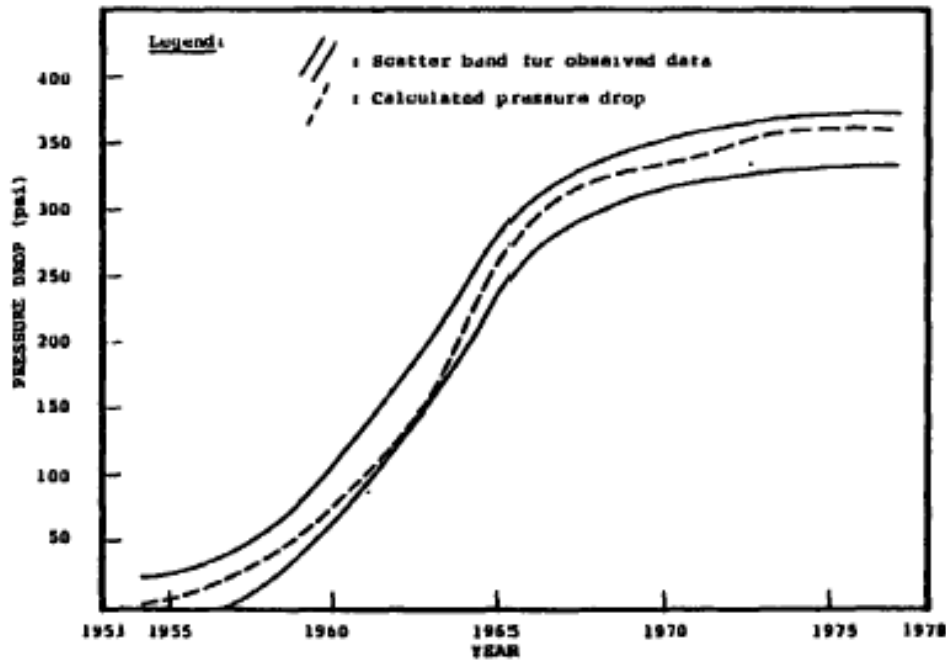
Wairakei Production History



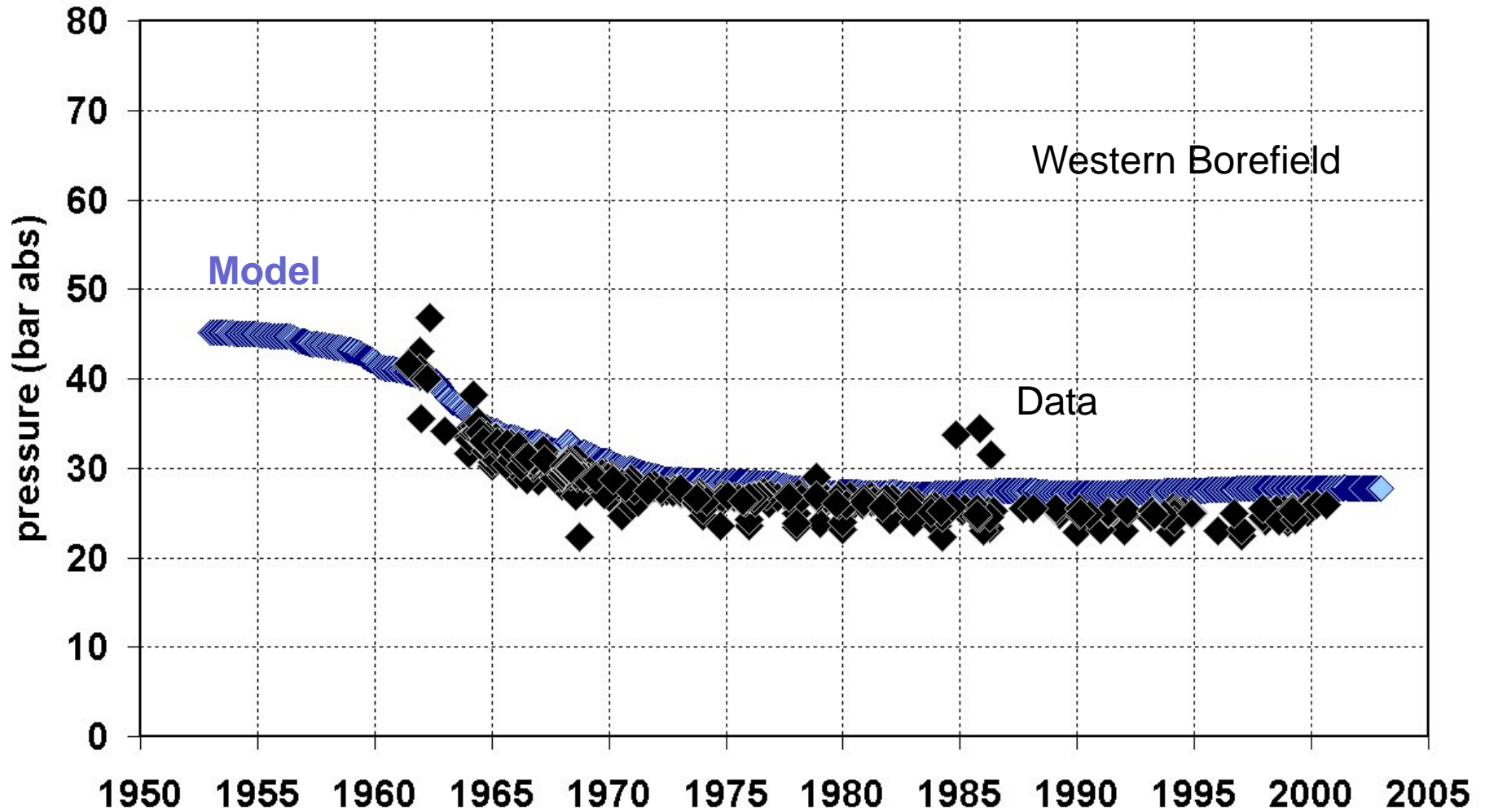
Models of Yesteryear



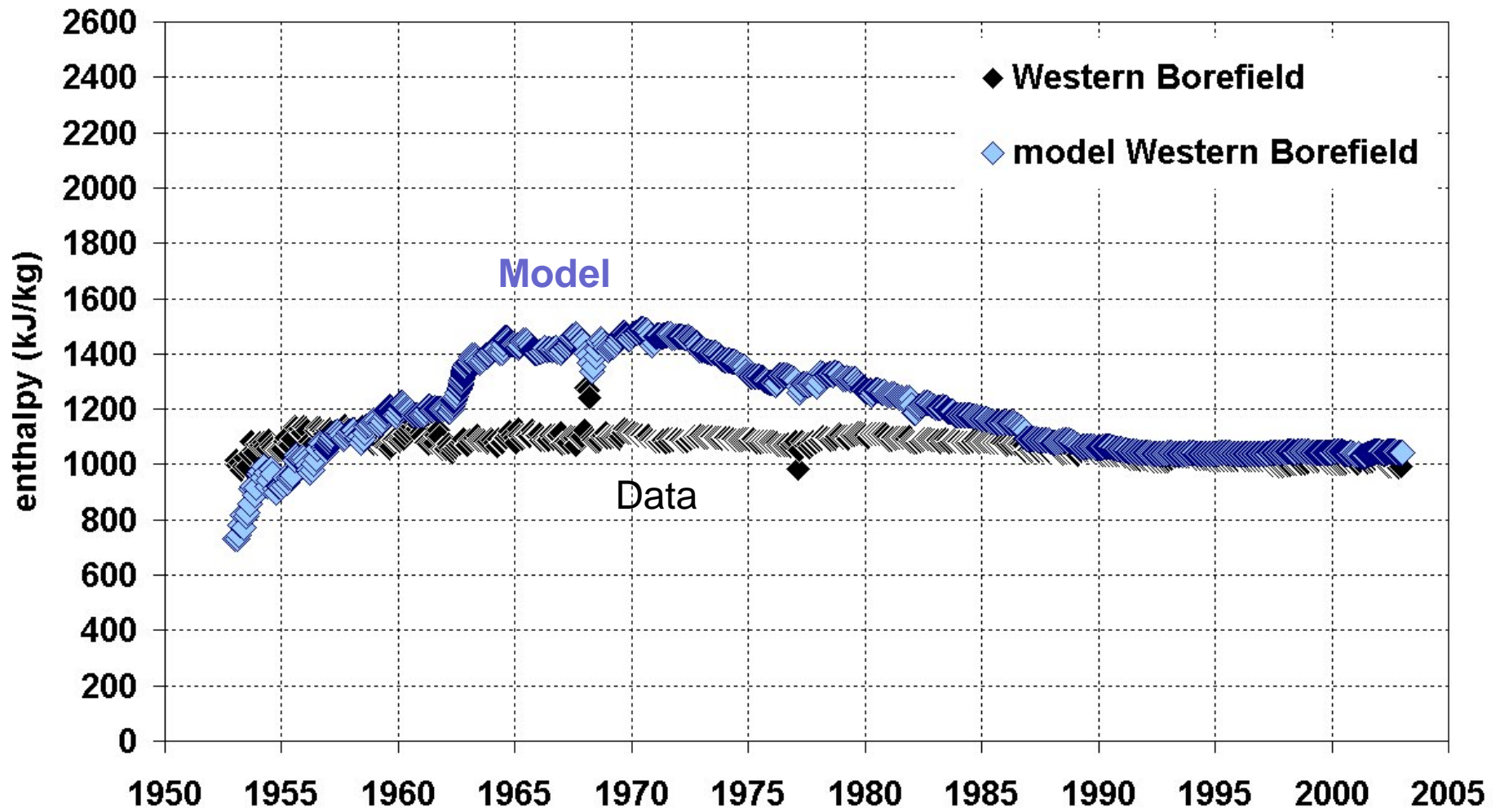
Models of Yesteryear



Models of Today



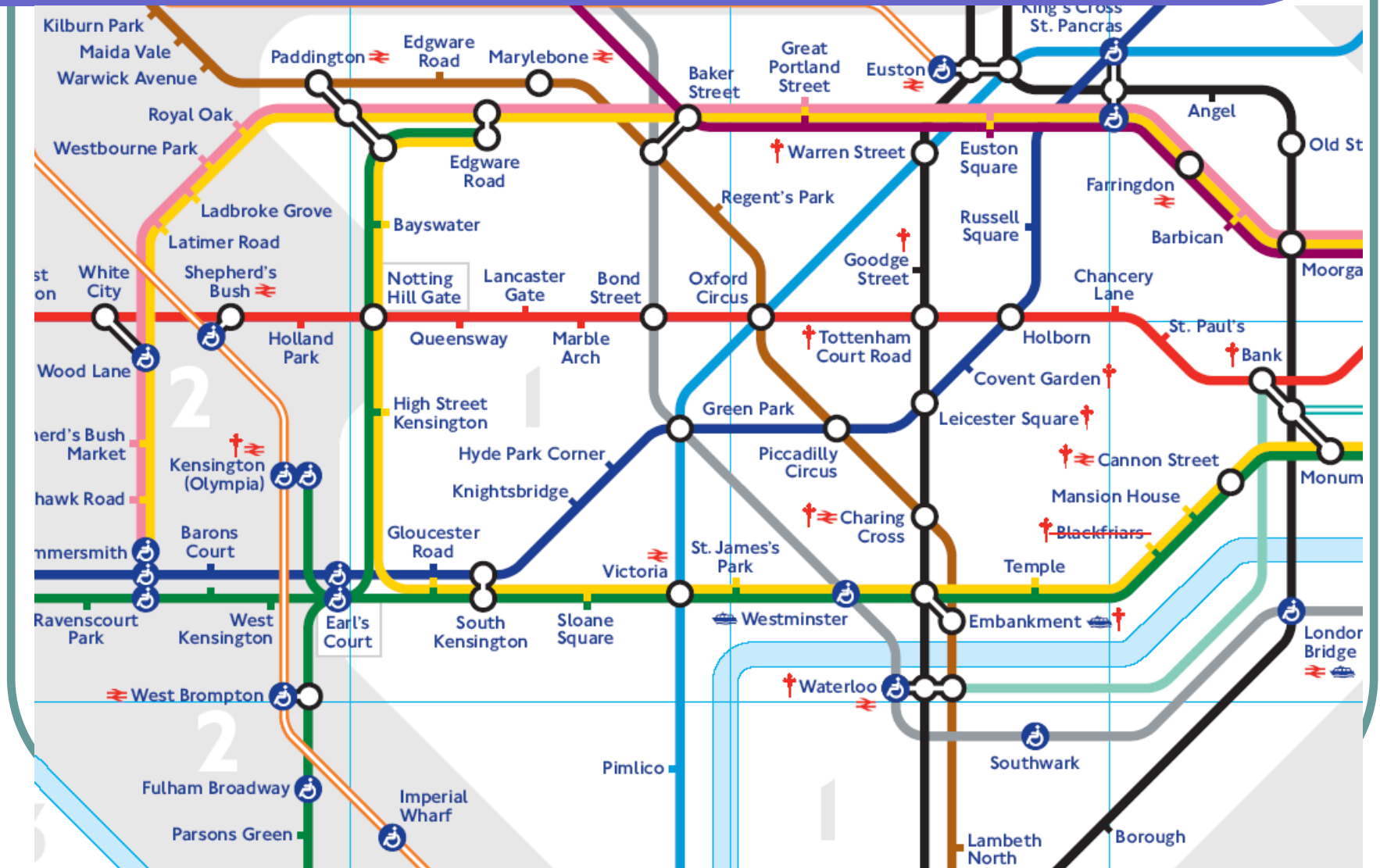
Models of Today



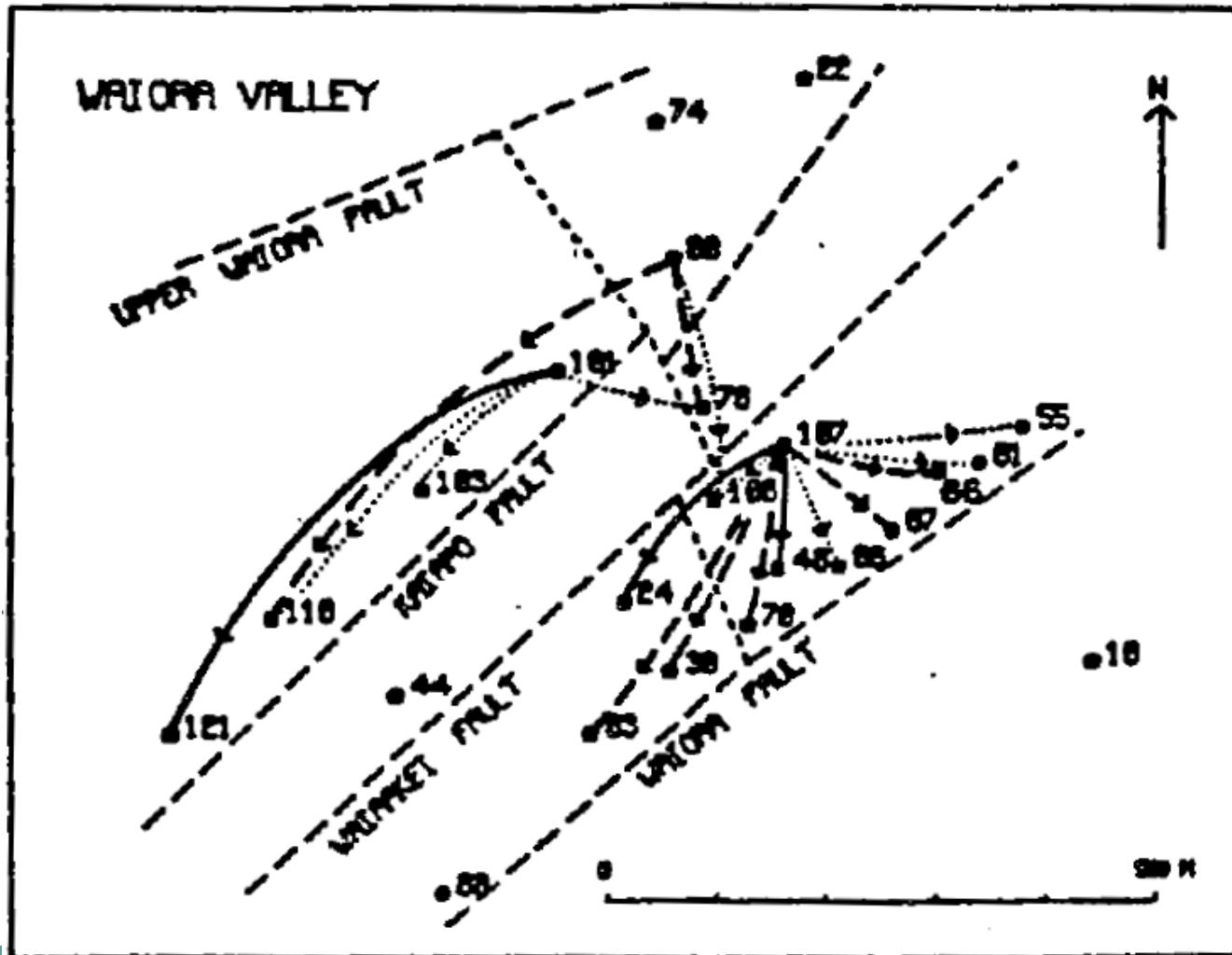
What do we want to know, and when?

- “Can they be assured that reinjection is viable? What are the injection well flow characteristics now, and how will they change with time? How will production well characteristics change (in detail) over the first 3-4 years of field operation?”
- These questions cannot be answered directly by modelling. However, well presented conceptual models can be used, together with the best available information to make reliable engineering decisions. Extra assurance can be built into a scheme by having a flexible design, so that, in the event of unforeseen changes, a fallback position is available without changing the overall scheme viability.”
 - (Bixley, SGW 1980)

A Subsurface Model



Another Subsurface Model



McCabe, Barry and Manning (1980)

Fractured vs. Porous Media

- Some behaviors of fractured media approximate those of porous media (e.g. material balance).
- Some do not (e.g. thermal breakthrough).
- At field scales (2-3 km) geothermal reservoirs often act as fractured media.
- Most reservoir models model porous media.



Reservoir Simulation

- Reasons to simulate:
 1. Generating potential of field?
 2. Appropriate well spacing?
 3. Decline rate of wells?
 4. Enthalpy and chemical changes with time?
 5. Effect of reinjection on well performance?
 6. Effect of reinjection of reservoir behavior?
 7. Location of reinjection wells?

1. Appropriate Well Spacing

- Based on estimates of storativity ϕh . Can be determined by interference testing.
- Also depends on recharge rate into reservoir.

2. Decline Rate

- Also depends on storativity and recharge.
- Mainly a function of well spacing and hence drainage volume.
- Can be measured in early well life.

3. Enthalpy/Chemical Changes

- Sensitive to recharge assumptions.
- Fracture behavior is probably important.

4. Reinjection

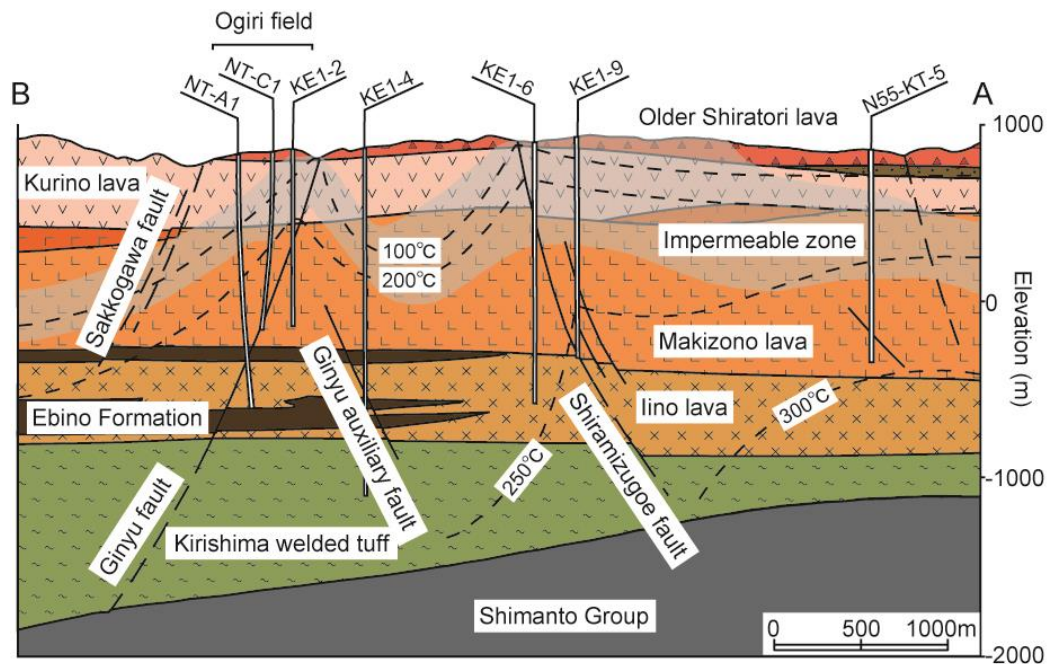
- Influence of fractures is major.
- Reinjection impacts are usually far more sudden than seen in large-block models.
- Location of injectors mainly a function of where specific fracture connections are.

Modeling Steps

1. Natural state modeling:
 - Reproducing the measured pressure, temperature and enthalpies prior to development.
2. History matching:
 - Matching the changes of pressure, temperature, enthalpy and chemistry during production.
3. Exploitation modeling:
 - Forecasting the future performance of the reservoir.

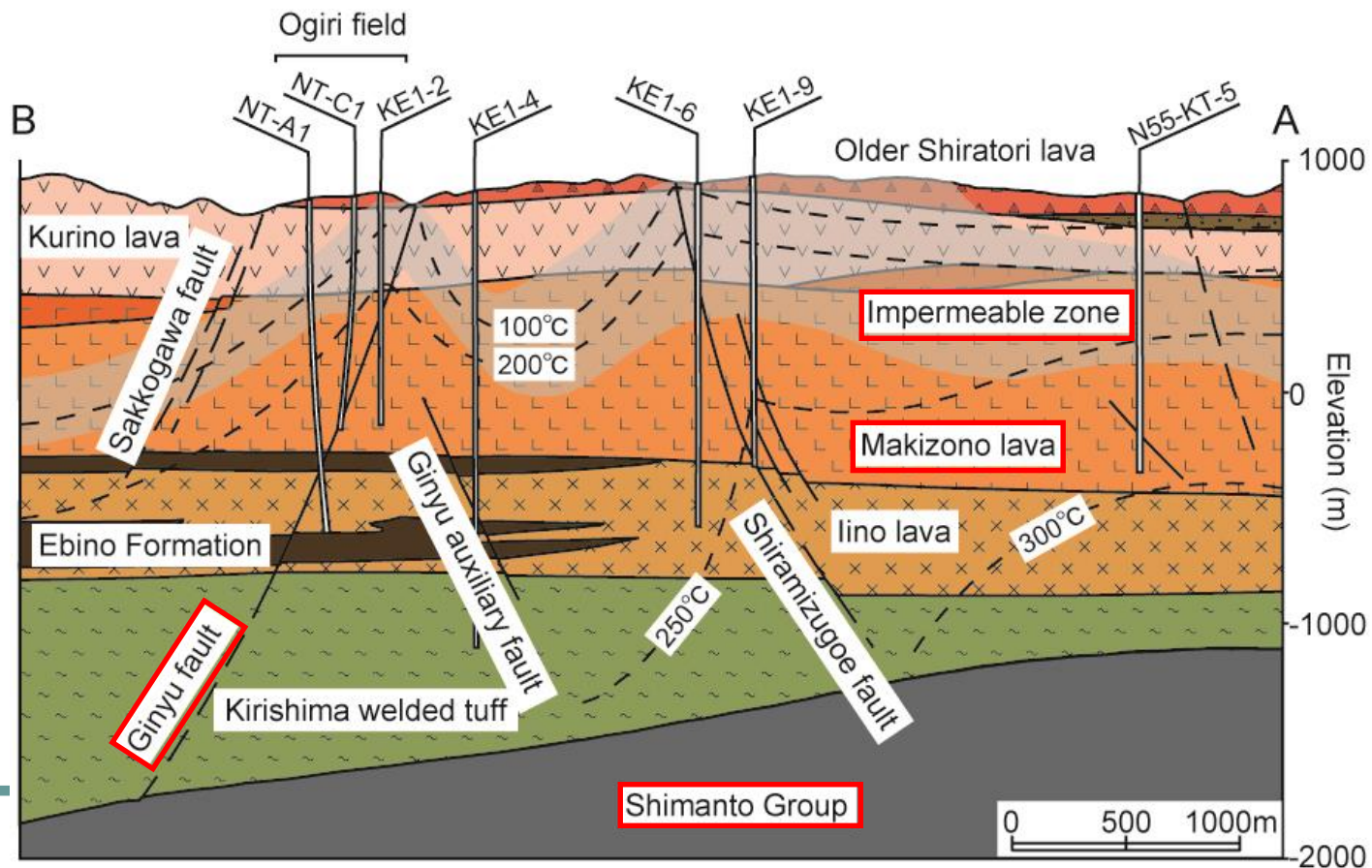
Natural State Modeling

- Example from Kumamoto, Y. Itoi, R. , Tanaka, T. and Hazama, Y., *SGW* 2008



Geological Cross Section

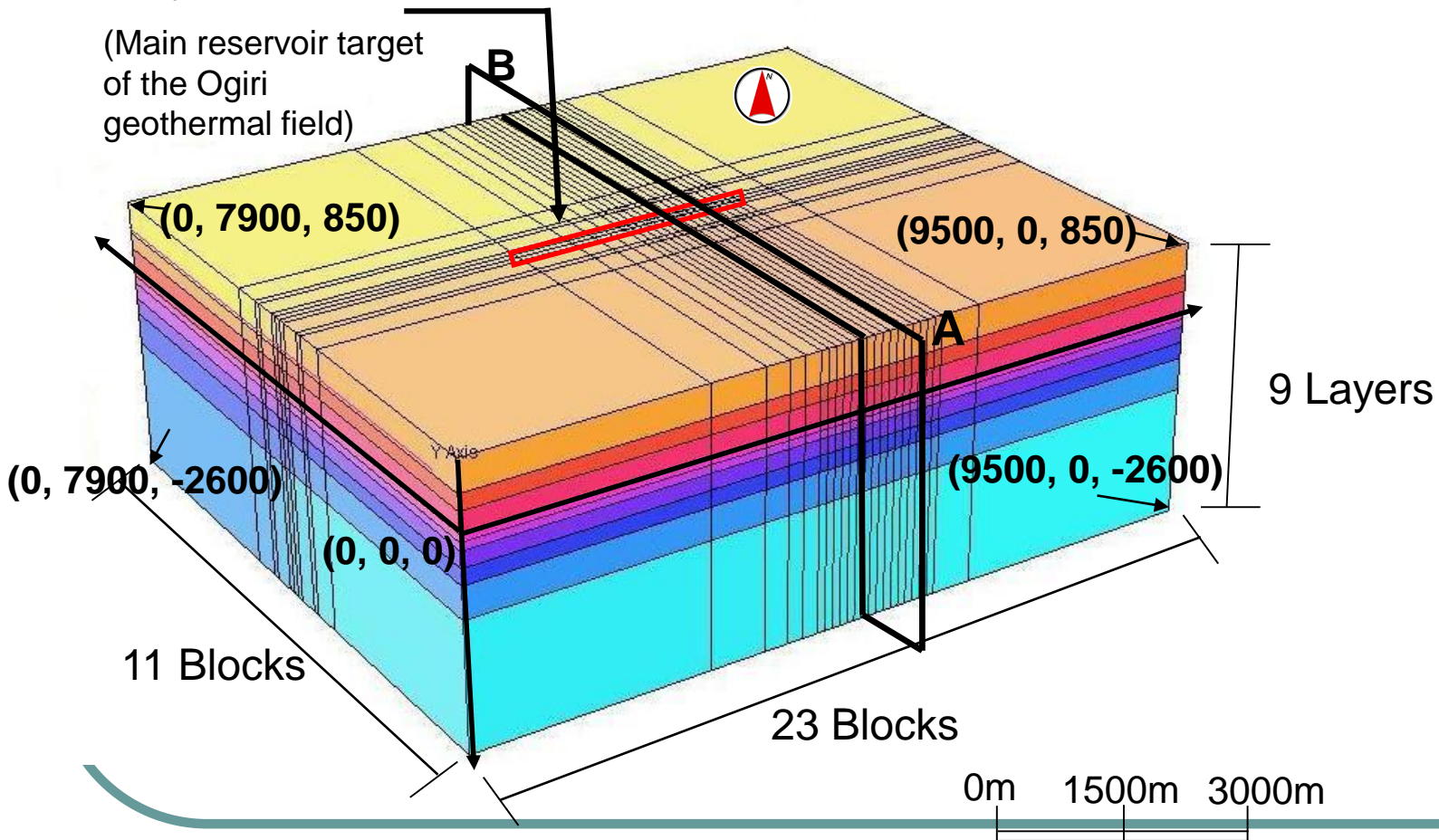
- The **Ginyu fault zone** has been the main reservoir targeted for development in Ogiri.
- Fractures in Makizono lava are cemented by mineral and that serves as cap rock.



Grid System of the Ogiri Geothermal Field

Ginyu fault

(Main reservoir target of the Ogiri geothermal field)



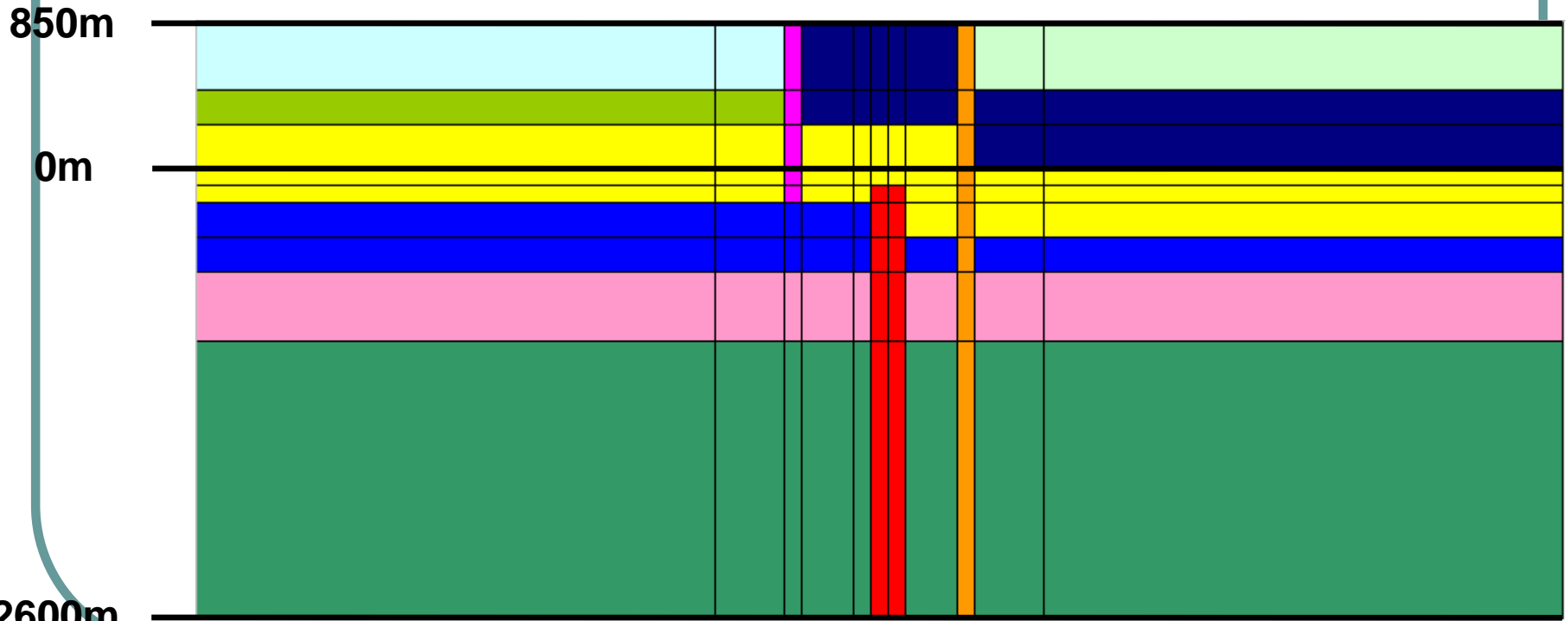
Vertical Slice of Grid System

※Other rock types : Ginyu fault (The injection area), NW1 fault

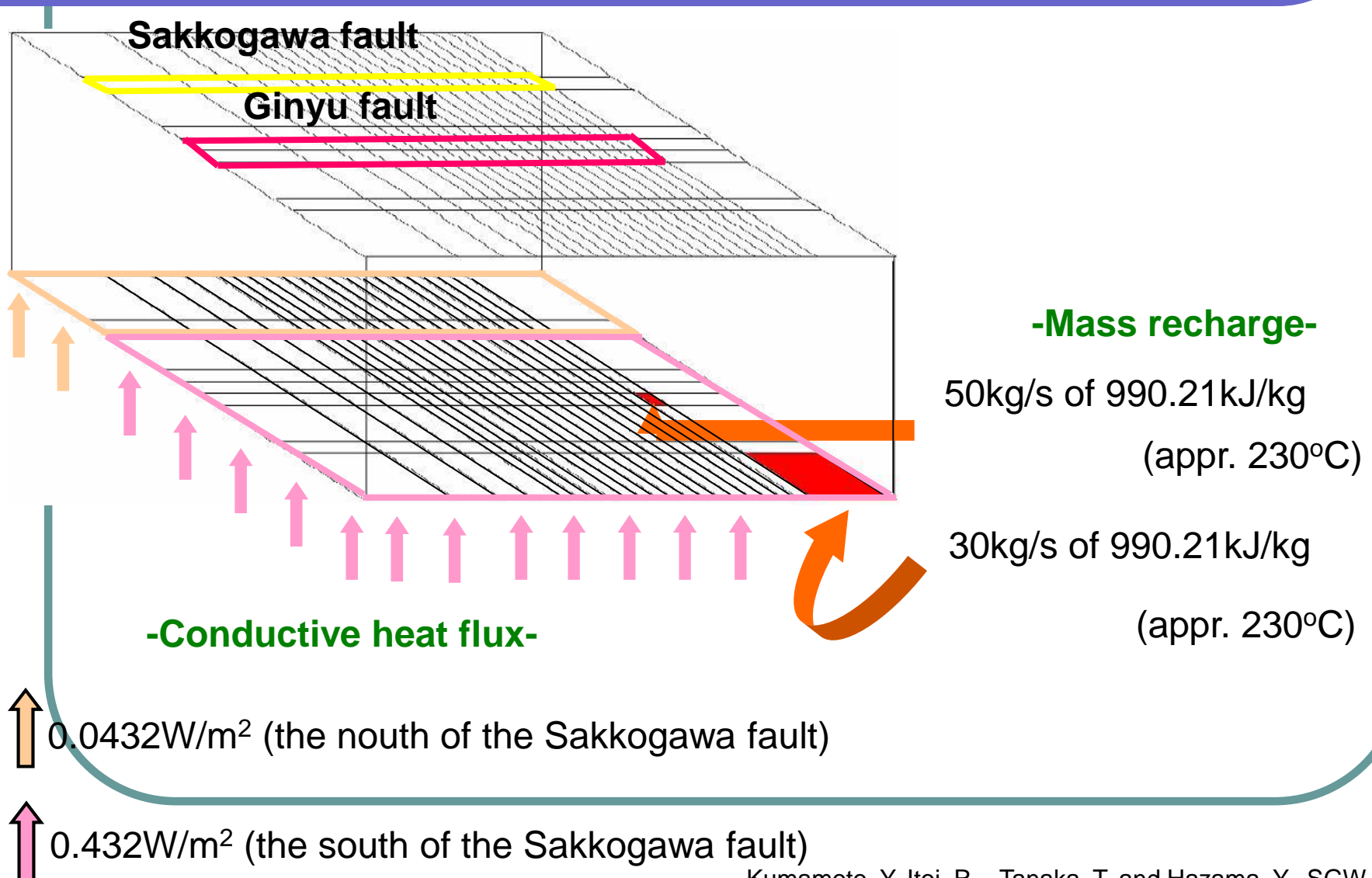
※ Warm color : High permeable zone, Cold color : Low permeable zone

B

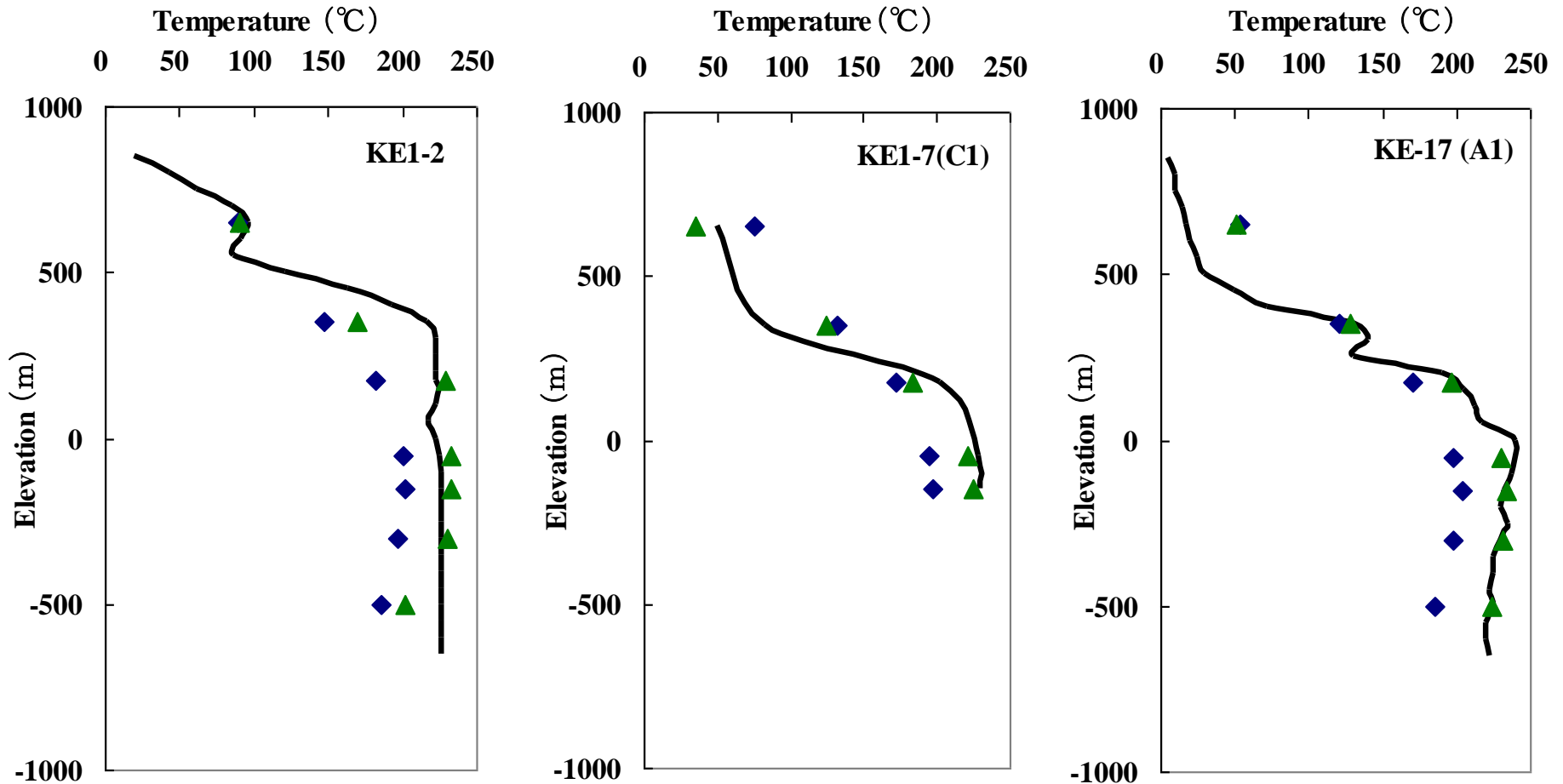
A



Recharge Conditions

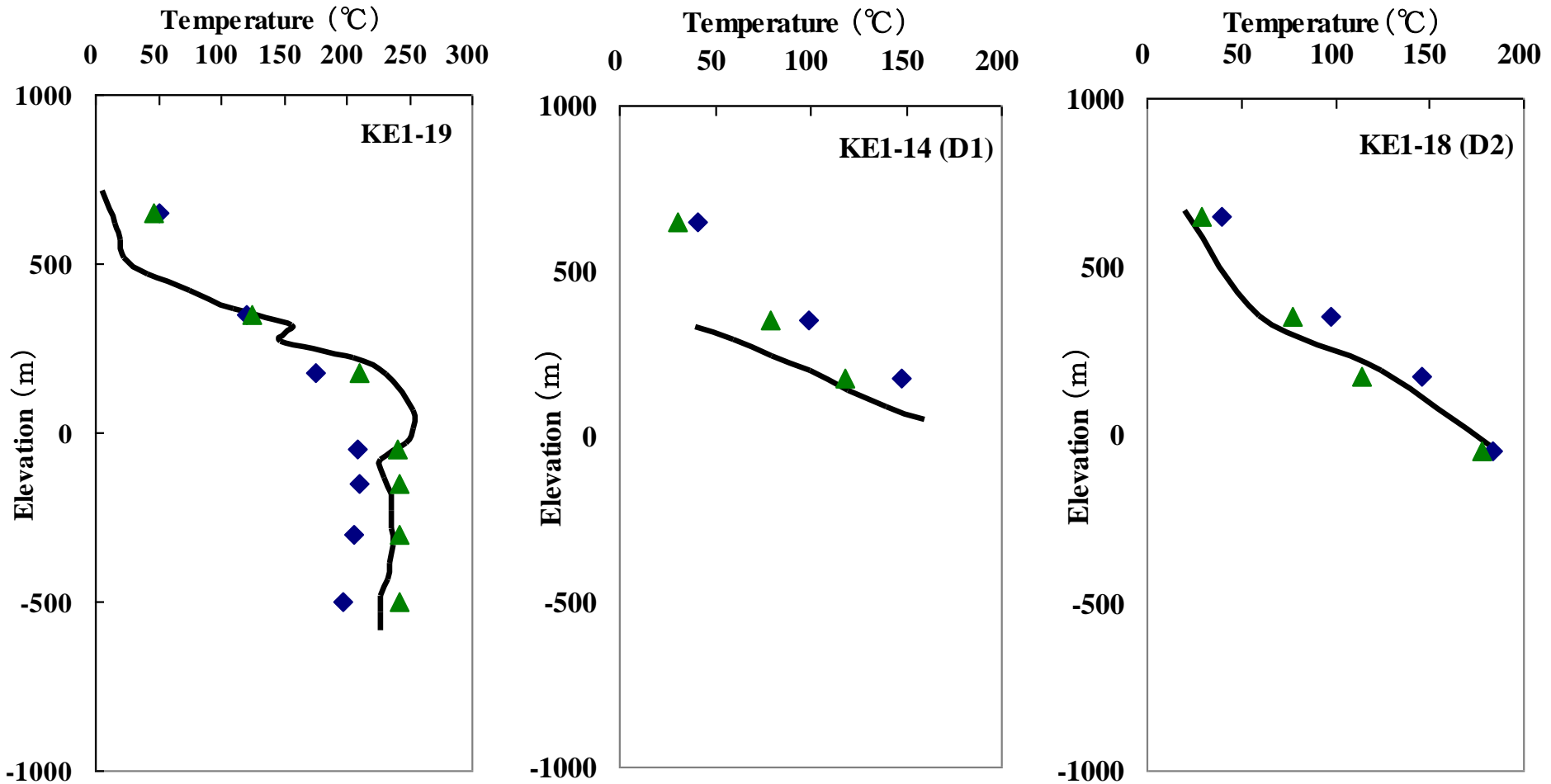


Comparison Between Measured and Computed Temperature Profiles (1)



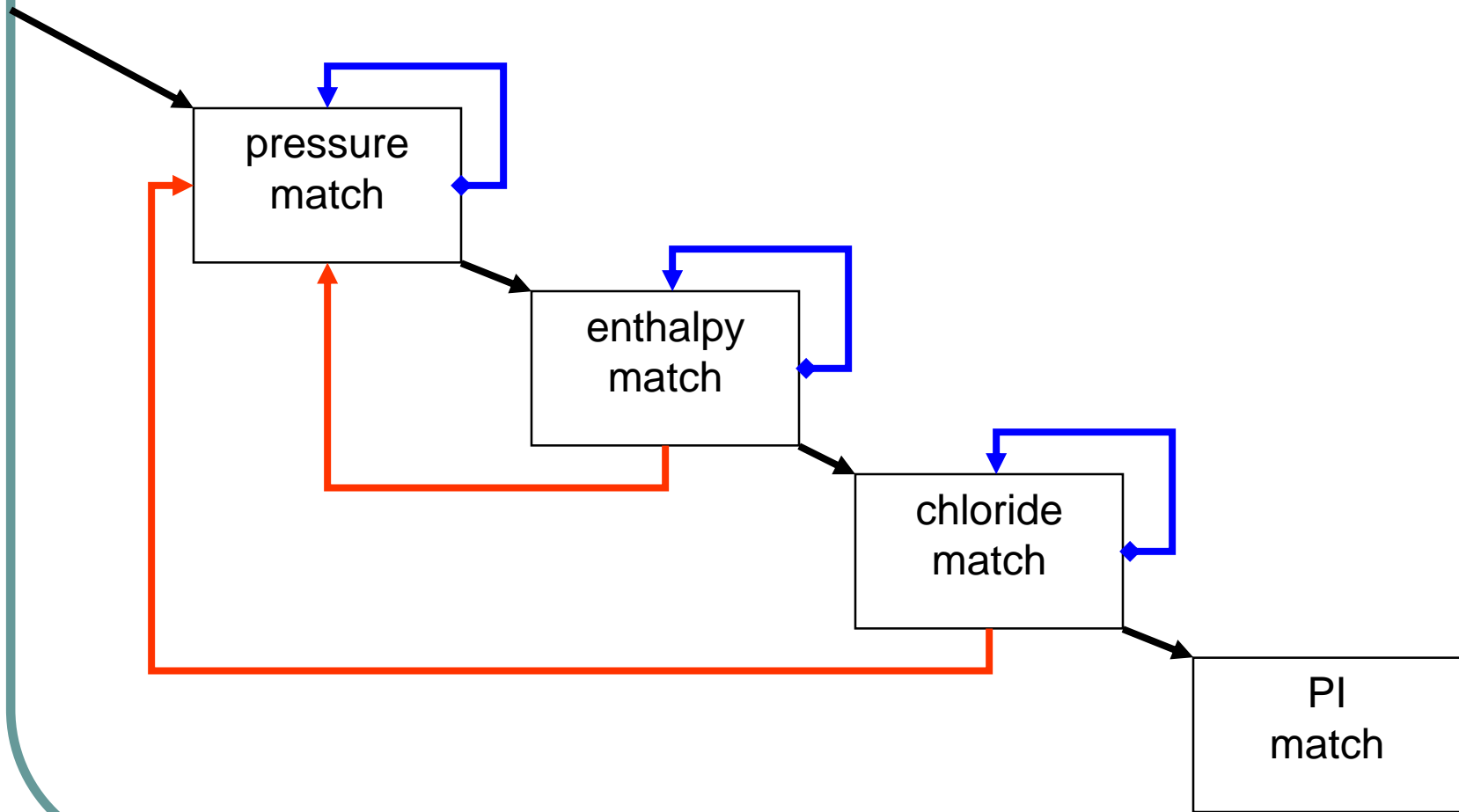
◆ Simulated with initial guess of parameters ▲ Simulated with the best model – Measured

Comparison Between Measured and Computed Temperature Profiles (2)



◆ Simulated with initial guess of parameters ▲ Simulated with the best model – Measured

History Matching



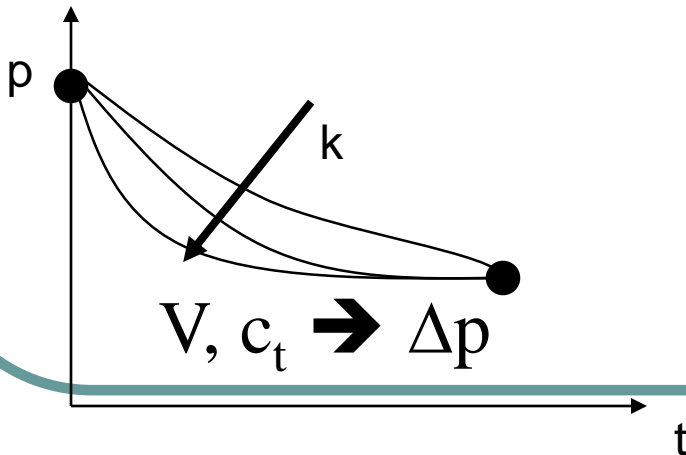
Pressure Match

1. Reservoir pressure level match.
2. Well pressure level match.
3. Well pressure history shape match.

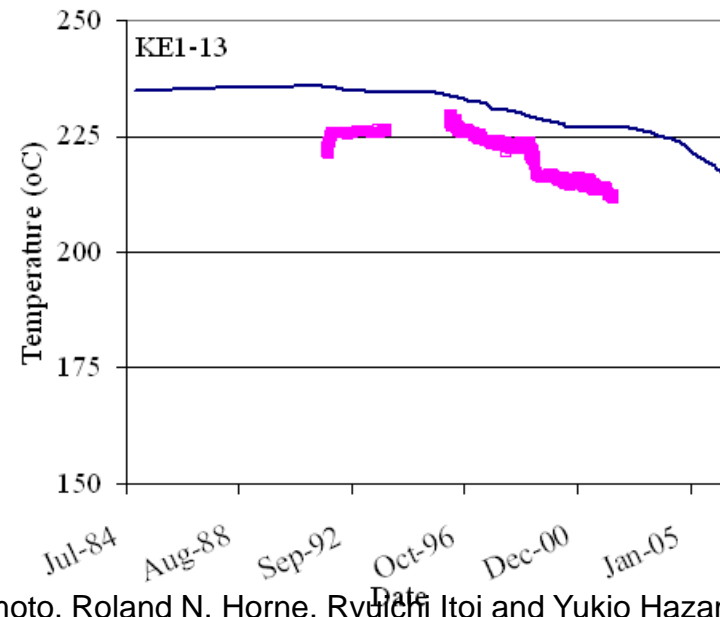
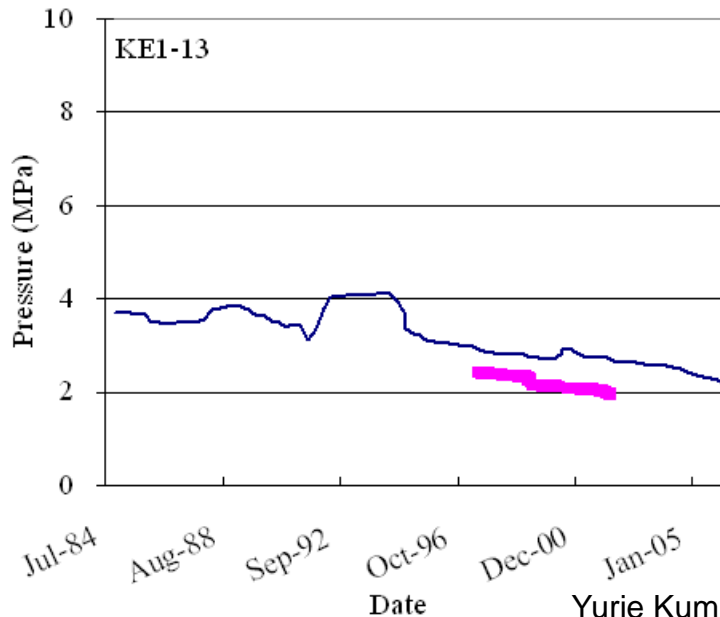
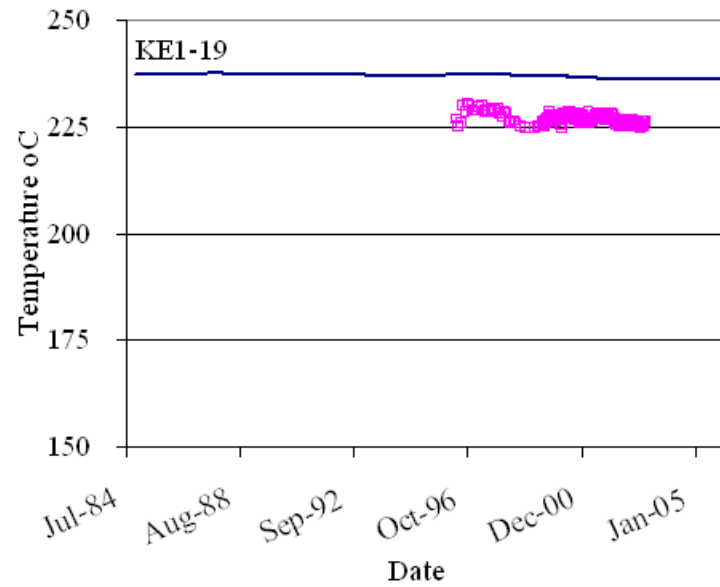
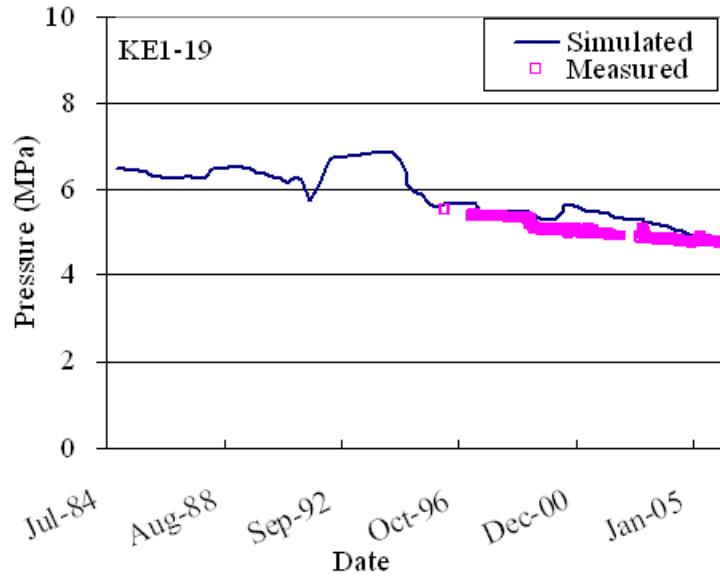
$$c_t = - \frac{1}{V} \frac{dV}{dp}$$

$$\Delta p = - \frac{\Delta V}{V c_t}$$

$$\Delta p = - \frac{q \Delta t}{V c_t}$$



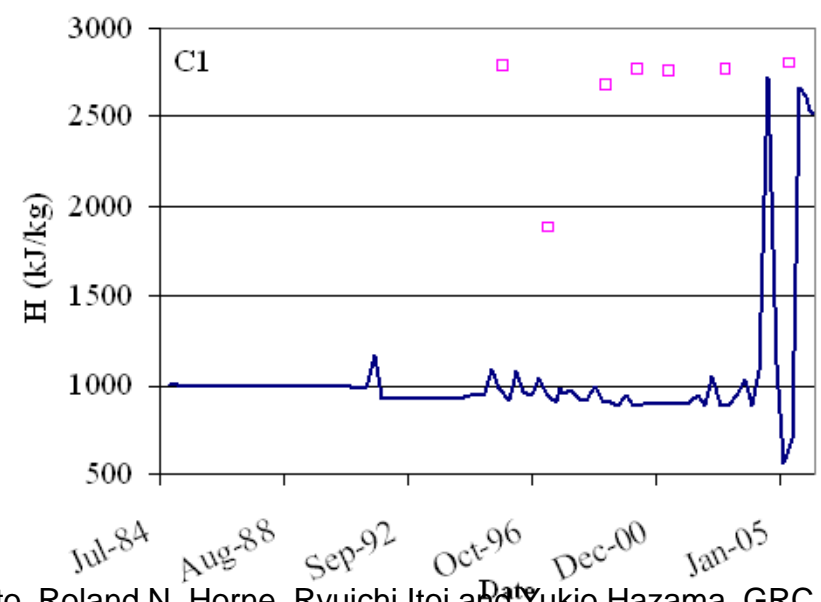
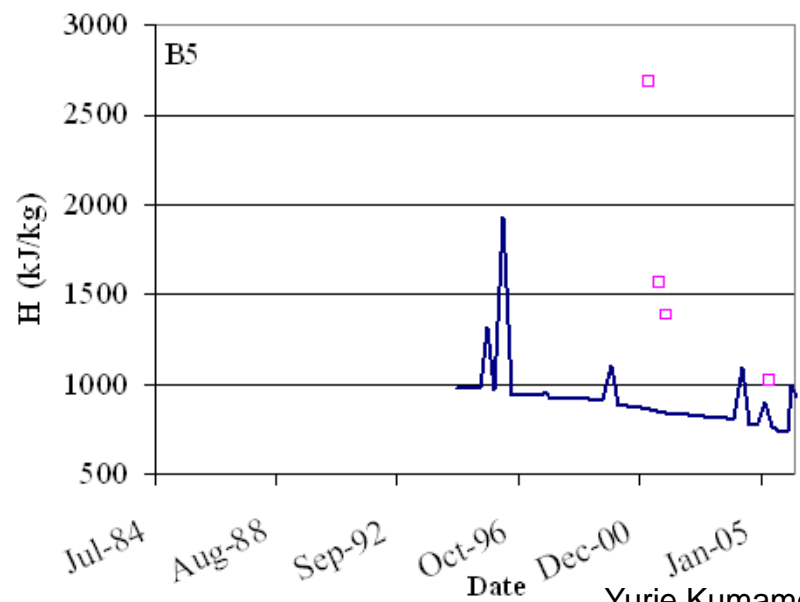
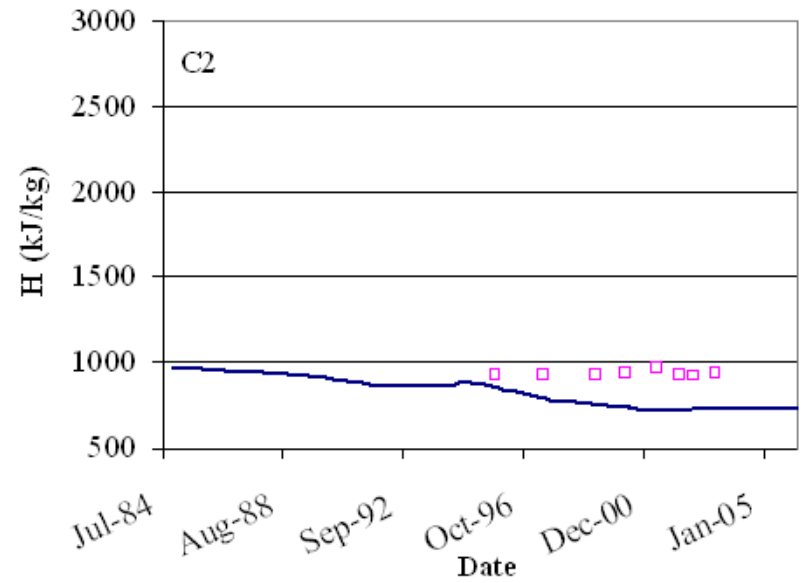
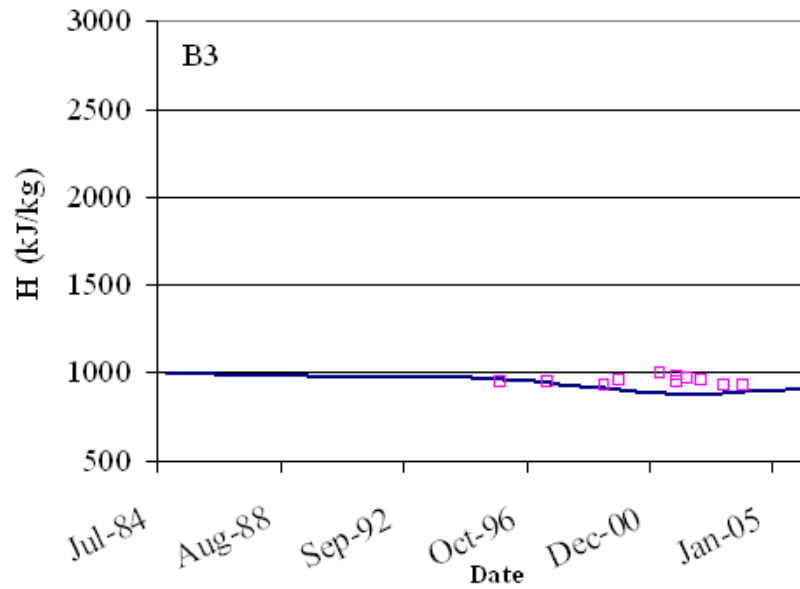
Pressure Match



Enthalpy Match

1. Match *in-place* enthalpy, not *flowing* enthalpy.
2. Function of:
 - a) Recharge
 - b) Permeability
 - c) Relative permeability

Enthalpy Match

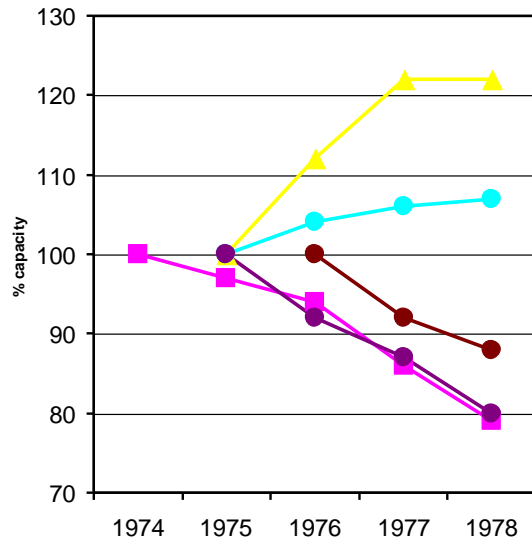


Exploitation Modeling

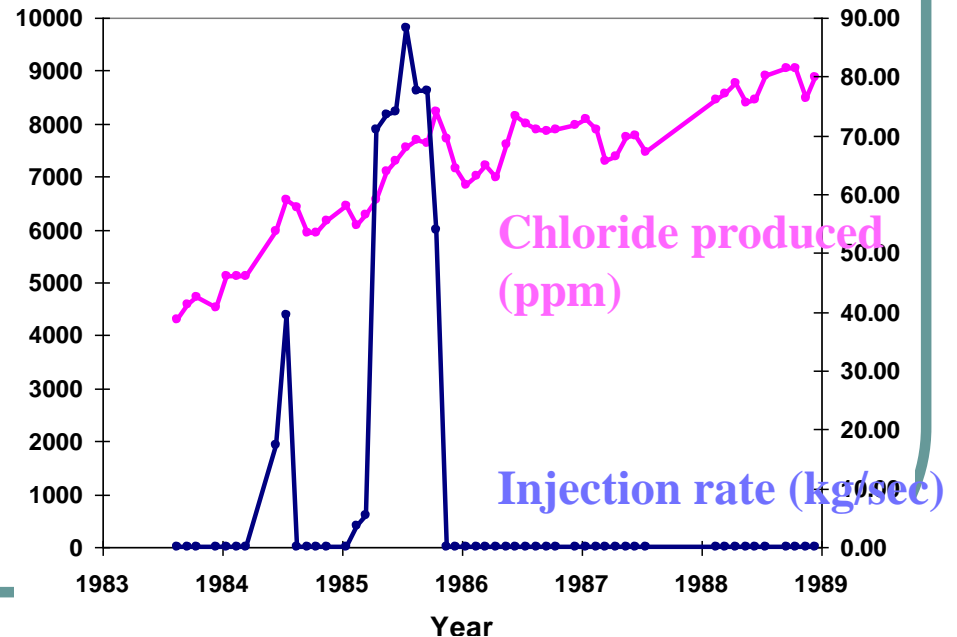
- In general, a future forecast cannot be expected to be reliable for a period longer than the duration of the history used to match the model.
- Updating the reservoir simulation model is a continuous process during the operating life of the reservoir.
- Most projects use a staged development approach because of the difficulty in forecasting the future performance of the reservoir.

Injection into Fractured Media

- Injection returns into production wells are a major concern for geothermal operators.
- Likelihood of thermal breakthrough may be inferred from analyzing injection returns.



Sullera & Horne (1999)

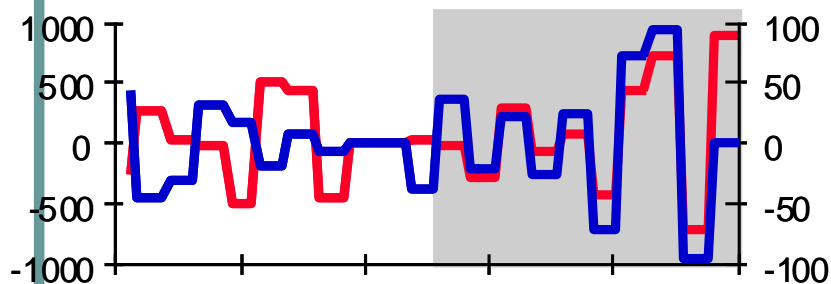


Fractured Reservoir Model

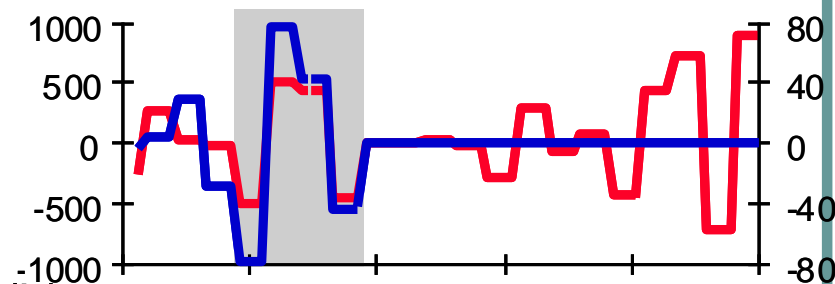
- Infer well-to-well connectivity from “tracer” returns, using historical geochemical monitoring data.

Wavelet Analysis – OK-7 CI

PN-6RD

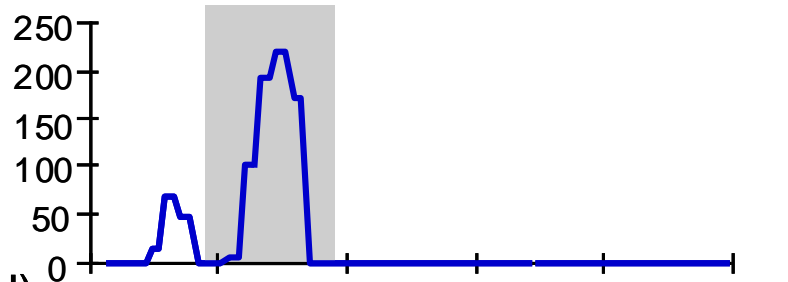
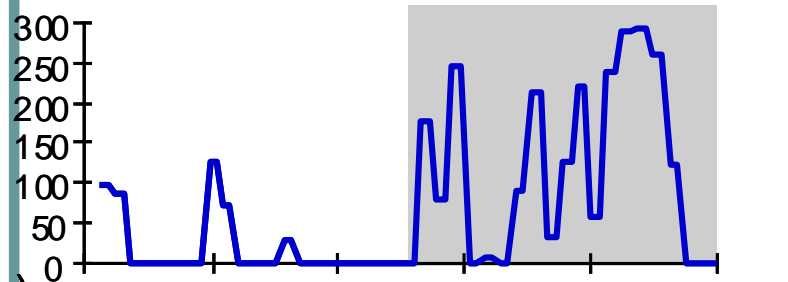


PN-9RD



(a) Jul-83 Nov-84 Mar-86 Aug-87 Dec-88 May-90

(b) Jul-83 Nov-84 Mar-86 Aug-87 Dec-88 May-90



(c) Jul-83 Nov-84 Mar-86 Aug-87 Dec-88 May-90

(d) Jul-83 Nov-84 Mar-86 Aug-87 Dec-88 May-90

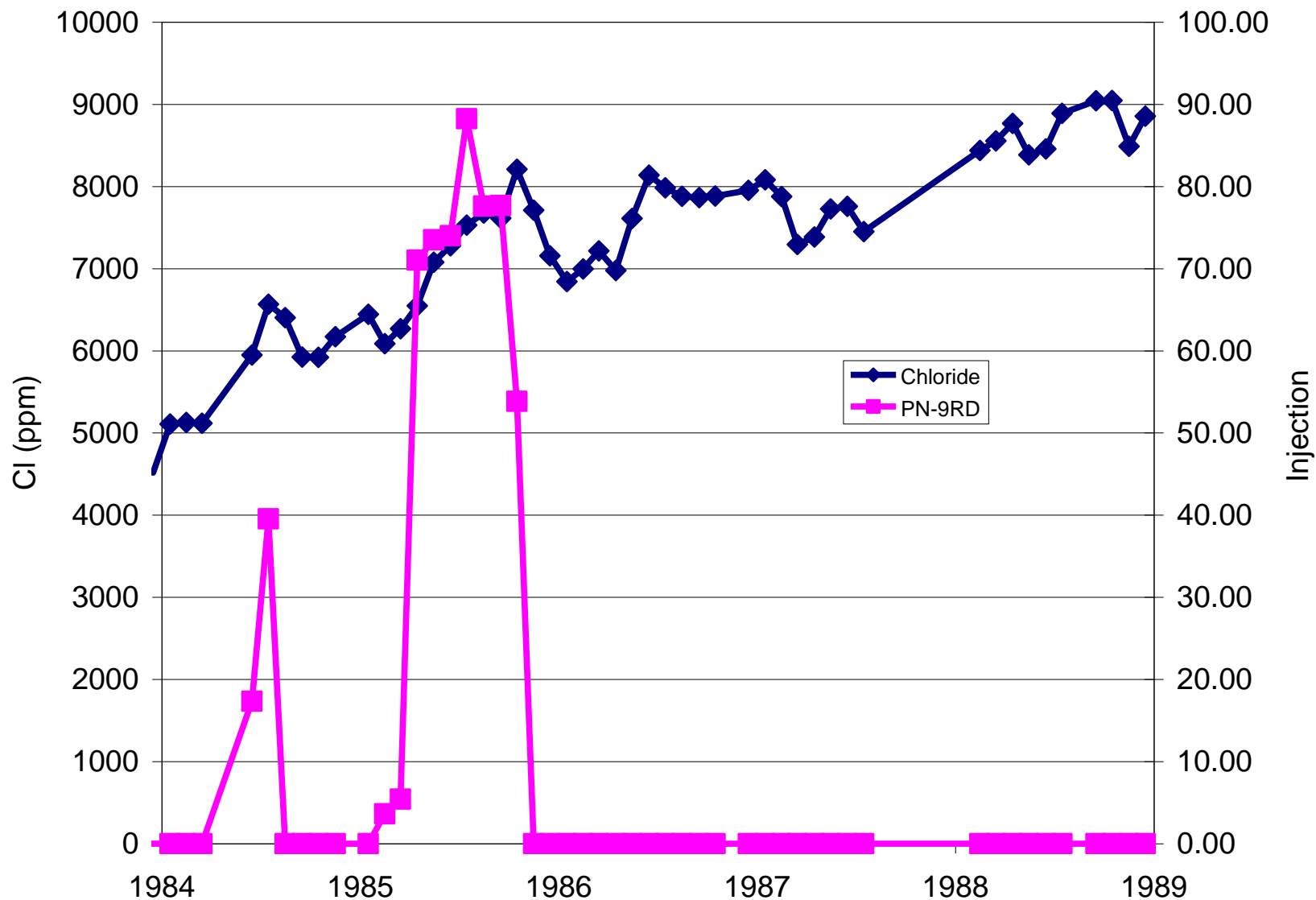
Nonparametric Regression

- The fundamental idea of nonparametric regression is to match the data without making assumptions about the underlying form of the model.
- In fact, a major advantage of the approach is that the nature of the model is revealed in the process.
- The magnitude of the connectivities can also be estimated, and these values are then useful for reinjection analysis and design.

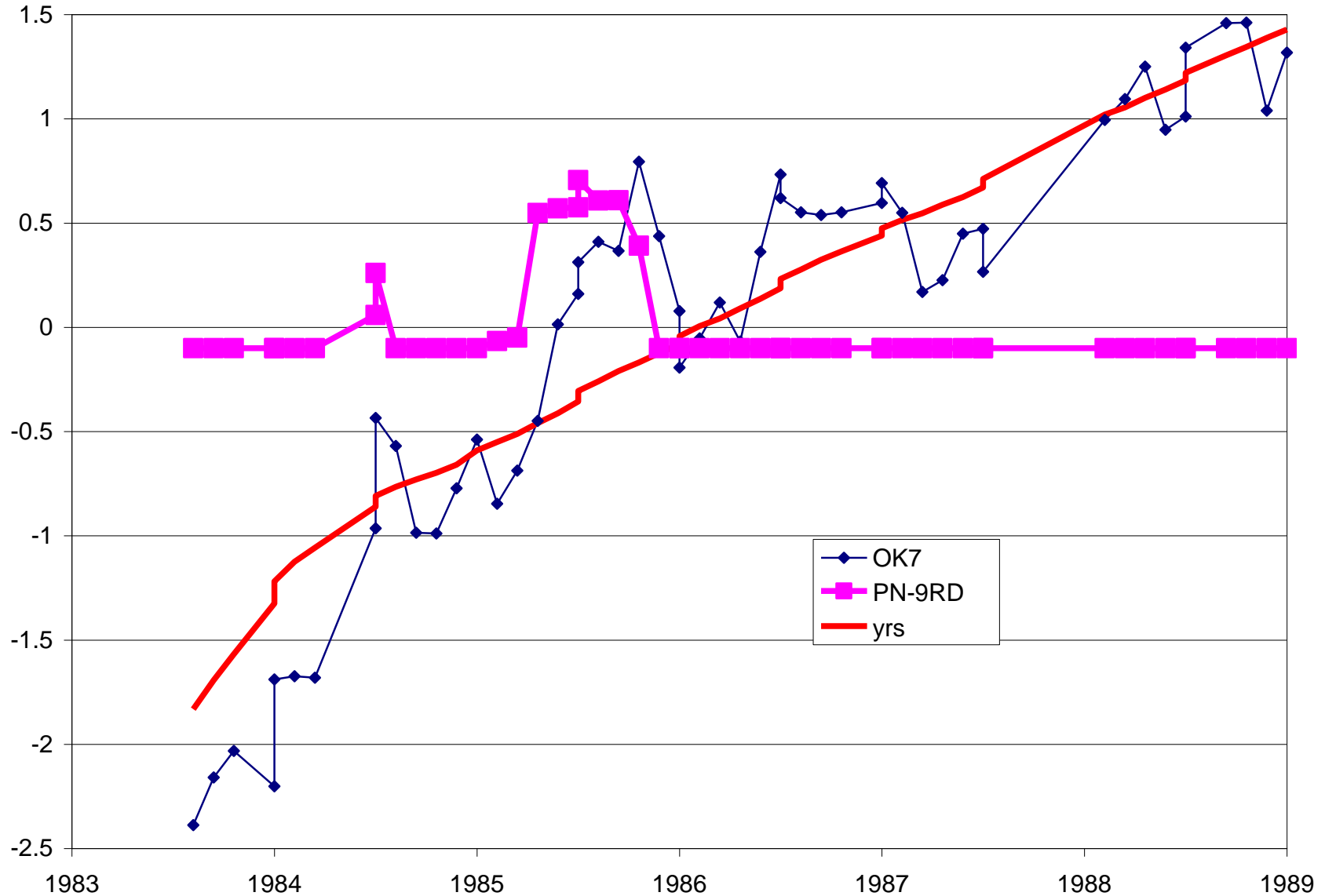
Palinpinon

- Prior to requiring full grid demand, the plant operated for some years at partial load.
- Injection and production wells were operated intermittently.
- The historical data are rich in “on-off” events.

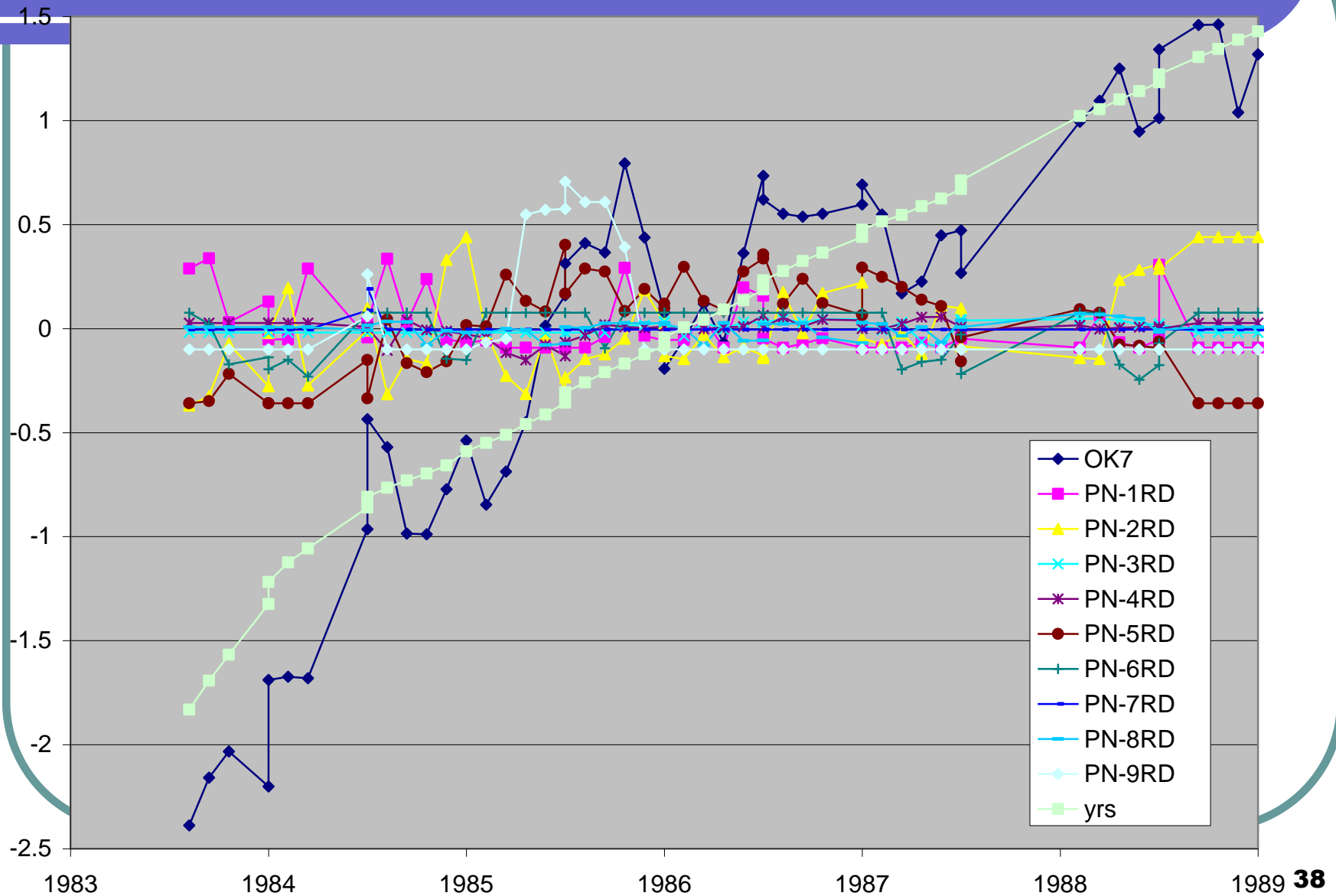
Data: OK-7 from PN-9RD



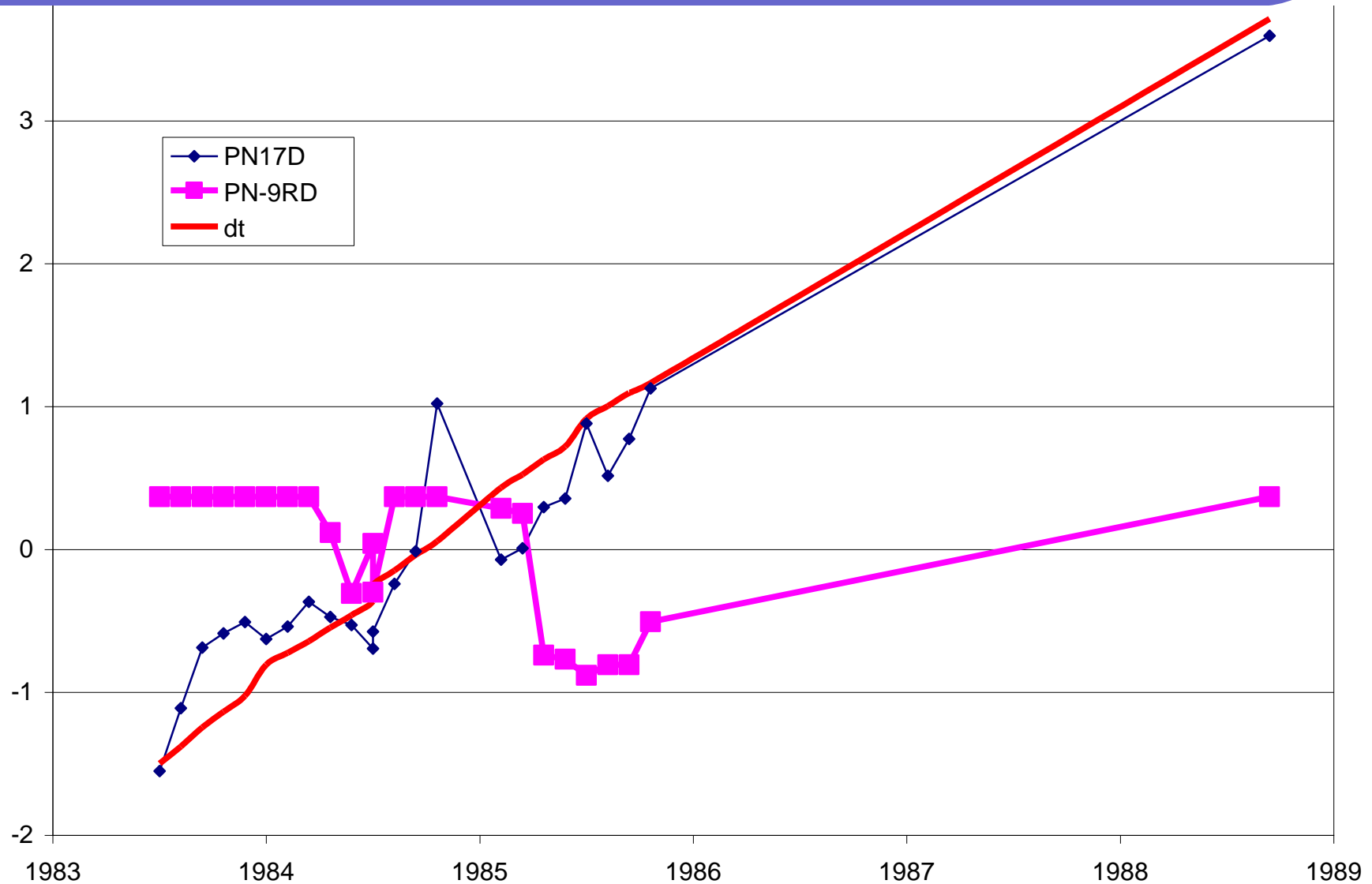
Results: OK-7 from PN-9RD



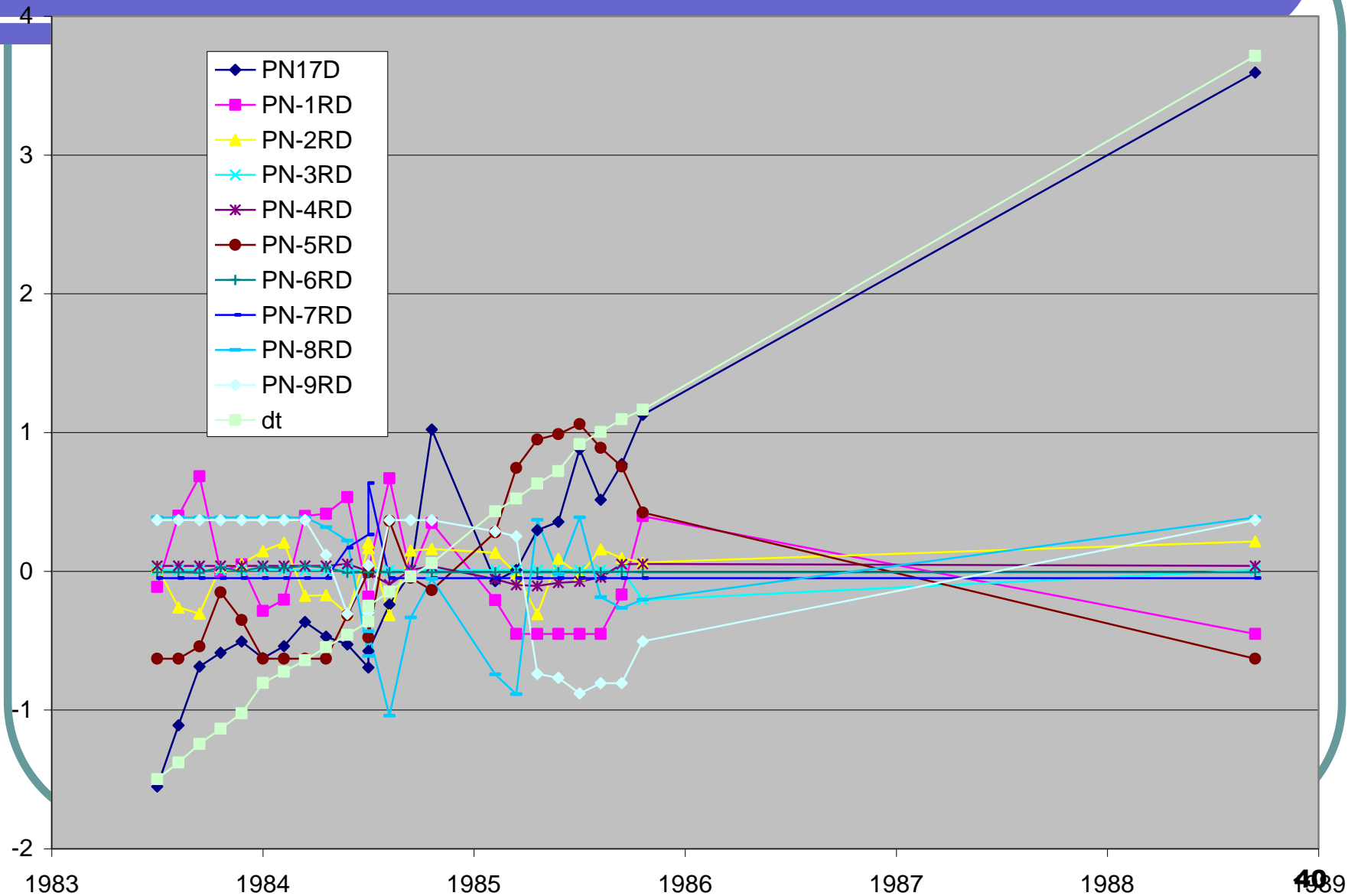
Results: OK-7 all



Results: PN-17D from PN-9RD



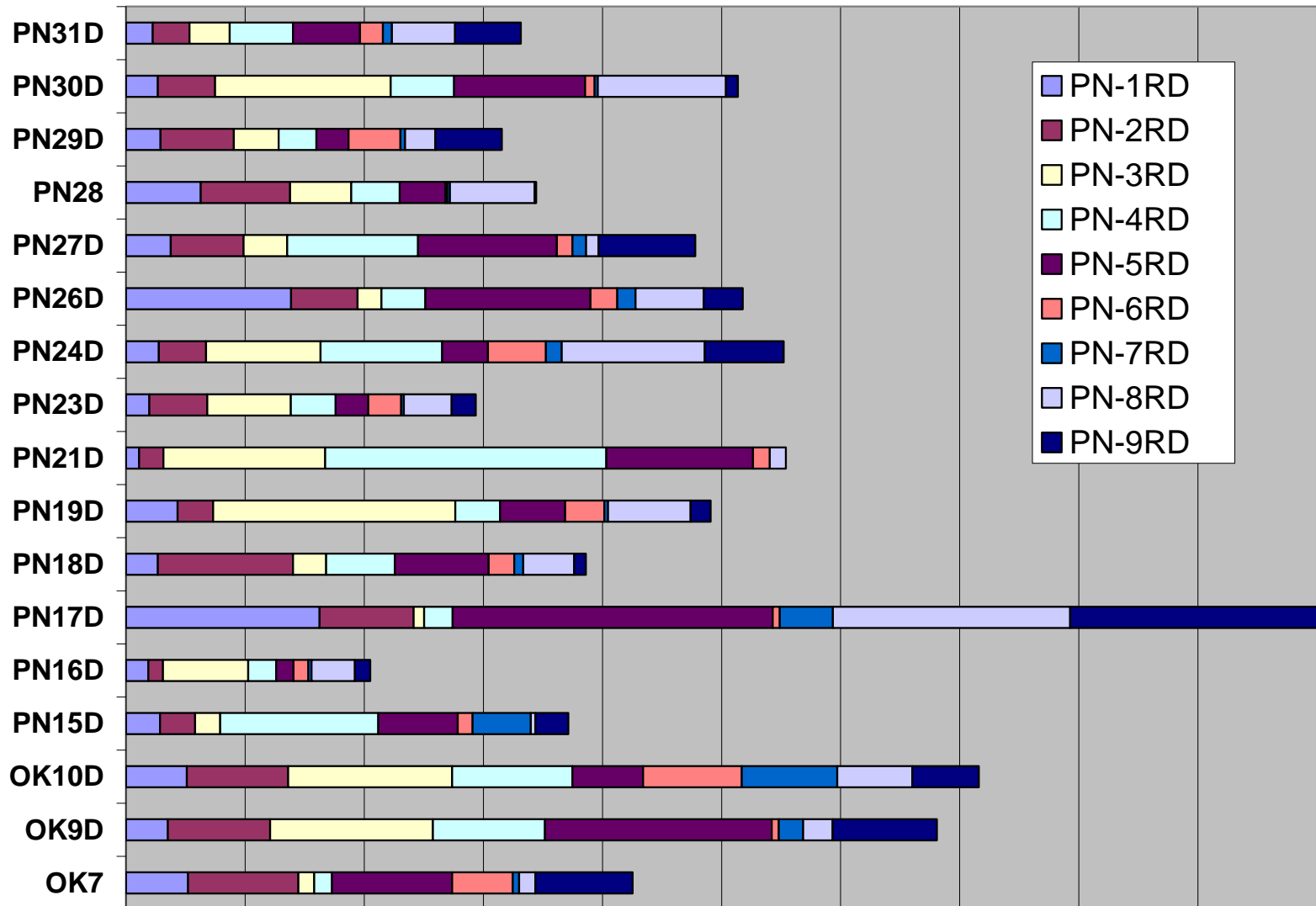
Results: PN-17D all



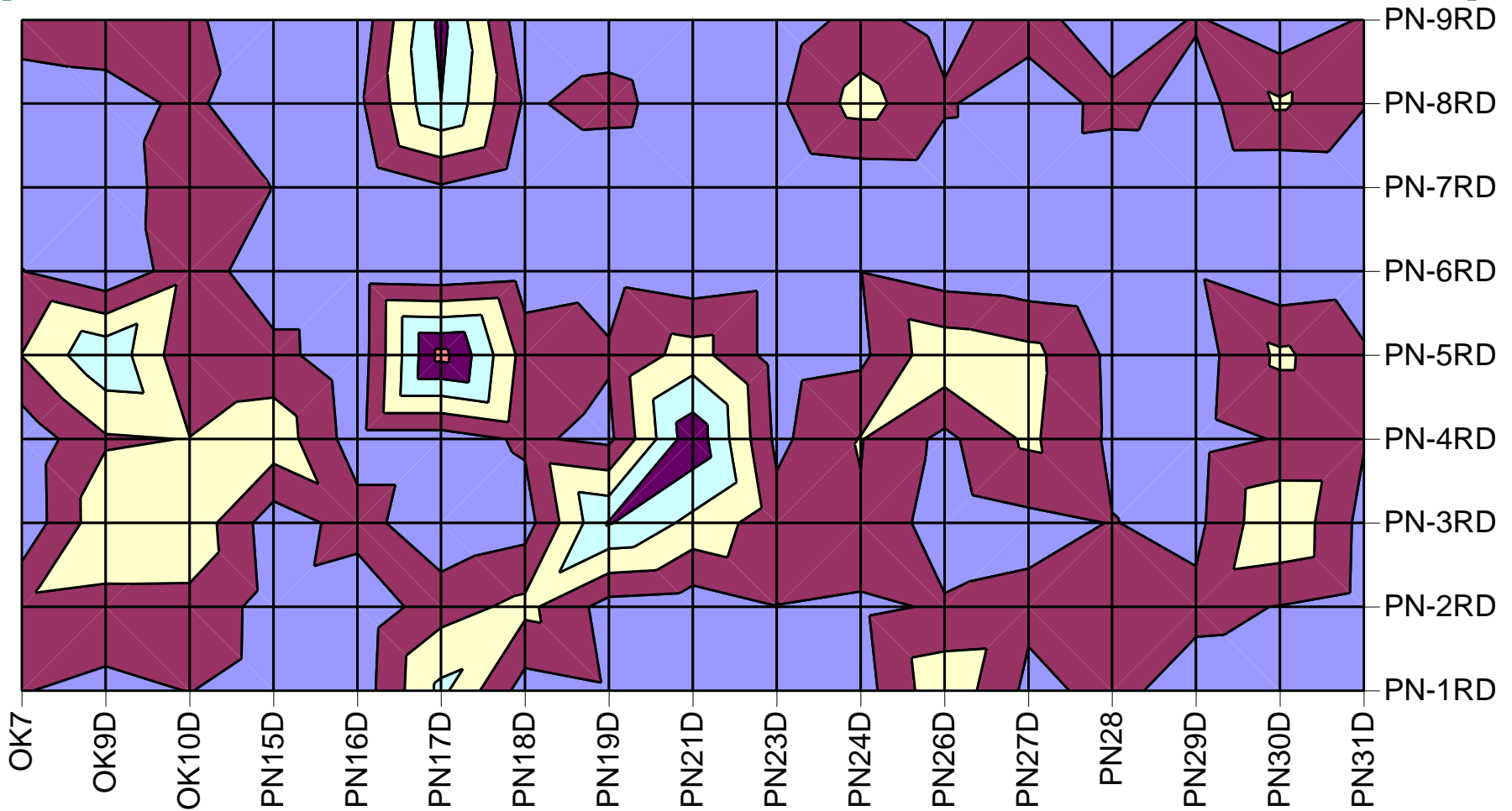
Collated Results

	<i>PN-1RD</i>	<i>PN-2RD</i>	<i>PN-3RD</i>	<i>PN-4RD</i>	<i>PN-5RD</i>	<i>PN-6RD</i>	<i>PN-7RD</i>	<i>PN-8RD</i>	<i>PN-9RD</i>	<i>dt</i>
OK7	0.10	0.19	0.03	0.03	0.20	0.10	0.01	0.03	0.16	0.69
OK9D	0.07	0.17	0.27	0.19	0.38	0.01	0.04	0.05	0.17	0.74
OK10D	0.10	0.17	0.28	0.20	0.12	0.17	0.16	0.13	0.11	0.56
PN15D	0.06	0.06	0.04	0.27	0.13	0.03	0.10	0.01	0.06	0.93
PN16D	0.04	0.02	0.14	0.05	0.03	0.03	0.01	0.07	0.03	0.84
PN17D	0.33	0.16	0.02	0.05	0.54	0.01	0.09	0.40	0.43	0.85
PN18D	0.05	0.23	0.06	0.12	0.16	0.04	0.02	0.09	0.02	0.69
PN19D	0.09	0.06	0.41	0.08	0.11	0.07	0.01	0.14	0.03	0.88
PN21D	0.02	0.04	0.27	0.47	0.25	0.03	0.00	0.03	0.00	0.88
PN23D	0.04	0.10	0.14	0.08	0.05	0.06	0.00	0.08	0.04	0.78
PN24D	0.06	0.08	0.19	0.20	0.08	0.10	0.03	0.24	0.13	0.79
PN26D	0.28	0.11	0.04	0.07	0.28	0.05	0.03	0.11	0.07	0.76
PN27D	0.08	0.12	0.07	0.22	0.23	0.03	0.02	0.02	0.16	0.88
PN28	0.13	0.15	0.10	0.08	0.08	0.00	0.00	0.14	0.00	0.74
PN29D	0.06	0.12	0.08	0.06	0.05	0.09	0.01	0.05	0.11	0.76
PN30D	0.05	0.10	0.29	0.11	0.22	0.02	0.01	0.22	0.02	0.57
PN31D	0.05	0.06	0.07	0.11	0.11	0.04	0.02	0.11	0.11	0.84

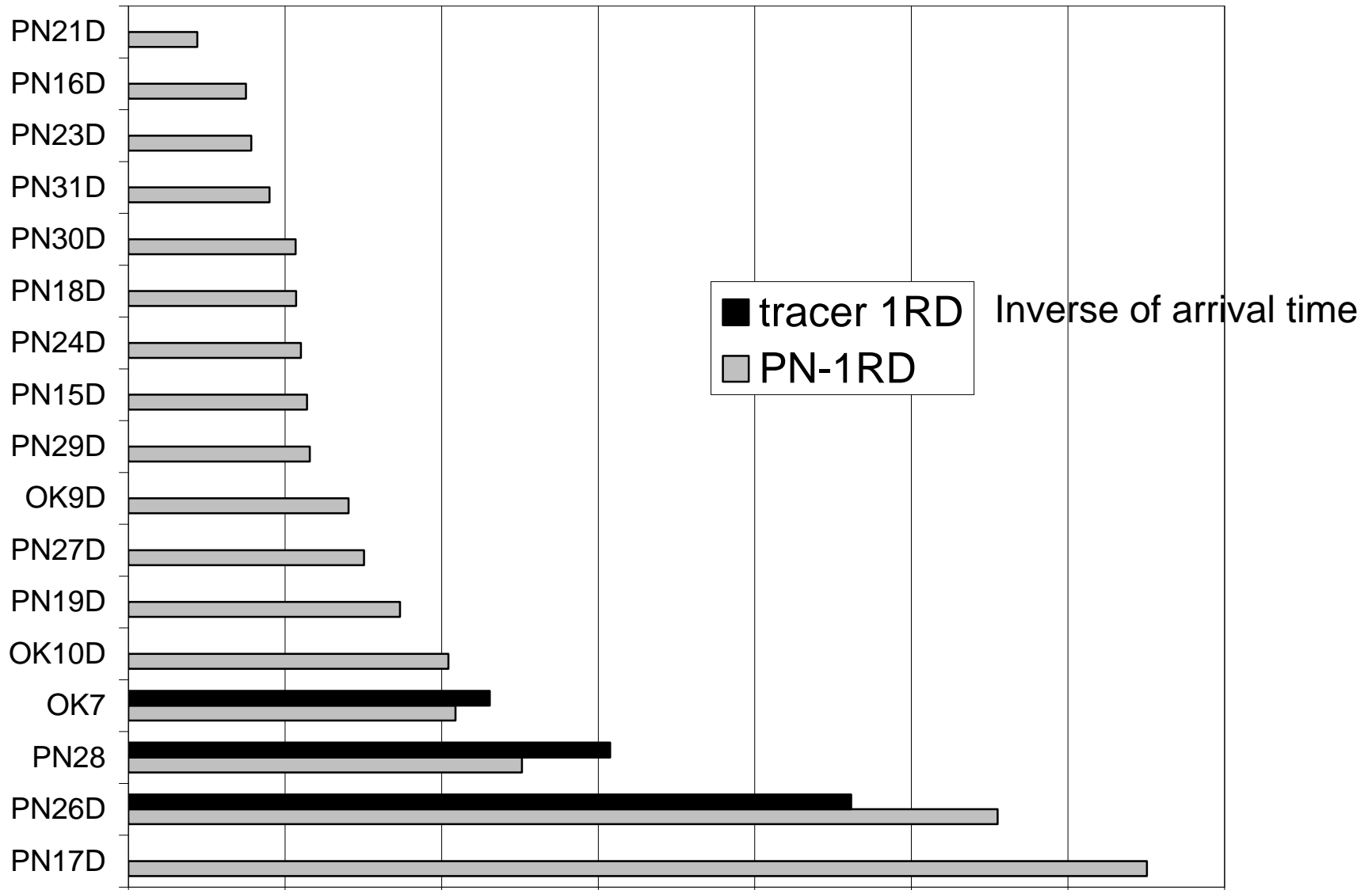
Collated Results



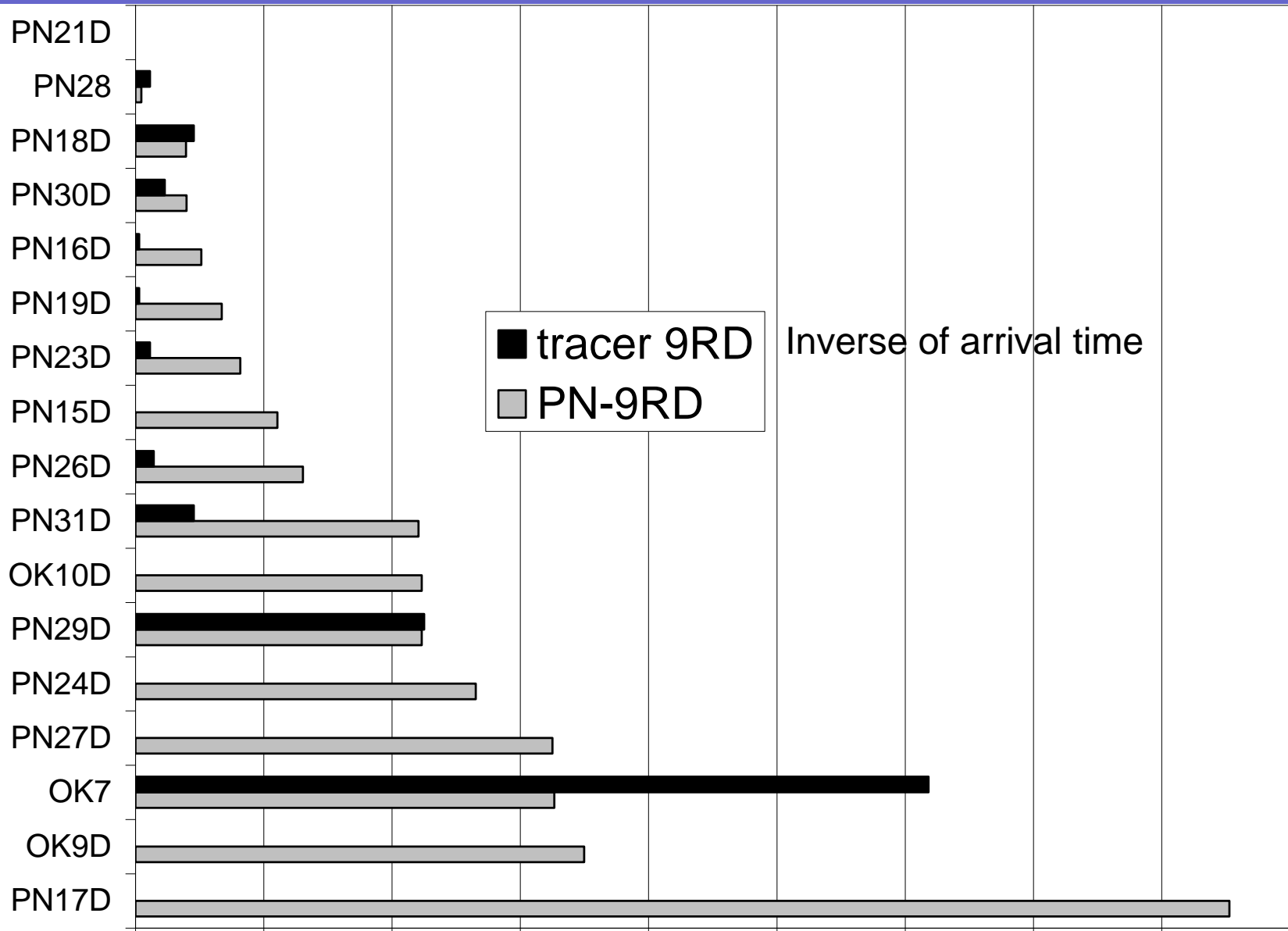
Collated Results



Comparison to Tracer Test (PN-1RD)



Comparison to Tracer Test (PN-9RD)



Nonparametric Modeling

- ACE is a useful method of 'data mining' to extract relationships from historical data.
- There is no assumption as to the underlying model.
- The well-to-well dependencies are estimated.
- Values are consistent with tracer tests.

Conclusion

- The data are the model.

Thank You

Scientific Investigation

- Nobody believes a modeling study – except the modeler.
- Everybody believes an experimental study – except the experimenter.