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## DR. CHRISTOPHER W. KLEIN

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### **PRESENT POSITION**

Senior Geochemist with GeothermEx since 1975

### **EXPERTISE**

- Fluids (liquid, gas) and solids geochemistry of geothermal and volcanic regions
- Isotope geochemistry
- Well testing and fluids sampling; exploration fluids sampling (springs, wells, fumaroles)
- Reservoir tracer test program design, execution and data evaluation.
- Design, procurement, management and training for field sampling programs and field analysis laboratories
- Applications of chemical geothermometry
- Mixing models
- Thermodynamic and kinetic modeling of fluids behavior
- Hydrogeologic and conceptual modeling of geothermal reservoirs and surroundings, to support exploration, well siting, reserves evaluations and numerical reservoir simulations
- Scale and corrosion prediction and control
- Non-condensable gas prediction and mitigation
- Geochemical effects of reservoir processes
- Petrography and hydrothermal mineralization
- Environmental chemistry / geothermal outflow zone sampling, analyses, reporting and monitoring
- Computer database design and development (MS-Access) and graphics for geochemical data management
- Geochemistry short course curricula and instruction

### **EDUCATION**

Ph.D. in Geology, Harvard University, 1975

B.A. in Chemistry, University of California, 1966

Speaks, reads and writes Spanish

### **EXPERIENCE**

*Peace Corps (Chile) during 1966 – 1969.*

## ***Minerals exploration and structural geology studies during 1969 - 1975.***

### ***Senior Geologist and Geochemist at GeothermEx, Inc. since 1975.***

Responsibilities at GeothermEx include: management and execution of exploration and well test fluids sampling programs; design, purchasing and management of field laboratories; training of sampling and field analysis personnel; computerized thermodynamic and kinetic modeling of fluids behavior; design and evaluation of scale and corrosion controls; interpretation and evaluation of chemical, geological, well logging, well test and reservoir engineering data from geothermal fields around the world.

On-the-ground geothermal exploration, fluids sampling and well-testing in: Mexico, Chile, Guatemala, El Salvador, Honduras, Nevis WI, Nicaragua, Costa Rica, Panama, Argentina, Iran (for the former Imperial Government), Indonesia, The Philippines, Papua New Guinea, Portugal (Azores), Japan, Yugoslavia and western U.S.A..

Major projects have included:

- Fluids sampling and design and implementation of a comprehensive integrated relational database (MS-Access) of geothermal resources in Peru, 2010.
- Management of reservoir performance monitoring and specific task of chemical monitoring, Germencik Geothermal Project, Turkey, for major international bank, 2007 - 2010.
- Reviews of geothermal data, modeling and project management at Lihir Gold Mine, Papua New Guinea, 2008 and 2010.
- Review and interpretation of data from geothermal exploration in Ecuador, 2010.
- Design and implementation of a comprehensive integrated relational database (MS-Access) of geothermal resources in Chile, 2009.
- Fluids chemistry and collaboration with conceptual modeling and exploration planning for a hot springs complex in the northern California Coast Ranges, 2009.
- Evaluation of several dozen geothermal project concessions in Western Anatolia, Turkey, for two international clients, 2009.
- Conceptual modeling, resource evaluation and reserves estimation, three geothermal resource areas in Sumatra, Indonesia, 2008 - 2009.
- Characterization and evaluation of non-condensable gases, stable isotopes and returns to production of injection-derived steam at the steam field of Northern California Power Agency, The Geysers, California, 2009.
- Fluids sampling, geochemical and conceptual modeling, reserves evaluation, exploration program evaluation and resource due-diligence for investment, at the geothermal resource on Nevis, West Indies, for Organization of American States, 2005 and private client, 2008 - 2009.

- Conceptual modeling, fluids chemistry studies, resource evaluations, reserves estimations and exploration advice, various geothermal resources of the Basin and Range Province and Snake River region, Western United States (Raft River, Salt Wells, Fallon, Blue Mountain, Mary's River, Alum, Barren Hills, Silver Peak, Reese River, Hot Sulphur Springs, Neal H.S., Crane Creek, McGee Mountain, Fish Lake, Stillwater, Emigrant, Darrough H.S., Gabbs, McGinness Hills, Smith Crk Valley), for various clients, 2006 - 2009.
- Evaluation and conceptual modeling of the geothermal resource at Suswa, the Rift Valley, Kenya, 2008 - 2009.
- Evaluation of geothermal resource areas in Serbia, 2008 - 2009.
- Evaluation of geothermal resources in Valle de Cura, Argentina, 2009.
- Evaluation of geothermal resources in Snohomish County, Washington, 2009.
- Hot spring sample collection and evaluation of geothermal fields in Province of Tacna, Peru, 2008.
- Preliminary evaluation of six geothermal resource areas in Chile, including field reconnaissance and water sample collection, 2008.
- Evaluation and recommendations concerning the geothermal resource and geothermal geotechnical program activities and management at the Lihir gold mine, Papua New Guinea, 2008.
- Well test fluids sampling (waters, gases, isotopes); training of field and laboratory personnel; tracer test design, execution and oversight; calcite scale inhibitor testing, evaluation and oversight; reservoir modeling; database design at the Ribeira Grande - Pico Vermelho geothermal field, São Miguel, Azores, Portugal, 1998 - 2008.
- Evaluation of reconnaissance-scale fluids chemistry data and detailed studies of selected geothermal prospects in British Columbia, 2007 - 2008.
- Evaluation of fluids chemistry program design (plans for supercritical fluids testing) at the Iceland Deep Drilling Project and evaluation of fluids chemistry, temperature, geophysical and drilling data from four geothermal fields in Iceland, 2006 - 2008.
- Ranking of proposals for five different geothermal projects in Nevada, for a major utility company, using integrated geologic, geochemical and geophysical data to establish potential reserves and project risk factors, 2008.
- Database design, compilation and evaluation for conceptual model and monitoring of groundwater in the outflow zone of the Steamboat, NV USA geothermal reservoir, 2006 - 2007.
- Evaluation of fluids chemistry data and reservoir modeling to support numerical simulation for the Germencik geothermal field, Turkey, 2007 - 2009.

- Conceptual hydrogeologic model (chemistry, geology, temperature distribution) and quantification of changes in response to exploitation of the Kawerau geothermal field, New Zealand, 2006 - 2007.
- Fluids chemistry studies of the Olkaria geothermal field (Olkaria I, II, III, IV and Domes Projects) to develop and support conceptual and numerical reservoir models, Kenya 2006-2007 and 2009.
- Fluids chemistry sampling, conceptual modeling of resource and reserves evaluation, Crump Geyser (Warner Valley), OR USA, 2006.
- Comprehensive evaluations of the geothermal prospects of the islands of Faial, Pico and São Miguel, Portuguese Azores, using data from geochemical, geological and geophysical surveys, 2006.
- Establishing a conceptual model of the geothermal resource associated with lithium brine deposits at Silver Peak, NV USA, 2006.
- Geochemistry and conceptual model of the thermal waters of central Jordan, for the Ministry of Energy and Mineral Resources, 2006.
- Fluids chemistry, temperature and geologic models of the Cerro Prieto geothermal field, to develop and support numerical reservoir simulation, Mexico, 1999 and 2005.
- Program management and resource studies (chemistry, geology, geophysics, temperature) for exploration program design and conceptual modeling at Lake City, Surprise Valley CA, 2005.
- Fluids sampling at tests of geothermal wells, conceptual modeling of the resource, Raft River, ID USA, 2004.
- Conceptual modeling, energy reserves estimations, exploration and development costs estimations, design and implementation of comprehensive integrated database (MS-Access) for geotechnical and costs data, at nearly 100 producing and prospective geothermal systems in the western U.S.A. and Mexico – Central America, 2002 – 2004.
- Conceptual models and reserves valuations for numerical simulations of the Los Azufres, Los Humeros and Tres Virgenes geothermal fields, for Comisión Federal de Electricidad, Mexico, 2003.
- Project management and detailed conceptual modeling to support numerical simulation of the Steamboat, NV geothermal reservoir, 2002 – 2003.
- Detailed hydrogeological, chemical and reservoir conceptual modeling, including mercury transport, at the geothermal system at Sulfur Bank Mercury Mine, California, 2002.
- Field sampling and analyses at springs, wells and fumaroles, data interpretation, project management, data compilation and management of over 2300 database

- records for master plan study of the geothermal resources of Nicaragua, 2000 - 2001.
- Hydrochemical and geothermal model development for country-wide study and ranking of the geothermal resources of India, 2001 - 2002.
  - Hydrochemical and geothermal model development for evaluation of the geothermal systems at Meager Mountain, British Columbia and Anderson Hot Springs, California, 2000 - 2001
  - Hydrochemical and geothermal model development for pre-feasibility and feasibility evaluations of the geothermal systems at Rincón de la Vieja, Costa Rica, 1999 - 2004.
  - Conceptual and geochemical modeling of the Karaha Bodas geothermal system, Indonesia, 1999.
  - Chemistry database software and chemical equilibrium thermodynamics software design, installation and training, for use by Akita Geothermal Energy Company in its operation of the Uenotai geothermal field, Japan, 1996 - 1997.
  - Design, project management and debugging of the WatchWorks, MS-Windows software program for geothermal fluids thermodynamics, 1995.
  - Well test fluids sampling and injection tracer testing, Upper and Lower Amatitlán geothermal fields, Guatemala, 1995 - 2000.
  - Fluid chemistry sampling and analysis, database management, field lab design, set-up and personnel training, well test monitoring, hydrogeochemical modeling as part of major exploration and field development projects. Dieng, Patuha and Wayang Windu geothermal fields, Indonesia, 1993 - 1998.
  - Evaluation of mass flux of zinc (Zn), thermodynamic modeling of the solubility of sphalerite (ZnS) and determination of controls on reservoir Zn concentration at the Salton Sea geothermal field, California, as part of a feasibility study for recovering zinc, 1995 - 1996.
  - Design and execution of fluid sampling program (waters, gases, and isotopes, including data for environmental studies) during drilling and testing of production wells, long-term monitoring of reservoir chemistry during production, and injection tracer testing, Bradys Hot Springs geothermal field, Nevada, 1991 - 1993.
  - Design and execution of sampling program for hot springs and other surface waters; surface gas discharge measurements; downhole sampling of fluids from 25 core holes; design, construction and operation of portable well sampling equipment; well testing and sample collection from three production test wells; thermodynamic and conceptual modeling of fluids chemistry in a unique sodium-(chloride=sulfate) hydrothermal system; scale and corrosion prediction; logging of temperature gradient wells; pressure transient testing; interpretation of results and integration with hydrogeologic models for thermal and non-thermal waters. Part of the initial

- work undertaken to develop an open-pit gold mine over an active geothermal system on Lihir Island, Papua New Guinea, 1987 - 1990.
- Design and management of fluid sampling programs and interpretation of results at numerous geothermal fields, including: Coso, California (1985 to 1986); Fish Lake, Nevada, 1985; Salton Sea, California (USDOE deep hole, 1987); Empire, Nevada (1985); and Steamboat, Nevada (1989).
  - Computerized thermodynamic modeling of geothermal fluid behavior, kinetic modeling of silica scale deposition, and modeling of gas mixing for scale control, Uenotai geothermal field, Japan, 1990.
  - Design and management of programs for: geochemical data gathering and management; interpretation of steam, gas and isotope chemistry; evaluation of corrosive steam behavior; and development of corrosion control systems in several portions of The Geysers geothermal field, California, 1983 - 1993.
  - Design, execution and analysis of a chemical tracer injection test, Bradys Hot Springs and Stillwater geothermal fields, Nevada, 1990 - 1991.
  - Review and interpretation of chemical data from Dixie Valley, Coso, Steamboat, Desert Peak, Mammoth and Puna geothermal fields, for various clients, 1980 - 1997.
  - Analysis and interpretation of liquid and gas geochemistry, identification of fluid sources, reservoir flow patterns and gas concentrations. Oku-Aizu, Onikobe and Uenotai geothermal fields, Japan, 1988 - 1989 (Uenotai work continued at intervals to 1997).
  - Data synthesis and interpretation of reservoir geochemistry for the National Power Corporation as part of development planning for power plant construction. Tiwi, Bulalo, and Palimpinon reservoirs, The Philippines, 1982 - 1984.
  - Sampling of thermal wells, interpretation of water chemistry, and determination of water flow patterns in multiple aquifers within the Central Sumatra Basin, leading to the definition of a thermal aquifer for use in a secondary oil recovery project. Duri region oil fields, Indonesia, 1982.
  - Supervision of deep well chemical sampling procedures, interpretation of regional geochemistry and characterization of the deep geothermal reservoir. Takigami geothermal field, Japan, 1983 - 1984.
  - Writing manuals for sampling and analyzing liquids and gases from springs, shallow wells, deep exploration wells and production wells for various clients, 1978 - 1988 and 1994 - 1996.
  - Geochemical exploration, field sampling, laboratory analyses, interpretation of results and calculation of geothermal energy reserves. Batong Buhay geothermal area, The Philippines, 1982.

- Geochemical exploration of San Juan Province; program design and field training, Argentina, 1982.
- Supervision of fluid sampling and analysis programs and interpretation of chemical and isotopic analyses in Honduras and Panama, for the United Nations, 1979 - 1980, and in Nicaragua, for the World Bank, 1978.
- Development of a conceptual geochemical-hydrologic-geologic model of Miravalles geothermal field, Costa Rica, for *Instituto Costarricense de Electricidad* (ICE, the national electric utility). 1979 and 1995 - 1996.
- Supervision of field sampling, design of laboratory procedures, and interpretation of data for four prospective geothermal areas in Iran (work conducted for the former Imperial Government of Iran). Included partial field analyses (NH<sub>4</sub>, pH, Ec) and detailed chemical and isotopic analyses of more than 2,000 soil, cool and thermal water, gas and rock samples. For the Ministry of Energy of the former Imperial Government of Iran, 1977 - 1978.
- Petrographic study of cores and cuttings from shallow and deep geothermal wells at The Geysers, California; Klamath Falls, Oregon; Miravalles, Costa Rica; and Puna, Hawaii. 1976 - 1988.
- Exploration, chemical sampling and data interpretation for several geothermal prospects in New Mexico, Nevada, California and Oregon, 1976 - 1978.
- Reconnaissance geochemical-geological field and laboratory study of the geothermal potential of a portion of eastern Idaho and western Wyoming, 1975 - 1976.

## **MEMBERSHIPS**

Geothermal Resources Council

American Chemical Society

International Geothermal Association

## **OTHER ACHIEVMENTS**

Winner of Geothermal Resources Council's "Best Paper Award" in 2001 (co-author)

## **CITIZENSHIP**

USA

## **SELECTED PUBLICATIONS**

Dr. Klein has been principal author or co-author of:

Advances in the Past 20 Years: Geochemistry in Geothermal Exploration, Resource Evaluation and Reservoir Management. Transactions, Geothermal Resources Council, vol. 31, 2007 (invited presentation).

Resource Exploitation at Steamboat, Nevada: What it takes to Document and Understand the Reservoir/Groundwater/Community Interaction. Transactions, Geothermal Resources Council, vol. 31, 2007 (with co-authors Stuart Johnson and Paul Spielman).

Assessing the Rye Patch Geothermal Field, A Classic Basin-And-Range Resource.

Transactions, Geothermal Resources Council, vol. 30, 2006 (with S.K. Sanyal, J.R. McNitt, S.J. Butler, C.W. Klein, and R.E. Ellis).

Numerical Simulation and Performance Evaluation of the Uenotai Geothermal Field, Akita Prefecture. Proceedings, World Geothermal Congress, 2005 (with Steven J. Butler, Subir K. Sanyal, Shun Iwata and Masahiro Itoh).

National Assessment of U.S. Geothermal Resources – A Perspective. Transactions, Geothermal Resources Council, vol. 28, 2004 (with Subir K. Sanyal, James W. Lovekin and Roger C. Henneberger).

Numerical Simulation and Performance Evaluation of the Uenotai Geothermal Field, Akita Prefecture. Transactions, Geothermal Resources Council, vol. 28, 2004 (with Subir K. Sanyal, Steven J. Butler, Shun Iwata and Masahiro Itoh).

New geothermal site identification and qualification. Consultant report for California Energy Commission, Publication No. P500-04-051, April 2004 (with James W. Lovekin and Subir K. Sanyal). Report and accompanying PIER Geothermal Database available on the web at: [http://www.energy.ca.gov/pier/final\\_project\\_reports/500-04-051.html](http://www.energy.ca.gov/pier/final_project_reports/500-04-051.html).

Updated numerical simulation of the Miravalles geothermal field, Costa Rica.

Transactions, Geothermal Resources Council, vol. 26, 2002.

A methodology for assessment of geothermal energy reserves associated with volcanic systems. Transactions, Geothermal Resources Council, vol. 26, 2002.

Overlooked geothermal resource opportunities in Nicaragua. Transactions, Geothermal Resources Council, vol. 26, 2002.

A new geothermal resource map of Nicaragua. Transactions, Geothermal Resources Council, vol. 25, 2001.

Reactive chemical transport simulation to study geothermal production with mineral recovery and silica scaling. Transactions, Geothermal Resources Council, vol. 25, 2001.

Development of injection capacity for the expansion of the Ribeira Grande geothermal project, São Miguel, Açores, Portugal. Transactions, Geothermal Resources Council, vol. 24, 2000.

Utility of the data gathered from the Fenton Hill project for development of enhanced geothermal systems. Transactions, Geothermal Resources Council, vol. 24, 2000.

Numerical modeling of the Cerro Prieto geothermal field, Mexico. Transactions, Geothermal Resources Council, vol. 24, 2000.

Assessment of steam supply for the expansion of generation capacity from 140 to 200 MW, Kamojang geothermal field, West Java, Indonesia. Transactions, Geothermal Resources Council, vol. 24, 2000.

User-oriented software for geothermal applications: the Watchworks program for Windows 95. Proceedings, World Geothermal Congress, 2000.

Development of a geothermal Master Plan for Nicaragua. Proceedings, World Geothermal Congress, 2000.

Assessment of steam supply for the expansion of generation capacity from 140 to 240 MW, Kamojang geothermal field, West Java, Indonesia. Proceedings, World Geothermal Congress, 2000.

Development of injection capacity for the expansion of the Ribeira Grande geothermal power project, São Miguel, Açores, Portugal. Proceedings, World Geothermal Congress, 2000.

Geothermal chemistry thermodynamics: the Watchworks program for MS-Windows. Transactions, Geothermal Resources Council, vol. 21, 1997.

History and results of surface exploration in the Kilauea East Rift Zone, Hawaii. Proceedings, World Geothermal Congress, 1995.

Chemical transients during production of high gas wells at the Northern Geysers steam field, California, USA. Proceedings, World Geothermal Congress, 1995.

Management of fluid injection in geothermal wells to avoid silica scaling at low levels of silica oversaturation. Proceedings, World Geothermal Congress 1995.

Prediction and prevention of silica scaling at low levels of oversaturation: case studies and calculations for Uenotai geothermal field, Akita Prefecture, Japan. Proceedings, Sixteenth Workshop on Geothermal Reservoir Engineering, Stanford University, 1991.

Corrosion versus temperature: field development options at Onikobe geothermal field, Miyagi Prefecture, Japan. Transactions, Geothermal Resources Council, vol. 14, 1990.

Heat source and fluid migration concepts at the Uenotai geothermal field, Akita Prefecture, Japan. Transactions, Geothermal Resources Council, vol. 14, 1990.

Effects of condensate re-injection on steam chemistry at The Geysers field. Transactions, Geothermal Resources Council, vol. 13, 1989.

Geochemistry of the Palimpinon Geothermal Field, Southern Negros, Philippines. Transactions, Geothermal Resources Council, vol. 6, 1982.

Reconnaissance geochemical survey and interpretation of thermal spring waters and gases, Honduras. Central American Energy Programme, Phase II, United Nations, April 1980.

Interpretations of groundwater chemistry in the thermal areas surrounding Volcan Miravalles, Guanacaste Province, Costa Rica. Report to *Instituto Costarricense de Electricidad*, Costa Rica, 1979.

Chemistry of thermal and non-thermal waters, volcanic lava plateaus of northeastern California and southern Oregon. Paper presented at the 2nd EPA Symposium on Geothermal Fluids, Las Vegas, NV, 1977.