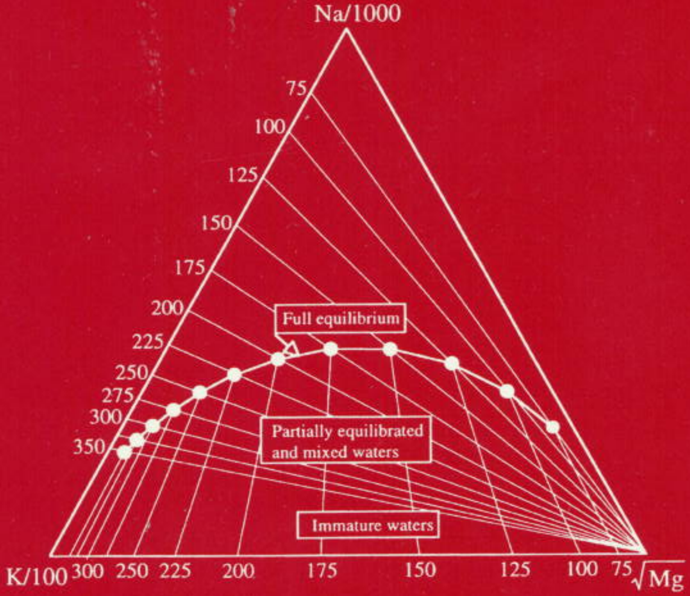
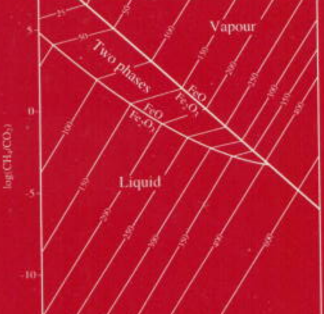



# ISOTOPIC AND CHEMICAL TECHNIQUES IN GEOTHERMAL EXPLORATION, DEVELOPMENT AND USE



# ISOTOPIC AND CHEMICAL TECHNIQUES IN GEOTHERMAL EXPLORATION, DEVELOPMENT AND USE

Edited by
Stefán Arnórsson

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BRAZIL
BULGARIA
BURKINA FASO
CAMBODIA
CAMEROON
CANADA
CHILE
CHINA
COLOMBIA
COSTA RICA
COTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIET NAM
YEMEN
YUGOSLAVIA
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".



Printed by the IAEA in Austria
September 2000
STI/PUB/1086

# ISOTOPIC AND CHEMICAL TECHNIQUES IN GEOTHERMAL EXPLORATION, DEVELOPMENT AND USE

## SAMPLING METHODS, DATA HANDLING, INTERPRETATION

Edited by
Stefán Arnórsson

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2000

**VIC Library Cataloguing in Publication Data**

Isotopic and chemical techniques in geothermal exploration, development and use: sampling methods, data handling, interpretation / edited by Stefán Arnórsson.. — Vienna : International Atomic Energy Agency, 2000.
351 p. ; 24 cm.
STI/PUB/1086
ISBN 92–0–101600–X
Includes bibliographical references.

1. Geothermal resources — Sampling. 2. Radioisotopes in geology. I. Arnórsson, Stefán. II. International Atomic Energy Agency.

VICL 00–00248

# FOREWORD

Since the eighties of the past century, the IAEA has been developing the applications of isotope and geochemical techniques applied to geothermal investigations. It has supported research on the development of isotope methods to geothermal development activities, with more emphasis on field applications, through its Technical Co-operation programmes. Twenty-five Member States have been recipients of assistance to undertake hydrological research and explore potential geothermal areas, manage reservoirs, protect the environment and establish laboratories in support of their energy programmes. This has resulted in intensive interaction with experts in industry and with Member States which use geothermal energy resources for electricity generation.

In 1995, an Advisory Group Meeting (AGM) was held on Isotope Applications in Geothermal Energy Development, with the participation of scientists from China, Ethiopia, Italy, Iceland, Indonesia, Japan, Mexico, New Zealand, Philippines, the Russian Federation, Switzerland, the United Kingdom and the USA. It was noted that the expanding applications of isotope techniques in geothermal operations, continuing IAEA technical co-operation on geothermal energy development and the increasing awareness for geothermal energy potential require a practical guide to facilitate field investigations as well as staff development in Member States. The meeting, therefore, recommended publication and dissemination of an updated manual of field methodologies on isotopes for sampling and data interpretation applied to geothermal investigations. This provided the IAEA an impetus to publish this book which was initially conceived in a Consultants Meeting on Instructional Manual on Methods for Isotope Sample Collection and Data Processing of Geothermal Fluids, organized in September 1997.

This book is designed as an instructional manual of essential nuclear and complementary methodologies for a multidisciplinary approach to geothermal exploration development and monitoring. It provides comprehensive procedures for carrying out isotope and geochemical investigations of geothermal systems, i.e. sampling, analysis and data interpretation. While it is intended for geoscientists working in various stages of geothermal projects, either in low or high enthalpy systems, this publication will also benefit those working in the cold water resources projects, where methods and principles of investigations are similar. The reader is also advised to consult the Agency's earlier two TECDOC publications on geothermal energy for case studies on exploration activities employing isotope techniques.

This book was edited by Stefán Arnórsson. Franco D'Amore made very important contributions to the text. In addition, the IAEA is grateful to L. Araguas-Araguas (Spain), M.A. Geyh (Germany) and scientists of the Philippine National Oil Company–Energy Development Corporation for reviewing the manuscripts.

# CONTENTS

# 1. INTRODUCTION

*Stefán Arnórsson*

Geothermal energy is an important small energy resource whose exploitation has relatively insignificant environmental impact. The use of geothermal energy has proven to be cost effective in many countries where geological, hydrological and geophysical conditions are favourable to the formation of geothermal systems. This is particularly the case in active volcanic regions where geothermal gradients and rock permeabilities are high. However, economic geothermal reservoirs have also been discovered in sedimentary strata and fractured volcanics outside areas of recent volcanism.

Geothermal resources account for only a very small part of the world's present day energy consumption. They are, however, of high economic importance in many developing countries. The estimated world use of geothermal energy is summarized in Table 1.1. As may be deduced from this table, most countries exploiting geothermal resources have emphasized their use for electric power generation. Some countries, on the other hand, use geothermal water directly on a large scale, particularly for space heating.

The main factor determining the potential use of a particular geothermal resource is the reservoir temperature as summarized in Fig. 1.1.

The existence of geothermal reservoirs is manifested by the presence of hot springs and/or fumaroles. Exploration has, however, revealed that also hidden reservoirs exist. Sometimes there is little relationship between the distribution and intensity of surface geothermal activities only in an area and the extent and productivity of the underlying geothermal reservoir.

Geothermal exploration serves the purpose of locating geothermal areas favourable to development and to finding sites within them for drilling. This exploration includes geological mapping as well as geochemical and geophysical surveys. The principal purpose of geochemical surveys is to predict subsurface temperatures, to obtain information on the origin of the geothermal fluid and to understand subsurface flow directions. The basic philosophy behind geochemical prospecting for geothermal resources is that the concentrations of many components in the geothermal fluid, i.e. natural aqueous solutions and gaseous steam, reflect thermal conditions at depth. Studies in many drilled geothermal fields have shown that the aqueous concentrations of some chemical and isotopic components in well discharges are controlled by equilibrium with minerals in the aquifer rock. The aqueous concentrations of other components are, on the other

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 92–0–101600–X