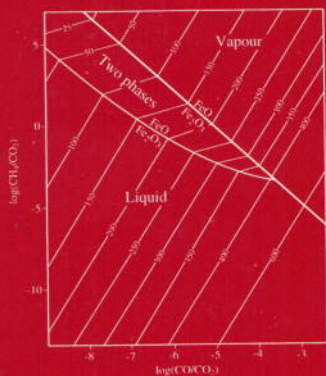


ISOTOPIC AND CHEMICAL TECHNIQUES IN GEOTHERMAL



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

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".

© IAEA, 2000

Permission to reproduce or translate the information contained in this publication may be obtained by writing to the International Atomic Energy Agency, Wagramer Strasse 5, P.O. Box 100, A-1400 Vienna, Austria.

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.

EDITORIAL NOTE

This book has been edited by the Editing Unit of the Publishing Section of the IAEA. However, the views expressed are the responsibility of the named contributors and are not necessarily those of the IAEA or of the governments of its Member States.

Although great care has been taken to maintain the accuracy of information contained in this publication, neither the IAEA nor its Member States assume any responsibility for consequences which may arise from its use.

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

CONTENTS

1.	INTRODUCTION	1
	<i>Stefán Arnórsson</i>	
2.	STRATEGY IN GEOTHERMAL EXPLORATION, DEVELOPMENT AND PRODUCTION	5
	<i>Stefán Arnórsson</i>	
3.	CHEMICAL REACTIONS AND CHEMICAL EQUILIBRIA	9
	<i>Stefán Arnórsson</i>	
3.1.	Some thermodynamic considerations	9
3.2.	Progressive water-rock interaction	12
3.3.	Demonstration/assumption of chemical equilibrium	15
3.4.	Thermodynamic treatment of equilibrium	18
3.5.	Effects of temperature and pressure	19
3.6.	Aqueous speciation	23
3.7.	Concentration and activity	25
3.8.	Calculation of aqueous speciation	26
4.	REACTIVE AND CONSERVATIVE COMPONENTS	40
	<i>Stefán Arnórsson</i>	
5.	ISOTOPES FOR GEOTHERMAL INVESTIGATIONS	49
	<i>Jane Gerardo-Abaya, Franco D'Amore and Stefán Arnórsson</i>	
5.1.	Notations	49
5.2.	Use of isotopes in geothermal investigation	53
5.3.	Origin of geothermal water	54
5.4.	Stages of geothermal development where isotopes are employed	57
6.	THE SOURCE OF CHEMICAL AND ISOTOPIC COMPONENTS IN GEOTHERMAL FLUIDS	66
	<i>Stefán Arnórsson and Franco D'Amore</i>	

7.	GEOTHERMAL MANIFESTATIONS AND HYDROTHERMAL ALTERATION	73
	<i>Franco D'Amore and Stefán Arnórsson</i>	
7.1.	Thermal springs	73
7.2.	Fumaroles and steam heated waters	75
7.3.	Hydrothermal alteration	77
7.4.	Acid surface leaching and mineral deposition	81
8.	SAMPLING OF GEOTHERMAL FLUIDS: ON-SITE MEASUREMENTS AND SAMPLE TREATMENT	84
	<i>Stefán Arnórsson and Franco D'Amore</i>	
8.1.	Objectives	84
8.2.	Selection of elements and components for analysis	85
8.3.	Selection of sites for sampling of thermal waters for geochemical exploration	86
8.4.	Sampling of surface waters, springs and hot and cold water wells	87
8.5.	Sampling of fumaroles and gases from thermal springs	89
8.6.	Sampling of wet steam wells	91
8.7.	General information of material selection, acid washing and reasons for sample treatment	96
9.	PRESENTATION OF ANALYTICAL RESULTS, ANALYTICAL PRECISION AND ACCURACY	143
	<i>Stefán Arnórsson</i>	
9.1.	Analytical precision and accuracy	144
9.2.	Presentation of analytical results	148
10.	GEOTHERMOMETRY	152
	<i>Franco D'Amore and Stefán Arnórsson</i>	
10.1.	Water geothermometers	154
10.2.	Steam (gas) geothermometers	171

10.3. Multiple mineral equilibrium approach	174
10.4. Discussion on chemical geothermometers	175
10.5. Isotope geothermometers	178
11. MIXING PROCESSES IN UPFLOW ZONES AND MIXING MODELS	200
<i>Stefán Arnórsson</i>	
11.1. Mixing processes	200
11.2. Mixing models	202
12. ASSESSMENT OF RESERVOIR FLUID COMPOSITION FROM WET STEAM WELL DATA	212
<i>Stefán Arnórsson</i>	
13. HYDROGEN AND OXYGEN ISOTOPIC FRACTIONATION DURING BOILING	229
<i>Franco D'Amore, Jane Gerardo-Abaya and Stefán Arnórsson</i>	
14. MINERAL SATURATION	241
<i>Stefán Arnórsson</i>	
14.1. Aquifer chemistry	246
14.2. Effects of boiling and cooling	247
14.3. Errors in calculations of saturation indices	248
15. ESTIMATION OF AQUIFER STEAM FRACTION	267
<i>Stefán Arnórsson and Franco D'Amore</i>	
15.1. General remarks on boiling in geothermal systems	267
15.2. Equilibrium steam	270
15.3. Notations on geothermal gas chemistry	271
15.4. Calculation of aquifer gas partial pressures	278
15.5. Estimation of initial aquifer steam fractions and aquifer gas pressures	284
15.6. Discussion	292

16. MONITORING OF RESERVOIR RESPONSE TO PRODUCTION	309
<i>Stefán Arnórsson and Franco D'Amore</i>	
16.1. Response of geothermal reservoirs to production load	309
16.2. Injection	310
16.3. Frequency of sampling for monitoring studies and the selection of chemical and isotopic components for analysis	311
16.4. Presentation of monitoring data	312
16.5. Conservative components	313
16.6. Reactive aqueous components	319
16.7. Reactive gaseous components	328
16.8. Deuterium and ¹⁸ O	334
 BIBLIOGRAPHY	 343

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

可联系文章作者询问电子版图书!
仅用于学习交流,请及时删除!支持正版!

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA

ISBN 92-0-101600-X