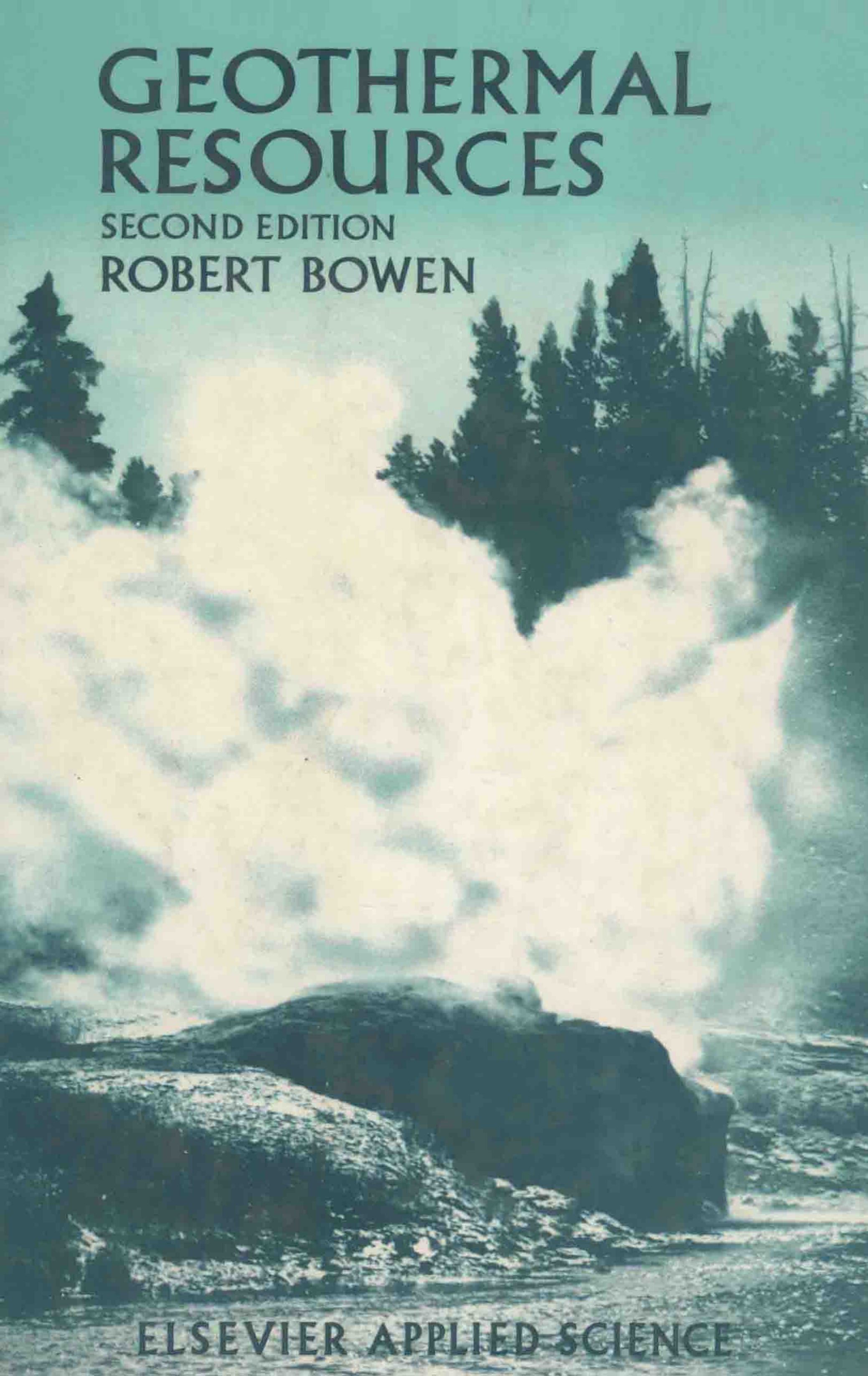
GEOTHERMAL RESOURCES

SECOND EDITION

ROBERT BOWEN



ELSEVIER APPLIED SCIENCE

GEOTHERMAL RESOURCES

SECOND EDITION

ROBERT BOWEN

Professor of Geology, Institute of Geology and Palaeontology, Westfälische Wilhelms-University, Münster, Federal Republic of Germany

ELSEVIER APPLIED SCIENCE

LONDON and NEW YORK

ELSEVIER SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
655 Avenue of the Americas, New York, NY 10010, USA

First edition 1979
Second edition 1989

WITH 59 TABLES AND 60 ILLUSTRATIONS

British Library Cataloguing in Publication Data

Bowen, Robert
Geothermal resources—2nd ed.
1. Energy sources: Geothermal energy
I. Title
621.44

ISBN 1-85166-287-1

Library of Congress Cataloging-in-Publication Data

Bowen, Robert
Geothermal resources/Robert Bowen—2nd ed.
p. cm.
Bibliography: p.
Includes indexes.
ISBN 1-85166-287-1
1. Geothermal resources. 2. Geothermal engineering.
I. Title.
GB1199.5.B68 1989
333.8′8—dc 19

Printed in Great Britain by Galliard (Printers) Ltd, Great Yarmouth

Preface

Since the Arab oil embargo of 1974, it has been clear that the days of almost limitless quantities of low-cost energy have passed. In addition, ever-worsening pollution due to fossil fuel consumption, for instance oil and chemical spills, strip mining, sulphur emission and accumulation of solid wastes, has, among other things, led to an increase of as much as 10% in the carbon dioxide content of the atmosphere in this century. This has induced a warming trend through the 'greenhouse effect' which prevents infrared radiation from leaving it. Many people think the average planetary temperatures may rise by 4°C or so by 2050. This is probably true since Antarctic ice cores evidence indicates that, over the last 160 000 years, ice ages coincided with reduced levels of carbon dioxide and warmer interglacial episodes with increased levels of the gas in the atmosphere. Consequently, such an elevation of temperature over such a relatively short span of time would have catastrophic results in terms of rising sea level and associated flooding of vast tracts of low-lying lands.

Reducing the burning of fossil fuels makes sense on both economic and environmental grounds. One of the most attractive alternatives is geothermal resources, especially in developing countries, for instance in El Salvador where geothermal energy provides about a fifth of total installed electrical power already. In fact, by the middle 1980s, at least 121 geothermal power plants were operating worldwide, most being of the dry steam type.

The largest electricity producer from geothermal energy on Earth is the USA with a 2022-MW capacity as of 1985, this being expected to reach 4370 MW by 1992. Actually, by that year, world geothermal electrical installed power could reach 10 300 MW, representing approximately 0·5% of world total electrical installed power. This may seem rather insignificant, but the bare statistic rather misleads because, in the Third World, contributions made by geothermal resources are important; for example, in the Philippines no less than 11·9% of total installed electric power in 1982 was produced geothermally. In addition, in countries like Iceland with highly adverse climates, geothermal energy is valuable both in space and process heating.

The proliferation of research and development programmes in the area of geothermics together with their practical implementation over the past quarter of a century necessitates the producing of many more specialists in geothermal energy than had been anticipated. Indeed, four training centres now exist in Iceland, Italy, Japan and New Zealand for this purpose and the author is indebted to one of them, the International School of Geothermics in Pisa, Italy, and in particular to its Director, Dr Mario Fanelli, as well as to Dr Enrico Barbier and Dr Mary Dickson, for supplying essential literature and photographs cited in the book. It is appropriate here also to thank John Wiley & Sons Ltd, UK, for permission to reproduce Figs 1.13, 2.5 and 7.2 from their publication, *Geothermal Systems: Principles and Case Histories*, edited in 1981 by L. Rybach and L. J. P. Muffler. I am also grateful to Mr Charles R. Imbrecht, who is Chairman of the California Energy Commission, USA, to the Pacific Gas and Electric Company, and Southern California Edison Company as they supplied geothermal photographs from that state. Mr Ed Macumber, Energy Division Lead of the Economic Development and Stabilization Board of the State of Wyoming at Cheyenne, and Ms Cindy Hendrickson of the Wyoming Travel Commission are sincerely thanked for sending me geothermal photographs from there. Icelandic photographs were kindly given by Ms Gil Middleton of Broomhill, Sheffield. The Athlone Press, UK, kindly permitted me to quote from *The Man with a Nose* by H. G. Wells.

The future looks even more promising when hot dry rock (HDR) experiments in the USA and Great Britain are taken into account. At Los Alamos National Laboratory, work has been going on for over a decade: 5 MW of geothermal energy has been produced and the artificial reservoir exploited for more than a year with a temperature drop of under 10°C. Economically, electricity so generated is highly competitive in price. The centre of activity was outside the Valles Caldera in north-central New Mexico and entailed two phases, one drilling to 3000 m into granite at 185°C to create hydraulic fractures at 2600 m by means of water under pressure, a second extending the work by constructing a larger, hotter and deeper system. This project at Fenton Hill informally cooperated with work of the Camborne School of Mines going on in the Carnmenellis granite at Rosemanowes, part of the batholith underlying the southwestern peninsula of the UK. Here explosive stimulation pre-treated the well prior to hydraulic fracturing and then the injection of water under pressure produced unsatisfactory results so that two other wells were drilled. Water was used together with a viscous gel because the connections with the new well were not optimal. A reservoir resulted and has been circulating continuously since August 1985.

The author formerly worked in the geothermal energy area in Iran and was particularly concerned with developing a resource at Mount Damavand, from which it was intended to insert 50 MW of electrical power into supplies for the capital, Tehran. Studies were being conducted also in Azerbaijan around two extinct volcanoes, Mounts Sahand and Sabalon. Accessibility was a problem here, not even to mention political danger partly connected with the close proximity of Turkey and the USSR. Support for the projects came from the energy ministry. Unfortunately, they had to be abandoned after the departure of the Shah and the arrival of the Ayatollah Khomeini in 1979. The first edition of this book was written back in England and periodic interest taken in potential development of geothermal energy in Eire, this in connection with the late Dr David Burdon, an old friend from earlier mutual collaboration in the United Nations.

The meteoric rise in geothermal data since 1979 justifies the appearance of this greatly enlarged and better illustrated second edition of *Geothermal Resources*. Commencing with an examination of the origins of earth heat, it proceeds to deal with geothermal systems and models, exploration and resources assessment, the exploitation and environmental impact (mostly benign) of geothermal fields, and the various uses to which geothermal energy can be put. There is a glossary of relevant terms and appendices on geothermal miscellanea, companies, organizations, places and world geothermal localities, and full Author and Subject Indexes are included.

The aim of the writer has been both to interest and to stimulate the reader in addition to offering a compact, but comprehensive, source of geothermal information for office and field use by earth scientists, engineers and isotope geologists, environmentalists, sociologists and land planners. I hope that this book fulfils this end.

ROBERT BOWEN
Münster

Contents

APPENDIXES

Introduction

'Now these things are so.'
HERODOTUS, 5th Century BC ('Father of History')

It has been known for a long time that the temperature of the Earth rises with depth below ground, heat flow from subterranean hot regions manifesting itself in this geothermal temperature gradient. It is enhanced by the continued generation of heat due to radioactive decay of uranium, thorium and potassium within the crust. But the natural heat flux driven by such temperature gradients is very low, the world average being around $50\,mW/m^2$. This is three orders of magnitude lower than the mean solar input to northern Europe in winter; therefore such heat flows are much too small to be exploited directly. Nevertheless, over millions of years, they accumulate heat stores which can sometimes be mined.

However, the high concentrations of heat energy occurring in geothermal fields are another matter and these are much more attractive propositions from an economic point of view. For mankind, geothermal energy constitutes an integrative and practically self-renewing alternative energy source which as yet is far from fully exploited as compared with the conventional fossil fuel ones, despite its now-demonstrated capability of contributing significantly to the needs of many countries, particularly in the developing world. Geothermal exploration is necessary to find fields of commercial significance, and can identify them from related anomalies connected to the upwards movement of magma. Of course, factors such as temperature and enthalpy, the distribution of permeability and the depth of a suitable aquifer acting as a reservoir play a significant role in producing a spectrum of geothermal systems, including both convective and conductive varieties; the former include hydrothermal systems among which are almost all of those used until now to generate electric power commercially.

In 1970 the geothermoelectric power installed throughout the world was approximately 680 MW, over half of this being in Italy (384 MW). To the middle of the 1970s, there was a growth of approximately 7% annually; a similar development occurred with non-electrical usage of geothermal resources, the oil crisis of 1973 having acted as a great stimulus because of the necessity to reduce petroleum imports. By 1985 the global geothermoelectric power produced was approximately 4765 MW, a 600% increase in a mere 15 years. Almost two-thirds of this is in Asia. The inference that such power is crucial to the poorer countries is correct. Concomitant with all this, a greater understanding of geothermal resources has grown and more specialists are being trained in centres such as Pisa. There is an increasing number of case histories available and hot dry rock experiments are in progress, as also are investigations into geothermal aquifers, geopressurized reservoirs and even magma.

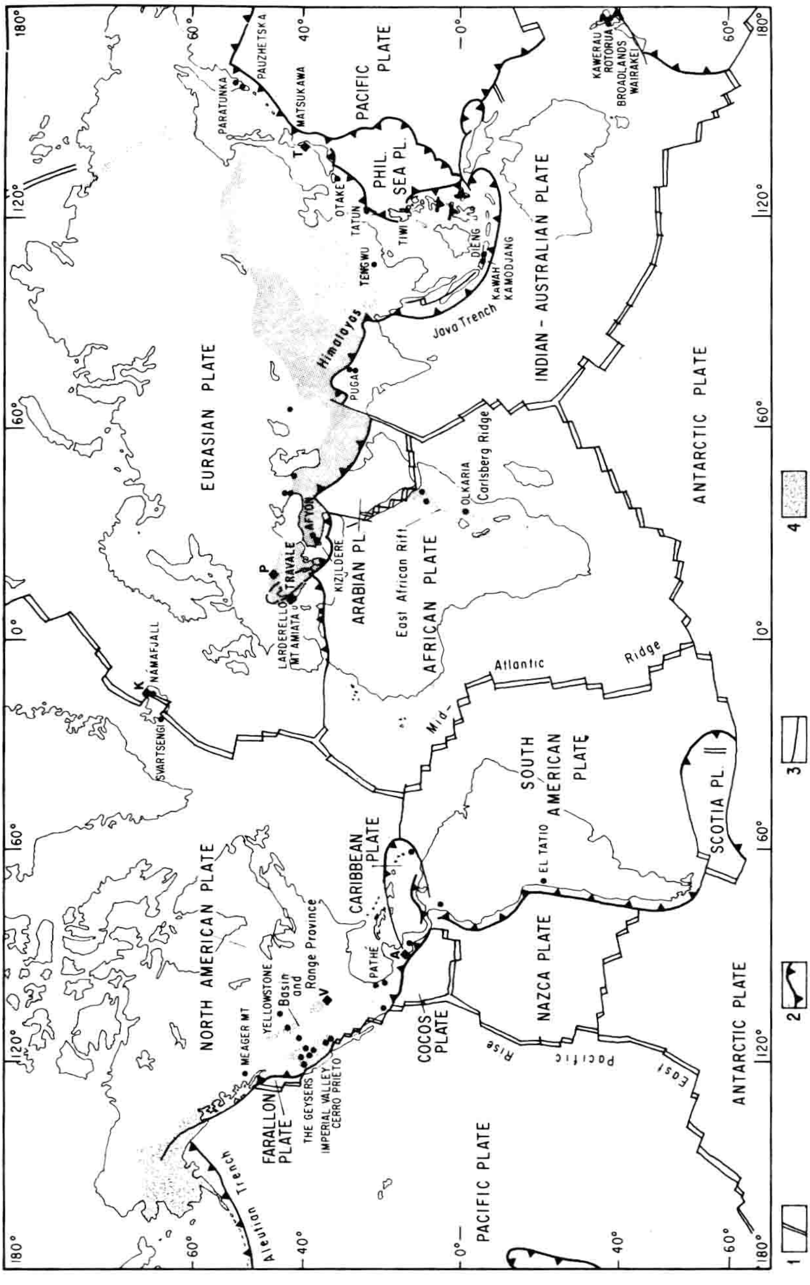
From that synthesis of data from the earth sciences called plate tectonics (see Chapter 1, Section 1.3.3) the distribution of geothermal resources on Earth becomes explicable, i.e. their locations relate to plate boundaries and parallel those of earthquakes and volcanoes as well as hot springs and geysers. The therapeutic value of some thermal sources was well known even in Roman times and natural heat was put to work in New Zealand ever since that country became inhabited, the Maoris having poetic legends to explain it. Geothermal anomalies and increases in geothermal gradients result from ascending heat embodied in mobile masses such as magma bodies. Such thermal sources as can be exploited are situated in rather shallow crustal levels of less than 10 km and constitute transient stores of heat.[1] It must be stated immediately that the word 'transient' is used here in a geological sense and refers to the geological time-scale.

In human terms, such energy sources are integrative and self-renewing. The associated magmas may be basaltic or silicic in type. The former arise from the material of the mantle by partial melting and either disperse their thermal energy through direct ascent to the surface and emplacement as dikes and sills or solidify near the base of the crust in such extensional regimes as the Basin and Range Province of the USA and hence increase the regional heat flow.[2,3] This may well induce hydrothermal convection along steep fault systems resulting from the extensional regime.[4] Silicic magmas are generated by the partial melting of mantle material and also by the differentiation of basalt, often associated with remelting of crustal material as well.[5] Because they are more viscous than basaltic magmas, they can be arrested several kilometres down in the crust.

According to R. L. Smith and H. R. Shaw in 1973, continental geothermal resources are more likely to occur in connection with silicic volcanism than with the basaltic variety.[6] Igneous intrusions possess variable temperatures which can be as high as 1200°C; therefore they can heat their emplacement environment considerably and produce a corresponding surface heat flow greater than several watts per square metre. Obviously, the effect is limited chronologically because of both conductive and convective cooling effects after intrusion occurs. Thus normally only Quaternary intrusions, i.e. those younger than a million years or so, in the shallow part of the crust, i.e. not deeper than 10 km, remain thermally active now.[7]

In overall terms, magmatic activity globally can be integrated into the plate tectonics hypothesis, which also permits the delineation of geographic regions with geothermal potential. The concept allows the inference that the upwelling of magma is most probable along the boundaries of plates, and geothermal resources associated with the intrusions of magma bodies will be found mostly along spreading mid-oceanic ridges, convergent plate margins (subduction zones) and intraplate melting anomalies (see Fig. 1). The rigid outer shell of the planet, i.e. the lithosphere, is split into seven large and numerous small plates which slide on a more viscous base, the asthenosphere, at velocities relative to each other of up to several centimetres yearly. The boundary between the asthenosphere and the overlying lithosphere is a zone of decoupling. Of course, there is interference at the plate boundaries. At the divergent ones (spreading ridges) new crust is created by upwelling molten material. At the convergent ones, one plate slides under another in a subduction zone. Along transform faults, plates pass each other horizontally and their margins are conserved. Where two plate boundaries or three plates meet is called a triple junction.

Apropos the spreading ridges, it is believed that up to one-third of planetary heat loss takes place along the system of submarine ridges roughly 40 000 km long and occupying a mere 1% or less of the terrestrial surface. Along these ridges lithospheric plates are sundered while basalt wells up from the mantle and fills in the gap to create new, oceanic lithosphere. Accompanying volcanism probably arises from the pressure release melting in the underlying mantle, as E. R. Oxburgh and D. L. Turcotte suggested in 1968.[8] Adjacent to the ridge axes, the neighbouring sea-floor slopes downwards, the hot lithosphere cooling with increasing distance and age from these features, a phenomenon accompanied by falling heat flow. As well as conductive cooling, there is hydrothermal convection in the oceanic crust and, if this is sufficiently permeable, cooling of the uppermost 6 or 7 km may take place. It was estimated that the



NORTH AMERICAN PLATE
EURASIAN PLATE
PACIFIC PLATE
PHIL. SEA PL.
INDIAN - AUSTRALIAN PLATE
ANTARCTIC PLATE
AFRICAN PLATE
ARABIAN PL.
SOUTH AMERICAN PLATE
NAZCA PLATE
COCOS PLATE
CARIBBEAN PLATE
SCOTIA PL.
FARALLON PLATE
Aleutian Trench
Java Trench
Himalayas
East African Rift
Carlsberg Ridge
Mid-Atlantic Ridge
East Pacific Rise
Basin and Range Province
MEAGER MT
YELLOWSTONE
THE GEYSERS
IMPERIAL VALLEY
CERRO PRIETO
PATHÉ
EL TATIO
SVARTSENGI
NAMAFJALL
LARDERELLO
MT AMIATA
TRAVALE
KIZILDERE
AFYON
OLKARIA
PUGA
TENGWU
TATUN
TIWI
OTAKE
MATSUKAWA
PARATUNKA
PAUZHETSKA
DIENG
KAWAH KAMODJANG
KAWERAU
ROTORUA
BROADLANDS
WAIRAKEI
180°
120°
60°
0°
40°
1
2
3
4

hydrothermal mass flow through the sea-floor from contemporary to 2 Ma in age is around 10^{11} g/km of ridge annually.[9]

Although there are some differences from a submarine oceanic ridge, Iceland constitutes the best place to see part of a ridge above sea level. The heat there is transferred to the surface by volcanism, conduction and hydrothermal activity, the output from the neovolcanic zone crossing the country totalling 56 MWt/km of ridge length. Of this, 21 MW/km come from volcanism, the same quantity from conduction, and 14 MW/km are contributed hydrothermally.[10]

Spreading at a much slower rate also occurs by the breaking up of continental lithosphere and manifests itself as rifts, below which pressure relief permits upwelling of molten material. The associated geothermal activity is lower-key and, in 1976, C. R. B. Lister estimated that the probability of finding a large-scale hydrothermal system is only 0·025 per km rift length and per cm/year spreading rate.[11] Continental rifting requires that a zone of weakness exists in the upper part of the crust and becomes associated with extensional tectonics, thereafter undergoing plastic deformation consequent upon rise in the thermal contribution from depth. This process induces faults to form and a central faulted block may result with an accompanying basal crustal mantle feature impregnated by basaltic material arising from the upper portion of the mantle because of the release of lithostatic pressure.[12] Of course, processes of this type are episodic, but geothermal activity persists for a long time. Probably the most famous continental rift structure on Earth is the East African Rift, which contains geothermal areas in Kenya and Uganda (discussed in Chapter 4), but there are many others of smaller size, e.g. the Basin and Range Province of the western USA, the Baikal Rift and the Upper Rhine Graben in central

---

FIG. 1. Lithospheric plate boundaries provide the framework for the global distribution of major geothermal systems. Plate boundary types: Spreading ridge (1), subduction/trench (2), transform fault (3). Shaded areas (4): Plate interior undergoing active extensional, compressional or strike-slip faulting. Base map and plate boundaries after Hamilton, W. (1976) and Panza, G. F. and Mueller, St. (1979); geothermal systems (dots) after Muffler, L. J. P. (1976*a*,*b*). Systems discussed in detail in Summary of Section I: Present status of resources development. In: *2nd UN Symp. on the Development and Use of Geothermal Resources, San Francisco*, pp. xxiii–xliv. A (Ahuachapán/El Salvador), K (Krafla/Iceland), P (Pannonian Basin/Hungary), T (Takinoue/Japan), V (Valles Caldera, Jemez Mts/USA). (Reproduced from Fig. 1.13 in Chapter 1, Geothermal systems, conductive heat flow, geothermal anomalies, L. Rybach. In: *Geothermal Systems: Principles and Case Histories*, ed. L. Rybach and L. J. P. Muffler, 1981. By permission of the publishers, John Wiley & Sons Ltd.)

Europe. The extension, subsidence and shoulder uplift of the last was discussed in 1986 by T. Villemin and others.[13]

Deep basins on continental crust are divisible into two major kinds, namely those with normal faults and with basement tilted either in the same direction (S-type) or in opposite directions (A-type), according to E. V. Artyushkov in 1987.[14] A large amount of stretch is involved in the former under a large angle of block tilting. This may be typical also in narrow S-type basins which do not exceed the thickness of the pre-stretched crust. It is only in basins of these two varieties that extension suffices to explain the subsidence by stretching. They may be called 'rifts'. Extended basins in the Basin and Range Province exemplify them. Deep basins of the A-type with a small angle of block tilting and deep basins of S-type width exceeding the thickness of the pre-stretched crust cannot be produced by stretching. They can be termed 'grabens'. Famous instances include the Fen-wei in central China and the Viking in the North Sea. In sum, Artyushkov proposed that deep basins created by stretching constitute rifts and narrow basins in which extension produced only a minor portion of the subsidence comprise grabens.[14] Deep internal processes and continental rifting were discussed in detail in a special issue of *Tectonophysics* in 1987.[15] In addition, in 1987 another special issue of the same journal discussed the main and regional characteristics of continental rifts.[16]

Subduction zones constitute regions in which oceanic lithosphere created at spreading ridges and moving laterally away from them are consumed by sliding under another plate, which is usually of 'continental' structure. The track of the descending plate is characterized by earthquakes occurring in brittle materials and comprises the Benioff zone. The material being subducted is in a state of both thermal and gravitational instability, being cooler and denser than the adjacent asthenosphere. Some frictional heating of the upper part will occur, but the earthquakes take place in the coldest (interior) part. Anyhow, substantial heating could occur only if the descent of the downwardly moving plate is resisted by large shear stresses (several hundred megapascals (MPa)) and these are very improbable given the rheological properties of the asthenosphere. In fact, P. Bird in 1978 reported stress values under 20 MPa from the topmost 100 km of subduction zones.[17] There are geothermal zones related to subduction zones in Kawah Kamodjang in Indonesia (thrusting of the India plate under the China one); in the Puga, Chumathang and Parbati Valleys, Himalayas, northwestern India (with same cause but in a complicated region of convergence of continental crust of each plate); and in El Tatio, Chile (connected with the subduction of oceanic lithosphere below the continental plate along the west coast of South America). An excellent recent survey of structures and processes in subduction zones appeared in 1985.[18]

Some observations on intraplate thermal anomalies are appropriate here. These are found in oceanic lithosphere in the Hawaiian Islands, the Azores and a number of volcanic chains and seamounts in the Pacific, e.g. Easter Island and the Cook–Austral Islands. In continental lithosphere, Africa possesses many Cenozoic volcanic centres clearly not related to plate marginal processes, e.g. the Tibesti, Hoggar and Bayuda ones. Domal uplifts occur in the first two and it is interesting that ancient rock art with pastoral motifs is found on the Tibesti Massif. Both it and the Hoggar record the last ice age in the shape of cryonivational zones of slow mass movement. The Nile describes a great bend around the region of Bayuda volcanics, an area of central Sudan. In fact, the Central African Rift System ends here, thereafter bearing southwest through the Jebel Marra complex to Mount Cameroun.[19]

The magma sources probably lie deep under the lithosphere and, while the latter can move over them, they go on acting as heat creators from fixed positions relative to the mantle, inducing mantle plumes. Because these do not move much relative to each other, they constitute potential reference frames for plate motions. Chemical plumes can be formed from the inhomogeneous distribution of radionuclides or from convective upwelling. Such perturbations may extend as far as 700 km laterally, produce heating up to 400°C and promote a heat flow anomaly of the order of as much as $70\,mW/m^2$. Associated effects in the overlying lithosphere include expansion due to heat, uplift, thinning, fracturing and eventual intraplate volcanism. That taking place in Africa is alkaline in type with differing degrees of silica-saturation and -undersaturation.[20]

It is possible to explain mid-plate volcanism in terms of the thicknesses of plates and their velocities because, according to L. Rybach in 1981, penetrative magmatism goes on with a time-scale one to several orders of magnitude greater than heat conduction.[21] In the cratonic portions of continental lithosphere having thicknesses around 200 km and heat flow of less than $45\,mW/m^2$, the rather slow movement of plates (under 2 cm annually) tends to suppress the upwards ascent of sub-lithospheric thermal anomalies and thus to suppress mid-plate volcanism also. Thinner lithosphere and slower plate movement are necessary in order to develop volcanism and thermal anomalies at the surface, and the time-scale will be 10 million years or so.[21]

However, there is another possible explanation for intraplate volcanism,