SALT SYSTEMS OF THE EARTH

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WILEY

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Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

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Distribution, Tectonic and Kinematic History, Salt-Naphthids Interrelations, Discharge Foci, Recycling

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This edition first published 2018 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

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Wiley Global Headquarters
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Library of Congress Cataloging-in-Publication Data

ISBN 978-1-119-47905-5

Cover image: Dead Sea Salt
Cover design by Kris Hackerott

Set in size of 11pt and Minion Pro by Exeter Premedia Services Private Ltd., Chennai, India

Printed in the USA

Dedication

To my beloved son Oleg is dedicated

Abstract

Book's main subject is a systemic study of world salt bearing basins. It includes geological-tectonic review, analysis of tectonic and kinematic patterns of their positioning, structure and evolution, estimate of the nature and scale of the salt recycling processes, kinematic associations between salts and hydrocarbons. The study is based on a critical analysis of the published materials and author's own researchs. The author applied integrated approaches and methods of the modern sedimentary geology analyses types.

The analysis uncovered features of the salt basins' neo-geodynamic position, trends in their paleo-geodynamic evolution and patterns of space-time distribution. Salt bodies are classified by their kinematic features. The specifics of placement, morphology and tectonic evolution for different groups of bodies are reviewed. Special emphasis is made on a description of allochthonous salt nappes. For the first time is shown the significance of injection and injection-depositional processes in the salt and oil ontogenesis.

The author made a number of important conclusions regarding the patterns of tectonic evolution and general trends of morpho-kinetic evolution of salt bodies in the subsurface, showed the role of salts and naphthides recycling (their rebirth or regeneration) in their tectonic and kinematic history. A description of benchmark salt-naphthide objects as the centers of a recycling salt- and oil-accumulation is given. Their examples are used for a discussion and substantiation of genetic conclusions. As benchmark, the next objects of various geodynamic type and different scale are reviewed: salt-naftide belts along the margins of young oceans; the Mexican salt-petroleum «reactor», the Mediterranean salt bearing super-giant with the well-known Messinian events and paradoxes; the small oil-salt node Dead Sea. Also reviewed are various forecast and exploration aspects of the application of established tectonic and kinematic interconnections between the salt and hydrocarbons.

The book intended for scientists and field geologists, experts in theory and practice of salt geology, salt and petroleum geology, salt tectonics, geoecology and in a number of general issues of basin analysis, tectonics,

fluid-geodynamics, hydro-geochemistry, etc. It can contribute to the forecast of oil and gas potential. The study results may be useful for professors, postgraduates and students.

Keywords: Salt bearing basin, Salt tectonics, allochthonous salt nappe, kinematic evolution, injection, salt dome basin, salt recycling, Mediterranean basin, Messinian events, Mexican basin, Dead Sea, naphthide pools, hydrogen sulfide hydrocarbons.

This researchs were carried out at the Russian Geological Research Institute (VSEGEI, St. Petersburg, Russia). They were supported by the Ministry of Natural Resources and Environment of the Russian Federation and the Russian Foundation for Basic Research (projects Nos. 03-05- 65100-a, 07-05-00907-a, 10-05-00555-a, 10-05-11523-d, 12-05-00513-d).

The author will be pleased to accept any comments and suggestions by e-mail: gab_2212@mail.ru

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Contents

Introduction

The main object of this book is Earth's natural salt-bearing basins. The main subject is a study of their life cycle (ontogenesis[1]) based on a systemic analysis of a wide range of theoretical and applied issues of their geology. Basic among these issues are geologo-tectonic analysis of the salt distribution in Earth's crust, exposure of tectonic and kinematic patterns of their placement, structure and evolution, substantiation of the crust recycling processes' participation in the salt accumulation, and evaluation of kinematic interconnections between the salt and hydrocarbons.

Earth's subsurface is very rich in salts and brines. Salt-bearing sedimentary basins, i.e., large sedimentary rock bodies (geo-lenses) with the

[1] The ***ontogenesis*** (Greek on (ontos) things in existence + genos birth, origin) is the evolution history of an individual during his life; an aggregate of changes and transformations he has undergone since the moment of the origin to the end of life. This known biologic term is used by geologists in the study of evolution of not only organisms but also minerals, rocks, deposits of economic minerals, hydrocarbon accumulations and other geological objects of various scale (Geologic…, 2011). In this book, we view ontogenesis of the salt bearing systems as their evolution processes during the complete life cycles from the moment of nascence to the completion.

"stuffing" of thick salt sequences, are very common all over the planet. Currently, they are identified within all continents, seas, and oceanic margins. The salts are absent only in the abyssal space of the oceans proper, although even there salts often invade their near-continental margins. Both on the dry land and in the aquatoria salts are penetrated at all subsurface depths currently accessible to drilling. More than half (over a hundred) of relatively large sedimentary basins of the world are salt bearing. About 20 giants are drastically distinct in the volume of salt contained in them. Every one of those contains more than 100 thous. km^3 of salt and 14 of them, more than 500 thous. km^3. Four super-giants (the North Caspian, Mexican, East Siberian and Mediterranean) contain salt masses on the order of 1.5–2.5 mln. km^3 each. It is indicative that such amounts of the salt mass are comparable or even exceed the volumes of well-known geological super-giants of magmatic nature – trap complexes whose volumes, on the order of 1.0–2.0 mln. km^3 by various evaluations, are considered as a peculiar standard of super-large natural bodies. The total salt mass in all major basins of the globe is around 25 mln. km^3 (Belenitskaya, 2004b). About the same their mass is "over Earth's subsurface", in the surficial hydrosphere, in water of the World ocean and its seas (i.e., in brines with salinity on the order of 36 g/l). The amount of underground brines (high concentration and super strong) in the subsurface is similar. So that, if anything, it would not be an exaggeration to call our Earth "a Planet of the Salt".

The world of natural salts is diverse. There are the salts proper (the rock salt, or "simply salt" halite NaCl), closely associated with potassium-magnesium, more rare sulfate- and carbonate-sodium salts, their numerous associates bromine, boron, native sulfur, high-concentration brines (up to super-strong, 500–600 g/l and stronger) and also hydrocarbon gases, oil, condensate, hydrogen sulphide… All these so dissimilar geological formations localize around the salt and form the natural *halophilic* (salt-loving: *halo* is salt, *phil* is to love) community (Belenitskaya, 1998).

The facial-paleogeographic and paleogeodynamic environments of the salt-bearing basins accumulation are manifold. With every environment belong certain geochemical types of salt. The largest basins form in the deep-water marine paleo-environments within two groups of geodynamic regimes: extension (intra- and inter-continent-rift) and compression (active-marginal and collision belts). Essential is that the landscape-geodynamic types of the salt body paleo-environments carry important information about their composition and structure, about the nature of the salt-enclosing lateral and vertical formational series, depth structure, mineragenic and petroleum potential (Belenitskaya, 1998; Reef…, 2015; etc.)

The most important specific feature of the salt is high chemical activity and mobility in the subsurface environments, therefore chemical non-equilibrium and rheological instability. Besides, these features sharply strengthen with growing tectono-thermal activity. Due to this salts, brines and other members of the halophilic community are most active components of fluid-dynamic and injection intra-earthen systems. They are participants and catalysts of many chemical, physical and kinetic interactions. They are participants and the motivating force of the ascending and sublateral displacements of mobile masses up to their removal from the subsurface. The result of the latter are huge salt pillars-diapirs, extended salt walls often rising over many kilometers. The results of the latter are also grandiose underwater and underground allochthonous[2] salt nappes and salt glaciers spreading on the Earth's surface, fracture intrusions (salt dykes and sills) as well as powerful ascending streams, flows and explosive ejecta of brine-salt masses, hydrocarbon gases, oils, hydrogen sulfide and their mixes.

Eventually, one of the numerous important features of many salt-bearing basins is modification by the salt tectonics.[3] An intense modification is a characteristic feature of more than half large salt-bearing basins and of the overwhelming majority of the largest ones. The largest basins include a few hundred to a thousand and more salt dome structures each. The salt structures themselves include at least 50–60% of the entire mass of salt.

Mostly for a reason of the salt mass' rheological instability in tectonically active environments, their overwhelming part currently is (preserved) only in sediment cover complexes not subjected to tectonic deformations. Whereas within the tectonically deformed complexes of nappe-folded

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[2] ***Allochthonous*** (allos, *Greek*. – other, chthon, *Greek*. – Earth) – formed someplace else, alien to the place of the present occurrence.

[3] Under the term ***salt tectonics***, according to (Geological…, 2010; Tectonics…, 2004; The glossary…, 1979), we will understand a combination of structural-morphological manifestations of the injection-folded salt mass and enclosing rocks deformations caused by the processes of a differentiated rise, injection and invasion of a plastic salt in the overlying rocks or on their surface and their subsequent spreading. Trusheim (1990) proposed a close and quite convenient term "halokinesis" (Greek *hals* for the salt and *kinesis* for motion). However, there is an inconsistency in the understanding of this term and its interrelation with the term salt tectonics. The inconsistency depends on the authors' concepts of the forces causing the salt mass motion. This inconsistency increased after the discovery of various forms of the salt motion (squeezing out, slipping, flow, etc.). In view of this, we will be using for different forms of the salt mass motion mostly the term salt tectonics. We will call the motions caused by the tectonic forces proper, deforming also enclosing sedimentary series, the proper tectonic or ortho-tectonic ones.

areas and in platform basements the salts are incomparably less common. However, they are still present there, sometimes in significant amounts. Usually they are either relics of the original salt bodies or their migration derivatives, evidences of larger past salt bearing.

The salts are variably and at large scale developed in giant relatively young (Mesozoic-Cenozoic) salt dome basins and entire belts emerged due to Pangea disintegration. Their tectonic and kinematic history is more easily amenable to a reconstruction (compared with the Paleozoic basins). Among them are grandiose, extended over many thousands of km, Circum-Atlantic passive-marginal "ring", the East-African-Arabian intra-intercontinental-rift and Mediterranean collision belts. Within their limits are concentrated giant salt dome basins Mexican, Quanza-Cameroon, East Brazilian, West and East Mediterranean, Persian Gulf, Suez-Red Sea and a number of smaller ones (the Dead Sea, Palmira, Danakil, etc.) Characteristic for each basin is a very broad distribution of both the salt and other members of the salt community found in the subsurface, in the composition of ascending discharges and in numerous diverse surface manifestations. They all are powerful brine-salt "nodes". A special place is devoted in the book to a description and analysis of the life cycles of some of them.

Many salt-bearing basins, first of all the largest ones have exceptionally high petroleum potential. Many of these basins correspond with global maxima of naftide accumulation. A coincidence of large-scale naftide basins with the salt (and salt dome ones) giants enabled the identification of global "salt-naftide nodes" (Belenitskaya, 2013a). The aforementioned largest brine-salt "nodes" are among them.

A broad domain of the theoretical and applied issues of the salt geology was developed by researchers in various geological disciplines and scientific schools. Those have been tectonists, salt geologists, marine geologists, petroleum geologists, etc. In many countries, the scientists elucidated a broad spectrum of salt tectonic issues and its accompanying phenomena. Among these scientists are M.A. Ala, R.E. Kent, F. Lotze, C. Talbot, H. Richter-Bernburg, F. Trusheim, Yu.A. Volozh, R.G. Garetsky, M.V. Gorfunkel, V.S. Zhuravlev, A.T. Ismail-Zadeh, M.K. Kalinko, V.I. Kityk, V.S. Konishchev, A.I. Konyukhov, Yu.A. Kosygin, N.Ya. Kunin, A. Levorsen, Yu.G. Leonov, N.V. Nevolin, H.G. Sokolin, A.I. Timurziyev, V.E. Khain, V.N. Kholodov, I.I. Chaikovsky, A.Yu. Yunov and many others). These issues have been of an especial interest for the petroleum people. The very fact of the salt presence in the section of a petroleum basin had been for them one of the major landmarks at the conducting of any operations and at any stage. The issues of interconnection between the

salt and hydrocarbons are reviewed in broad generalizations (Aisenstadt, Gorfunkel. 1965; Aksenov *et al.*, 1985; Belenitskaya, 2011a, 2013a, 2014a, 2016; Geological…, 1977; Kalinko, 1973a; Kapchenko, 1974; Kudryavtsev, 1966; Levorsen, 1970; Perrodon, 1994; Sokolin, 1976; Jackson *et al.*, 1984; Volozh *et al.*, 2003; Dribus *et al.*, 2008; Cramez Carlos, 2006 and many others).

Our knowledge in many important issues of salt geology and especially salt tectonics has substantially expanded in recent decades. A versatile integrated analysis has been conducted of the salt formation and placement patterns. It fine-tuned or even changed a number of concepts including the concept of their paleotectonic position and history (Zharkov, 1978; Konishchev, 1980; Belenitskaya, 1998, 2000a). The data of halophilic (salt-loving) associations have been systematized (Belenitskaya, 1998, 2000a, 2008a). Thick salt sequences have been penetrated for the first time in sections of the Lower Pre-Cambrian (Gorbachev *et al.*, 2011). An avalanche-like growth of information about global salt-bearing basins is occurring. It is caused by an active development of the marine geologo-geophysical studies, by the blistering technical progress in marine drilling including ever deeper and deep-water[4]. The entire salt dome basin belts have been discovered broadly developed at great depths including in the substrate of deep-water aquatoria in marginal and internal seas, marginal young oceans. Significant success had been achieved in the study of the salt behavior at great depths under the environment of elevated fluid-dynamic activity, in tracing of their migration processes including the sublateral, forming expansive allochthonous salt nappes. Ever more specialized studies are devoted to these issues (Kropotkin, Valyaev, 1970; Pautot *et al.*, 1973; McBride, 1998; Combellas-Bigott, Galloway, 2006; Hudec, Jackson, 2006; Cramez, 2006; Moore, 2010; Brun, Fort, 2011, 2012; Rowan *et al.*, 2012; Rowan, 2014; Jackson *et al.*, 2015; Belenitskaya, 2016, 2017a; etc.). This ncreases the relevance and significance of the interconnection issues between the salt and hydrocarbons. A waterfall of data about the conjugation with the petroleum occurrences continuously accompanies the entire new information obtained at the study of giant salt dome basins and belts, at the salt penetration at all accessible depths. Many impressive discoveries in the knowledge of petroleum occurrences

[4] At the sea drilling, as deep-water are currently considered aquatorial areas at a depth of more than 300 m, and as super-deep-water, at a depth of more than 1,500 m (Dribus *et al.*, 2008). As the drilling technology evolves, the understanding of these terms changes (they mostly increase).

concern the potential of exactly salt-bearing basins, and especially often the subsalt sediments. They include "sub-allochthonous", overlain by the allochthonous salt nappes. The pictures of the salt and hydrocarbon joint migration in the subsurface are instrumentally and visually recorded. Their kinetic interconnections are traced. Salt-associated giant gas accumulations with unique hydrogen sulfide content and reserves have been discovered. The world leader among them is the North Caspian salt dome basin.

Despite great achievements in various domains of the salt geology (and sometimes due to them), the development of a number of important and pressing issues becomes insufficient. It concerns to the fullest extent the salt placement patterns in Earth's crust subsurface, its tectonic history and kinematic transformation at various stages of the geodynamic evolution. It also concerns the role of salt tectonic and ortho-tectonic processes in large-scale salt migration and its participation in the processes of a repeat salt accumulation. Extremely poorly characterized the salts positioned (preserved) in tectonically deformed complexes of the nappe-folded areas and in platform basements. The data of their presence within these areas are scattered in regional publications and are not systematized. The studies recovering the wholesome picture are absent. In the meantime, a systematization of the information about these salts, about the patterns of their joint placement, structure and morphology as well as the reconstruction of their original distribution and tectonic evolution is an important link in the general chain of restoring vital cycles of the salt-bearing basins. The particulars of salt kinematic and tectonic evolution and recycling processes in their reflection in the subsurface oil and gas occurrences as well as a conjugated nature of evolution and interconnection between various scale petroleum and salt objects are insufficiently studied.

The issue of the salt origin had always been in the spotlight of researchers' attention. A vast amount of publications is devoted to this issue. Currently, all over the world the evaporite (climatic) concept is commonly accepted. According to it, the main source of the salt is Earth's surface water and the main mechanism of its accumulation is the natural (sun) evaporation of this water. At the same time, the resolution of many issues of the salt genesis (within the evaporite "paradigm") remains far from unique, and causes discussions and arguments, sometimes embittered. One of the diehard representatives of the "evaporite school", major salt scholar M.P. Fiveg wrote: "Only a limited circle of experts know how disputable and complex the issue of the rock salt origin remains whereas in daily use it is believed that this «simple» problem has been solved long ago" (Fiveg, 1983, p. 5). In the meantime, along with the evaporite

concepts, a group of alternative hypotheses exists. These are injection-(brine-)-sedimentary (aclimatic) hypotheses. The hypotheses of this group consider as the major source of the salt accumulation the ascending discharges of brines or brine-salt mass from the subsurface into the sedimentary basins. One of them, "exhalation-sedimentary" maintains that the brines are of the mantle-magmatogene nature (Kudryavtsev, 1966; Sozansky, 1973; Dzhinoridze *et al.*, 1980; etc.). Under another one, "regeneration" (or recycling), these are buried paleo-sedimentary brine-salt masses reborn at depth and involved in the ascending discharge (Belenitskaya, 1989, 1998; partially Trusheim, 1990). The regeneration hypothesis substantially changes also the idea of the role of the processes of the salt tectonics and ortho-tectonics in salt accumulation. It substantiates the participation of these processes in moving more ancient salt masses at new depth and stratigraphic levels and their accumulation at these levels. Studies in recent decades substantially affected many ideas of the salt migration processes in the subsurface by seriously fortifying the factual base of the regeneration hypothesis. We will attempt to substantiate its applicability regarding the salt in this book.

The need of a critical analysis and synthesis of the data related to all the aforementioned issues utilizing new up-to-date approaches served as the main stimulus and basis for writing this book.

The book's objective is to describe the tectonic and kinematic patterns in the placement, structure and evolution of salt-bearing objects, to expose the nature and scale of the injection processes participation in the regeneration (geological rebirth, recycling) of the salt. The objective, further, is to examine tectonic and kinematic interconnections of the salt and hydrocarbons and to indicate the opportunities of their use for the forecast and exploration purposes. At that, we attempted to introduce all these issues in context of the unified more general and broader issue, the issue of the salt-bearing systems' ontogenesis. That allows viewing each of them as a factor in the ontogenetic evolution, and the kinematic evolution and recycling processes, as legitimate stages of the ontogenetic cycles.

The main **tasks** of the book have been a solution of the following issues:

- to systematize the information about global salt-bearing basins and to provide their review with the geologo-tectonic characteristic of all major basins;
- to open particulars of the neo-geodynamic position of the salt-bearing basins, the trends of their paleo-geodynamic evolution and general patterns of the spatial-temporal distribution and evolution;

- to systematize salt bodies by the type of their deformation, morphologic and kinematic particulars; to review the particulars in the placement and morphology of various group bodies paying special attention to the description of established only in recent decades allochthonous nappes; to conduct the evolutionary-kinematic analysis of salt bodies against the background of tectonic evolution of their enclosing structures;
- to lay open the significance of injection processes in the life of salt completing its kinematic history in the subsurface and preparing a new accumulative stage in its ontogenesis implemented in the discharge foci of the salt-bearing subsurface;
- to substantiate the author's concept of salt bodies' recycling (their rebirth or regeneration), to describe its kinematic, landscape-tectonic and synsedimentary aspects;
- to expound on examples of a number of the largest, various geodynamic type and scale salt-bearing objects, the role of salt bodies recycling phenomena in their tectonic and kinematic history, to show the possibilities of utilizing new approaches and genetic concepts at their analysis; to describe these objects as benchmark representatives of the regeneration naftide-brine-salt systems;
- to elucidate the nature of tectonic and kinematic interconnection between the salt and hydrocarbons and to show a possibility of using it at the solution of forecast-exploration tasks, at the evaluation of placement, scale and geochemical features of hydrocarbons;
- to evaluate some aspects of the impact of the natural salt, brines and hydrocarbon discharge processes, their explosive (crush) release and other manifestations on the natural medium, to review their probable ecologic and geotechnogenic consequences.

The achievement of the performance targets will define the basic **significance** of the study and its **novelty**.

In the work **new approaches** and methods of modern type analysis of the sedimentary geology have been used. They integrate the developments in the three study directions of the sedimentary basins under intense development for many years at VSEGEI with the active participation of the author. These developments are as follows. The systemic basin analysis

of salt-bearing sedimentary basins (integrated study of their geology, mineragenу and formation environment). The litho-geodynamic direction (tectono-sedimentary analysis of depositional basins) and the fluidal direction in sedimentary geology (evaluation of the role of Earth's depth fluid discharges in sedimentary processes) (Belenitskaya, 1998, 2000a, 2004a, 2008a, 2011b,c; Litho-geodynamics…, 1998; Belenitskaya *et al.*, 2001; Reef…, 2015; etc.). A combination of these approaches applied to salt-bearing (and petroleum) structures is quite efficient.

The book includes four parts, Introduction and Conclusions. *Part one* (Chapters 1–3) is mainly empiric. It deals with a geologo-tectonic review of the world salt-bearing basins, with analysis of patterns in geodynamic history of the salt accumulation and kinematic evolution of salt bodies. *Part two* (Chapters 4, 5) is genetic. It includes a versatile analysis and typization of Earth's ascending injection systems and a review of the injection processes' participation in salt accumulation. It discusses the processes of the crustal salt-naftide recycling. It includes a substantiation of a new regeneration (recycling) salt accumulation model. *Part three* (Chapters 6–9) provides a description of benchmark salt-naftide objects as the centers of a recycling salt- and oil-accumulation. Their examples are used for a discussion and substantiation of genetic conclusions. As benchmark, the objects of various geodynamic type and different scale are reviewed. They are as follows. 1) Salt-naftide belts and "rings" along the margins of young oceans. 2) The Mexican salt-petroleum "reactor" as the center of natural and geotechnogenic oil catastrophes. 3) The Mediterranean salt-bearing supergiant with the well-known Messinian events and paradoxes. 4) The Dead Sea, a small oil-brine-salt node and discharge focus. *Part four* (Chapters 10, 11) discusses spatial, kinematic and some geochemical aspects of the salt and hydrocarbons interconnection. It includes their evaluation as factors in the placement and as forecast criteria. The salt-naftide nodes are considered the centers of major world petroleum potential and omphalos of technogenic hazards.

When writing the book, the author used the data obtained in more than 50 years of research in the theoretical and applied issues of salt geology, formation environments of the salt and associated economic minerals (Belenitskaya, 1989, 1998, 2000a, 2004a, 2014a,b, 2016, 2017a). The studies had been conducted in various regions of the USSR and Russia (on the Russian, Siberian, Turanian platforms, in the Urals, Tien Shan, Pamir, etc.). For the Russian territory had been conducted a detailed geologo-mineralogical and paleo-geodynamic analysis of salt-bearing basins in various types of geological structures (Reefogenic…, 1990; Reef…, 2015).

The results of all these studies enabled the identification of most significant global and regional features of the structure, placement and evolution of various rank salt objects.

The book is based on a broad critical synthesis of the author's and published material. Along with the results of previously conducted studies, analysis of new publications and Internet information is included.

Acknowledgment. The development at VSEGEI of the studies in new domains in the sedimentary geology in various years have been helped by the support and attention from Academician RAN A.D. Shcheglov, N.N. Predtechensky, O.V. Petrov, and N.N. Sobolev. Valuable and always good-minded advice, discussions and consultations by a RAN Corresponding Member L.I. Krasny have been extremely important for the author. It is a pleasure to express gratitude to my wonderful colleagues, VSEGEI fellow-laborers Ya.K. Pisarchik, S.I. Romanovsky, N.N. Predtechensky, M.S. Gurevich, M.A. Minayeva, S.M. Korenevsky, N.N. Sobolev, V.G. Kolokoltsev, A.K. Ioganson. N.M. Zadorozhnaya, E.M. Pinsky and A.V. Lapo. The author has been lucky to conduct together with them in different years the field and theoretical studies and to discuss a broad complex of sedimentary basins' geology and minerageny issues.

It is my especial pleasure to express a deep gratitude to Dr. Michael V. Gorfunkel, a petroleum geologist specializing in salt geology and familiar with the issues of salt geology and their interrelations with petroleum occurrences. He was the one who has initiated and organized the publication of this book and made its scientific translation.

I am extremely grateful to Phil Carmical, Publisher, Scrivener Publishing, for his benevolent help and support at all stages of the teamwork.

I am thankful to N.F. Polyakova, I.N. Mozoleva, Maria Viktorova and Tatiana Shmelkova for highly qualified and assiduous work in the computer preparation of the Figures.

This researchs were carried out at the Russian Geological Research Institute (VSEGEI, St. Petersburg, Russia). They were supported by the Ministry of Natural Resources and Environment of the Russian Federation and the Russian Foundation for Basic Research (projects Nos. 03-05-65100-a, 07-05-00907-a, 10-05-00555-a, 10-05-11523-d, 12-05-00513-d).