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THE ANALYSIS OF SUBSIDENCE ASSOCIATED WITH GEOTHERMAL DEVELOPMENT

VOLUME 1. HANDBOOK

A Report Prepared For:

THE NATIONAL SCIENCE FOUNDATION,
RESEARCH APPLIED TO NATIONAL NEEDS
UNDER GRANT No. AER75-17298

(Handwritten signature)

SYSTEMS CONTROL, INC.

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THE ANALYSIS OF SUBSIDENCE ASSOCIATED WITH GEOTHERMAL DEVELOPMENT:

Volume 1 - Handbook

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Research Applied to National Needs
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COVER STORY

The illustration presented on the cover is a contour map of land subsidence that occurred from 1964 to 1974 in the vicinity of the geothermal development at Wairakei, New Zealand. The reference where this figure first appeared is as follows:

"Ground Movement in New Zealand Geothermal Fields," by Stilwell, W.B.; Hall, W.K.; Tawhai, J.; Ministry of Works and Development, Wairakei, Private Bag Taupo, New Zealand; presented at the Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, California, 20-29 May 1975.

The above reference clearly documents that ground subsidence and horizontal movement can be directly related to the development and operational practices associated with water-dominated geothermal fields.

PREFACE

A significant national effort is underway to develop geothermal resources, which may involve the withdrawal of geofluids from geological formations at depths on the order of one kilometer. Land subsidence is associated with the mining of geofluids. If land subsidence occurs, it can have significant environmental impacts. Broadly stated, the objectives of this study were to evaluate the state of knowledge of subsidence associated with geothermal development and to provide preliminary methods to assess the potential of land subsidence for any specific geothermal site. While the technical approach to achieve the above objectives was generic, and not centered on any particular site, the study results are applicable to the geothermal development presently occurring in the Imperial Valley of California.

The results of this study are presented in three volumes:

Volume 1: Handbook: A concise layman's version of present knowledge associated with the understanding, prediction and control of land subsidence that may be caused by geothermal development.

Volume 2: Research Report: A technical presentation of physical processes, geological indicators, geophysical measurement and modeling methods pertinent to the understanding, prediction and control of subsidence that may be caused by geothermal development.

Volume 3: Information Bank - A list of references relevant to the study of subsidence, keywords corresponding to these references, other sources of pertinent information, and a glossary of related terms.

This study was initiated in the spring of 1975, and funded for one year by the National Science Foundation's Research Applied to National Needs Program. The research was managed and performed by Systems Control, Inc., of Palo Alto, California. The researchers involved in the study are listed in the volumes to which they contributed.

The Program Manager of the study was Dr. Robert B. Schainker; the Co-Principle Investigators were Dr. Robert W. Atherton and Dr. E. John Finnemore.

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We are grateful to the NSF for the opportunity to perform this study and bring the results to the many interested and affected parties. The NSF project monitor, Dr. Ralph M. Perhac, of the RANN Environmental Effects of Energy Program, established high standards for this effort and unhesitatingly met all requests for guidance and assistance. Also appreciated during this study were the stimulating discussions and suggestions of Messrs. David Anderson, Dennis Allen, Paul Atkinson, Shawn Biehler, David Boore, Don Helm, G.M. Homsy, Ben Lofgren, T.N. Narasimhan, and Marshall Reed.

Special appreciation is also due to Ms. Ruth Nameck for expertly typing the manuscript and patiently enduring the revision process.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Land subsidence is a local mass movement that involves principally the gradual downward sinking of the solid earth's surface. Horizontal motion may be experienced as well. The immediate cause of land subsidence is the removal of support caused by a reduction in pore pressure in a porous layer beneath the surface (Poland and Davis, 1969). In geothermal resources, pore pressure is provided by steam or water, and reduction occurs with the withdrawal of these fluids in the course of geothermal development.

The earth's heat, geothermal energy, has the potential to provide a substantial portion of the U.S. energy requirements before the end of this century. A recent assessment of the geothermal resources of the United States (White and Williams, 1975), indicates "that the total magnitude of geothermal resources that can be recovered by present and near current technology is very large." For hydrothermal reservoirs alone, the expected total energy contained in known geothermal fields in the United States is $3.2 (10)^{18}$ BTU's, (Schainker, et al., 1976).

It is not surprising, then, that in the past several years, the subject of geothermal power has received increased publicity and attention in industrial, governmental and public circles. Interest in geothermal energy has been stimulated in part, by the long term successful operation at the Geysers geothermal field, by discoveries of many other high temperature geothermal fields in the western United States, and by the increasing demand for non-petroleum energy resources. Of particular note, are the plans for the development of hydrothermal (hot water) resources in the Imperial Valley of California.

As with other energy sources, development and operation of geothermal energy resources must consider and mitigate potential environmental degradation. Land subsidence has resulted from the withdrawal of a variety of underground fluids in many different areas (Poland and Davis, 1969), and when it occurs, land subsidence can be a major environmental hazard.

The geothermal site at Wairakei, New Zealand has experienced over 4.5m of subsidence and an associated horizontal ground movement of 0.8m (Stilwell and others, 1975). This alteration of the earth's surface not only affected the run-off characteristics of the land, but it also damaged the network of pipes leading to and from the power generation plant. Thus, land subsidence is potentially an environmental, as well as power production hazard in the development of geothermal resources.

1.2 PURPOSE

This document is designed to serve as a concise reference, a handbook, for the evaluation of the potential for land subsidence from the development of geothermal resources. Its contents will be useful to those involved in understanding land subsidence and its environmental impacts, as well as those involved in developing geothermal resources; however, it is intended to be most useful to those who work in the intersection of these two fields and who are, consequently, interested in the understanding, prediction, and control of land subsidence that may be caused by geothermal development. This interdisciplinary field will be designated as geothermal subsidence.

Thus, the purpose of this Handbook is to present a synthesis of the available information relating to geothermal subsidence, and to provide guidance in its use for the evaluation of geothermal land subsidence. Not only does this Handbook serve to collect in one place available information on geothermal subsidence, but also it presents, for the first time, much unpublished information on subsidence and geothermics.

1.3 METHOD OF APPROACH

The study of land subsidence associated with geothermal development, geothermal subsidence, does not exist as a separate field of study. Rather, it must be approached as an interdisciplinary study drawing from such diverse disciplines as geology, geophysics, reservoir engineering, solid mechanics, fluid mechanics of flow in porous media, numerical methods, soil and rock mechanics, and modeling. To make a hard task even more difficult, in order to study satisfactorily many aspects of this complex problem, a detailed knowledge of some areas of these disciplines is required.

A superficial transfer of knowledge across disciplines does not suffice. Rather, the aspects of each discipline pertinent to geothermal subsidence must be identified and then correctly applied, to achieve an understanding of the complex phenomena involved. The result of this process is a synthesis of knowledge on geothermal subsidence formulated across several fields of knowledge. (See Figure 1.1.)

The synthesis contained herein was performed in part by gathering documents, published papers, and data on subsidence, geothermics, and related fields of knowledge. In addition, it involved a study of the geologic framework of subsidence, an evaluation of geophysical methods, and a review and evaluation of reservoir and subsidence models.

A key element in performing the synthesis was the forming of a project team whose members had training in several different disciplines.

Figure 1.1

**Geothermal Subsidence as a Synthesis Across Many
Fields of Knowledge**

1.4 ORGANIZATION OF THE HANDBOOK

This Handbook is divided into two parts: (A) "A Primer on Subsidence and Geothermics," and (B) "Subsidence Evaluation Procedures." The primer is designed to provide an overview of the areas of information important to understanding subsidence and geothermics. The second part presents concrete procedures for the evaluation of subsidence potential.

Part A, the primer, consists of seven chapters, Chapters 2 through 8. Chapter 2 contains a discussion of subsidence and its environmental effects. Chapter 3 provides an overview of geothermics, while Chapter 4 indicates the physical processes through which subsidence occurs. In Chapter 5, we discuss the geologic indicators of subsidence potential, and Chapter 6 presents the determination of subsidence indicators from geophysical measurements. Chapter 7 contains a survey of geothermal reservoir models and lastly Chapter 8 presents a survey of subsidence models.

Part B, subsidence evaluation procedures, consists of five chapters, Chapters 9 through 13. Chapter 9 gives an overview of subsidence prediction techniques. Chapter 10 discusses an analogy method for evaluating subsidence. Chapters 11 and 12 present a quantitative analysis method of evaluating subsidence by presenting first a lumped, fundamental reservoir model and then a Handbook calculatable model for reservoir compaction. Lastly, Chapter 13 discusses operating policies for the mitigation of subsidence.

1.5 REFERENCES

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PART A
A PRIMER ON GEOTHERMICS AND SUBSIDENCE

- Chapter 2: Subsidence and Its Environmental Effects**
- Chapter 3: An Overview of Geothermics**
- Chapter 4: Physical Processes of Subsidence**
- Chapter 5: Indicators of Subsidence Potential**
- Chapter 6: Subsidence Indicators From Geophysical Measurements**
- Chapter 7: Geothermal Reservoir Models**
- Chapter 8: Subsidence Models**

CHAPTER 2
SUBSIDENCE AND ITS ENVIRONMENTAL EFFECTS

2.1 INTRODUCTION

2.1.1 In General

The focus of this chapter is on assessing the impact of subsidence, given that it will occur. While land subsidence is not the only side effect of geothermal operations which has an environmental impact (Axtmann, 1974; Bowen, 1973), it is certainly one of the more dramatic (as illustrated in the photographs of the effect of subsidence on man-made structures presented by Poland and Davis, 1969).

We shall find that the impact of subsidence can vary widely. For instance, subsidence, when it occurs in a developed area, can be one of the most costly environmental impacts; subsidence near the Wilmington Oil Field of California caused estimated damage in the hundreds of millions of dollars (Huey, 1964). The effect on natural systems can also be quite dramatic. Axtmann (1975) has suggested that if the Broadlands, New Zealand geothermal field experiences the same magnitude of subsidence as Wairakei, a new lake will form from the Waikato River. On the other hand, however, subsidence offshore, away from coastal areas, will have little environmental impact.

2.1.2 Chapter Overview

The next section discusses subsidence and some examples of its occurrence. In the following sections, three key points concerning the environmental impacts of land subsidence are emphasized. These points include a general discussion of the potential impacts of subsidence (Section 2.3), a discussion of the potential for disruption of the industrial facilities used in geothermal development (Section 2.4), and emphasis on the variability of the potential for environmental impact (Section 2.5).

2.2 GROUND DEFORMATIONS ASSOCIATED WITH SUBSIDENCE

Three kinds of ground deformation may result from fluid withdrawal: vertical lowering of the ground surface, horizontal movements, and faulting (Yerkes and Castle, 1969). The term "subsidence" strictly refers only to vertical movements, but it is also frequently used to refer generally to both vertical and horizontal movements (see Section 5.1).

2.2.1 Vertical Lowering

Vertical lowering of the ground surface is the basic characteristic of subsidence areas. This lowering results from decreased fluid pressure and the concomitant increase in effective grain-to-grain stress (see Chapter 4). Conversely, increasing the fluid pressure can cause the land surface to rebound, as at Wilmington (Mayuga, 1970), although the rebound is generally small, as compared to the prior subsidence.

The maximum vertical lowering experienced at a hydrocarbon field was 8.75m at Wilmington (Allen and Mayuga, 1970); at a groundwater field it was 9.15m in the San Joaquin Valley (Lofgren, 1976); and at a geothermal field 4.7m at Wairakei (Stilwell, and others, 1975). The area affected depends on the lateral extent of the aquifer or reservoir and varies from tens of square kilometers for hydrocarbon and geothermal fields, to hundreds or thousands of square kilometers for groundwater fields.

The vertical movements generally produce a depression or "subsidence bowl" centered over the area of fluid production. (See Volume 2, Research Report, Chapter 3.) The deformation typically increases from the outer edge of the affected area to one or more maxima. In one important case, the Wairakei geothermal field, the subsidence bowl does not coincide with the main producing area, but is offset from it by a half a kilometer (Stilwell, and others, 1975).

2.2.2 Horizontal Movements

Horizontal movements in subsiding areas result from the horizontal component of the motion associated with the deformation. In addition, horizontal movements are associated with induced horizontal gradients in fluid pressure and associated seepage stresses (Lofgren, 1969). Measurements to detect such horizontal movements have been conducted in very few subsiding areas, but because the creation of horizontal fluid pressure gradients is a necessary consequence of fluid production, horizontal movements are generally thought to be present even in the surveyed areas. The greatest measured horizontal movements are 3.7m at Wilmington (Mayuga, 1970) and 0.8m at Wairakei (Stilwell, and others, 1975). The movements are generally directed toward the center of the subsidence bowl.

Repressuring, as at the Wilmington oil field, may release horizontal as well as vertical stresses, causing additional horizontal movements to occur as the surface rebounds. The direction of horizontal movement stimulated by the repressuring, may differ from its direction during subsidence (Allen, 1973).

2.2.3 Faulting

Faulting has been associated with fluid withdrawal and subsidence at many hydrocarbon fields (Yerkes and Castle, 1969) and at a few groundwater-producing areas (Poland and Davis, 1969). To date, no faulting has been induced by production at geothermal areas (Bowen, 1970), but previous experience indicates that faulting is a distinct possibility. Witherspoon and Gale (1970) have recently reviewed the mechanics of induced faulting, originally described by Hubbert and Rubey (1959).

2.3 SUBSIDENCE IMPACTS

In the previous section we discussed the ground motions associated with subsidence. We now consider the direct impacts of these movements on natural systems and man-made structures. Table 2.1 catalogues these impacts and briefly summarizes the severity of potential problems and identifies if any method of correcting the problem is possible. Potential impacts on natural systems include the alteration of drainage paths for surface waters, change of aquifer storage and transmissivity characteristics, triggering of minor earthquakes, and increase in flooded areas. The postulated Waikato Lake in New Zealand, mentioned in Section 2.1.1, is indicative of the potential of such impacts.

The presence of a number of man-made structures in a subsiding area also provides the potential for a large impact from subsidence. The ground movement associated with subsidence potentially can disturb any sizeable man-made structure. Complete failure of roads, pipelines, power lines, and dams can result. As at Long Beach, California, the costs of repairs can be in the hundreds of millions of dollars.

Obviously the impact of subsidence is related to the magnitude of subsidence. Subsidence of one to two centimeters can often be negligible, whereas subsidence of several meters usually results in a costly impact. Associated with subsidence are horizontal motions as well as vertical motions, and the horizontal movements may cause as much or more damage than the vertical movements.

Table 2.1

Direct Subsidence Impacts

Impacts	Potential Problem Severity	Methods of Correction
<u>ON NATURAL SYSTEMS</u>		
1. Alteration of drainage paths of surface water	Serious in developed areas, otherwise, moderate	If possible, develop the geothermal field several kilowatts distant from large streams, or re-route the streams
2. Increase in flooded areas	Serious in developed areas. Can result in new lakes, etc.	Same as above
3. Change of aquifer storage and transmissivity	Moderate to serious depending on need for groundwater	None
4. Triggering of minor earthquakes	Small	None
5. Disruption of vegetation	Small	Replant the vegetation
<u>ON MAN-MADE STRUCTURES</u>		
6. The geothermal plant	Complete failure	If possible, build away from geothermal field, accepting less thermal efficiency; or design structure to accept some ground deformation
7. Damage to wells and well casings	Serious, may cause leaks to groundwater	---
8. Pipelines	Complete failure	Use flexible piping
9. Houses and buildings	Serious	Build away from geothermal field
10. Irrigation channels	Complete failure	If possible, develop geothermal field several kilometers distant
11. Roads	Serious	Same as Item 10, fill and repair
12. Power lines	Complete failure	Same as Item 10, repair
13. Railroad tracks	Complete failure	Same as Item 10, repair
14. Sewers and drains	Complete failure	Same as Item 10, repair
15. Dams and levees	Complete failure	Same as Item 10, repair
16. Air fields	Serious	Same as Item 10, repair

2.4 IMPACT ON OPERATIONAL FACILITIES

A class of man-made structures of particular interest are the operational facilities associated with resource exploitation. Among these are the wells and well casing, the production gathering system, and the power plant. It is an interesting aspect of subsidence that the causative agent, the resource exploitation facilities, can be strongly impacted. Thus, a major concern to operators of a geothermal resource is the potential of subsidence damage to the production facilities.

For example, at Wairakei, the geothermal development experiencing the most subsidence to date, (Bolton, 1970; Stilwell and others, 1975), horizontal ground movements did create operational difficulties in the field (Axtmann, 1974). The center of the region of maximum subsidence lies only 460m north of the main steam mains, and horizontal ground movements impacted the piping system requiring the addition and removal of short lengths of pipe. In particular, one of the concrete wastewater channels suffered compressive failure, and the replacement joint indicated a movement of 10.2cm. Fortunately the main electric power generating station was not in the region of maximum subsidence. Nevertheless, this example indicates that operators of geothermal fields should be concerned with the potential of subsidence, for the practical reason of minimizing operational difficulties.

2.5 THE VARIABILITY OF THE POTENTIAL FOR IMPACT

The severity and nature of the environmental impact of subsidence depends strongly on the characteristics of natural and man-made structures near the site. For instance, flooding is not a problem in areas where there are no bodies of water or minimal yearly rainfall. Similarly, the lack of a substantial number of man-made structures reduces the potential for building damages.

To further emphasize this point, consider the potential impact of subsidence on the agricultural resources of the Imperial Valley, California. Even moderate subsidence is probably not acceptable in such an agricultural area. Any resultant alteration of irrigation and drainage patterns will drastically affect the crop yields and even the types of crops planted, if any. The same amount of subsidence, however, would not be as serious a problem, in nearby desert areas.

2.6 SUMMARY

Land subsidence, when it occurs, can and often does, have a significant environmental impact. The operational facilities of the developed geothermal field may be an area of strong impact. If subsidence occurs away from man-made structures or irrigation channels, it may have little impact.

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CHAPTER 3
AN OVERVIEW OF GEOTHERMICS

3.1 INTRODUCTION

The subject of geothermal subsidence is intimately connected with geothermics and in particular with reservoir engineering and the operation of the above-ground facilities. Thus, to view geothermal subsidence in its proper perspective, some knowledge of the total geothermal system is required. The complete geothermal system consists of the geothermal reservoir, the geothermal well, the surface gathering system, and the electric-power generating facility.

Presented in this chapter is an overview of these system components, as well as a summary of the types of geothermal resources, and the concept of a porous medium.

3.2 TYPES OF GEOTHERMAL RESOURCES

In a broad sense, the term "geothermal" refers to the heat of the earth; herein we use it to refer to physical systems in which the earth's heat is concentrated and thus forms an energy resource. The variety of geothermal systems which occur worldwide can be classified according to geological characteristics, hydrological characteristics, or mode of heat transfer (White and others, 1971; White and Williams, 1975). The usual method of classification involves the following five geothermal system types: vapor-dominated hydrothermal resources; liquid-dominated hydrothermal resources, geopressured resources, hot-dry rock resources; and magma resources.

These systems are discussed in detail in Volume 2, Research Report. In the sections which follow, we only briefly describe the characteristics of the above resource types, with particular emphasis on the resource types which have the most potential for subsidence.

3.2.1 Hydrothermal Systems

Geothermal resources that contain hot water and/or steam are known as hydrothermal systems. In general, both convective and conductive processes govern the transport of heat in these systems; however, in some sites one of these processes may dominate. In hydrothermal convection systems, most of the heat is transported by fluid flow through porous, permeable rocks. In hydrothermal conduction systems, the primary mode of heat transfer is from the hot rock to the fluid by kinetic molecular processes.

Liquid-dominated hydrothermal systems are those in which the fluid is predominately all liquid (see Chapter 11). Liquid-dominated, two-phase reservoirs contain both steam and water, but water is the dominate phase

by volume fraction (see Chapter 13). In vapor-dominated reservoirs, the steam phase occupies the larger volume fraction. Two-phase reservoirs are more likely to transport heat by convection.

In general, as a liquid-dominated resource is developed, it will progress through four stages characterized by the fluid phase. The second and third stages are two-phase (liquid and steam) systems, liquid-dominated and then vapor-dominated, respectively. The fourth and final stage of the reservoir is a pure steam system.

3.2.2 Geopressured Geothermal Systems

Geopressured geothermal resources are characterized by reservoir fluids existing at greater than hydrostatic pressure. Such systems are thought to be isolated with regard to flow and compartmentalized by faults. It is this isolation which allows the buildup of fluid pressure, in a manner analogous to heating a sealed can of water. The reservoir fluid in a geopressured system carries more of the total stress than in a normal pressured hydrothermal system.

3.2.3 Other Geothermal Systems

The remaining resource types are hot dry rock and magma. Hot dry rock is simply a geological formation having a high heat content, but no fluid to act as a heat transport medium. A major problem in the exploitation of hot dry rock is determining a method of introducing fluids to enable the heat to be transported (by convection) to surface generating facilities.

Magma, which is molten rock in the temperature range of 650°C, can be considered the ultimate geothermal heat source, but commercial development is in the distant future. In general, magma systems contain insufficient fluids to enable heat transport to surface generating facilities.

3.2.4 Geothermal Resource Types with Significant Potential for Subsidence

The potential for subsidence from a geothermal system is predominately related to the amount of pressure reduction in pores of subsurface rocks that occurs as the geothermal fluids are extracted. Of the varied types of geothermal resources extant, fluid withdrawal from geopressured and hydrothermal systems cause significant pore-pressure reduction; and hence, these resource types exhibit the greatest potential for subsidence.

In geopressured systems, the pore-pressure actually supports the rock strata above the resource and any withdrawal of fluids will irreversibly stimulate subsidence.

In hydrothermal systems, the pore-pressure is primarily determined by the type of fluid in the rocks. Systems containing substantially all liquid are the most prone to subsidence. Two-phase, liquid-dominated systems wherein water is produced are the next most likely to experience subsidence. Vapor-dominated, two-phase systems are the least likely to subside.

Chapter 11 discusses the above characteristics of geothermal systems in greater detail. The geothermal systems likely to be exploited with near-term technology are hydrothermal and geopressured systems. Thus, an assessment of their subsidence potential is timely, and major emphasis of this Handbook will be placed upon evaluating these types of geothermal systems. Since the remaining resource types, magma and hot, dry rock do not contain the fluid phase as a component of the natural system of stress equilibrium, it is unlikely they will be prone to subsidence. Furthermore, the small likelihood of near-term exploitation reduces their present importance; thus, less emphasis will be placed on them in subsequent discussions.

3.3 GEOHERMAL RESERVOIR CHARACTERISTICS

3.3.1 Porous Medium

Physically the geothermal reservoir is a geological layer or stratum which consists of a fluid occupying the interstices of a porous material. The reservoir may be considered in terms of a porous medium, a concept of fundamental importance.

A porous medium is a heterogeneous or composite material composed of a solid matrix and fluid-filled voids (see Figure 3.1). It is important to recognize that the spatial distribution of voids and rock matrix material is not entirely arbitrary. We note three essential characteristics of a porous medium (Bear, 1972): (1) there exists a representative elementary volume, with characteristic diameter, which contains both voids and solid matrix; (2) the specific surface area of the solid matrix is high; and (3) the diameter of the void space relative to the extent of the reservoir is small, and both the absolute and relative size of the pore spaces is significant in understanding the behavior of the porous medium. To gain an appreciation for the geothermal reservoir relative to other porous materials, listed in Table 3.1 is the lateral extent of a medium and the mean diameter of the pore space for several porous materials of interest (Homsy, 1975).

Darkened Area
Represents Rock

Figure 3.1 **Representation of a Porous Medium**

Table 3.1 Characteristics Dimensions of Porous Media

Porous Media	Extent (L)	Pore Diameter (d)
Packed Beds	3m	100 μ m
Geothermal Reservoir	1km	10cm
In-situ Coal	1km	1mm
Coal Processing	3m	3cm
Shale	1km	<<.1mm
Oil Reservoirs	.1 to 1 km	.1 to 1mm

A fundamental descriptive quantity for a porous medium is the porosity, ϕ , which is defined to be volume fraction of the composite material that is void space. Obviously, the porosity does not completely characterize the medium (Scheidegger, 1974). For geothermal reservoirs, the porosity is usually in the range 0.2 to 0.4. We remark that the existence of pore space is not sufficient for the existence of a reservoir; the pore spaces must be interconnected so that fluid may flow to a producing well.

3.3.2 Flow in Porous Media

The subject of flow in porous media is one of great technological importance, and consequently, one with a large literature (Bear, 1972; deWiest, 1969; Polubarinova-Kochina, 1962; Scheidegger, 1973). Because of the lack of knowledge of the detailed geometry of the pores, it is impractical to calculate in detail the flow of fluids through pore spaces. The usual approach is to assume a constitutive relation, such as Darcy's law, relating fluid velocity to pressure gradient. The permeability, which is a parameter in the constitutive relation, is a measure of the resistance of the material to flow. Permeability has dimensions of L^2 ; and a common unit is the darcy which has a value of $0.987 \times 10^{-8} \text{ cm}^2$.

Whether or not Darcy's law is valid depends, in part, upon the average pore size, which determines the hydrodynamics within the pores. Pore spaces may be classified as voids, capillaries, and force spaces (Scheidegger, 1974). Voids are the class of pores with the largest diameter and are characterized by the fact that the effect of the pore walls on interior flow is insignificant. The walls, of course, provide a no-slip boundary condition, which is important in describing the flow fields in capillaries, the next smaller size. When describing force spaces, the molecular nature of the fluids must be considered.

Darcy flow is most valid in describing slow flow through a porous medium whose pore spaces are predominately in the capillary class. In geothermal reservoirs, however, it has been widely suggested that a number of fractures, void spaces, are present. Thus, Darcy's law must be used with care in the analysis of geothermal reservoirs.

3.3.3 Thermodynamic Phases in Reservoirs

The thermodynamic state of the reservoir is a function of temperature and pressure, which may vary with position in the reservoir. For the moment let us consider the average properties of the reservoir. Considerations of fundamental thermodynamics as represented by a phase diagram dictate that the temperature and pressure determine the phase of the reservoir fluid. Below the critical point the phase diagram for water is divided into a steam region and a water region. Along the saturation curve, which forms the boundary of the two regions, both phases can exist simultaneously. Thus, if the average reservoir pressure and temperature fall on the saturation curve, a two-phase reservoir (liquid and vapor) will exist.

In studying liquid and two-phase reservoirs, the subject of flashing, the transition from water to steam, is important. Since temperature and pressure vary spatially at depth, the possibility exists that flashing can occur in any local region of the reservoir where the temperature and pressure reach a state on the saturation line. Such a region might occur near a well. In addition, as the overall pressure of the reservoir drops, flashing can and does occur on a large spatial scale. The mechanism of phase-transition within the reservoir is a complicated subject, and is only partially understood at the present state-of-the-art.

3.4 THE GEOTHERMAL WELL

Geothermal fluids are produced at the surface via the geothermal well. Most hydrothermal production worldwide presently comes from depths between 1,500 and 2,500 meters, although the average well depth is less in some areas. A few "wildcat" wells up to 3,300 meters deep have been drilled (McNitt, 1975), but drilling deeper than 3 km is unlikely, due to large costs for drilling (Muffer, 1975). The depth of present geothermal wells and those to be drilled in the near future, is comparable to the depths of oil and gas fields, and barely exceeds the maximum depth of groundwater aquifers.

The wellbore is an important part of the geothermal production system. At the surface we observe the mass flow rate, temperature, pressure, and phase of the produced fluid. The produced fluid is the feed to the power plant and is one of the major observable variables in studying reservoir behavior. Since significant physical transformations occur within the wellbore, a full understanding of the flow, temperature, and phase behavior is necessary to predict and control the well output and to calculate the downhole conditions as clues to reservoir behavior.

With regard to the design, analysis, and operation of geothermal systems, the diameter of the wellbore, the mass flow rate, the pressure drop, and the temperature of the produced fluids are important. The diameter of the wellbore is, of course, fixed. The first three variables however, are strongly interrelated, and in turn, are influenced by reservoir conditions in the neighborhood of the wellbore inlet. With regard to downhole conditions, the phase relationships at the outlet (mass fraction of steam) are not the same as those in the reservoir, since flow up the wellbore is a flashing flow. Thus, it is possible for a liquid

reservoir to produce predominantly steam at the wellhead. To quantify adequately the behavior of the geothermal well requires an accurate description of the coupled temperature and pressure profiles, as well as an accounting for the flow regime and phase changes (Gould, 1974; DeGance and Atherton, 1971).

3.5 GATHERING SYSTEM

The type of fluid produced from a geothermal well is usually a two-phase mixture (water and steam) which can either be separated into single phases at the wellhead and transported separately, or it can be separated at the power plant. In either case, the gathering system of the geothermal field consists of a simple branch network of pipes, connecting the wellbore to the power generating plant.

The gathering system collects the geothermal fluid of the wells, and transports it with as little reduction in enthalpy (heat energy) as is practical. It must be equipped with insulation sufficient to conserve heat, and of such a size as to offer minimum resistance to flow. The greater the power plant input temperature and pressure, the greater is the potential of produced power; consequently, the pressure and enthalpy losses in the gathering system must be minimized. Thus, the determination of the pipe size must consider not only the phase of the geothermal fluid, but also the influence of size (surface area and diameter), on both heat loss and pressure loss. The objective of maximizing steam flow and minimizing heat loss and cost, serves to define an optimization problem which confronts the design engineer in the synthesis of the geothermal surface facilities.

3.6 POWER PLANT

Like other power plants, the geothermal power plant involves the production of power by expanding a gas at a high pressure through a turbine and condensing it after it exits the turbine exhaust. Clearly, the geothermal plant differs from a fossil-fuel or nuclear plant insofar as the latter plants require steam generating facilities, whereas the former do not. Depending upon conditions in the reservoir and the wellbore, the geothermal fluids produced may be steam and hot water, or a single steam phase. Steam and hot water differ insofar as more hot water is required to produce a given amount of power. The actual difference is dependent upon the fluid temperature and pressure, and varies continuously over the range of steam quality. At the Geysers, the steam turbine inlet temperature is 180°C and the pressure is 8 kgcm^{-2} ; 0.8 kg of steam produce 1 kwh of electricity; whereas for a typical hot water system, $200\text{--}300^{\circ}\text{C}$ at 10 kgcm^{-2} , 5-10 kg of water may be required to generate 1 kwh of electricity.

If the geothermal fluid leaving the wellhead is a dry steam, then the power plant is just a steam power plant, i.e., essentially a steam turbine generating unit, and hence, is an example of a so-called open system (Laird, 1973). A steam turbine generating unit consists of a steam turbine, a generator, and steam condenser. The steam enters the turbine at a high pressure and exits at a lower pressure; the steam expansion is converted to electricity via the generator. The steam leaves the turbine and enters a condenser. Here the steam condenses by mixing with cooling-tower water. Noncondensable contaminants are treated and removed from the plant with separate waste unit processes.

If, however, the fluid leaving the wellhead is a steam-hot water mixture, a special power plant is required (Austin and Lundberg, 1976). There are several methods of producing power from such a system. One is to flash the steam-hot water mixture to steam at a reduced pressure and then treat the steam in the same manner as the dry steam power plant. This is the method successfully used in New Zealand and Mexico. Another method, the vapor-turbine cycle, described by Anderson (1973), uses a so-called closed system of heat exchangers and a turbine with a separate working fluid. Still another method is the total flow concept, which involves direct expansion of the entire wellhead fluid (Austin and Lundberg, 1976).

3.7 SUMMARY

The above material is only presented to briefly review some of the major topic areas associated with geothermal development and operational principles. For a more detailed discussion, the interested reader is encouraged to review the references cited, as well as Volume 3, of the Research Report.

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CHAPTER 4
PHYSICAL PROCESSES OF SUBSIDENCE

4.1 INTRODUCTION

Ground subsidence and associated horizontal movements are considered a potential consequence of production in geothermal areas (Lofgren, 1973; White, 1973; Whiting, 1973; Papadopoulos and others, 1975), because they have frequently accompanied the withdrawal of other fluid resources (e.g., Poland and Davis, 1969). According to Lofgren (1973), five types of ground movements may occur in geothermal areas: subsidence or rebound of the land surface, due to fluid pressure changes; lateral ground movement, due to induced fluid pressure gradients; vertical ground movement, due to thermal expansion or contraction of the rocks; tectonic faulting or folding; and landslides and mass wasting (slow downslope movement of rock materials due to gravity). Of this group, only tectonic movements, landslides, and mass wasting are unrelated to resource production.

This chapter is devoted to a discussion of the processes causing ground movements in geothermal areas. The potential severity of these processes is listed by resource type in Table 4.1. In the discussion following, major emphasis is given to compaction due to fluid withdrawal. Fluid extraction results in a transfer of load from the pore fluid to the solid framework of a rock, and causes compaction primarily through textural changes on a grain-to-grain scale. This process has produced subsidence of as much as 8.8m and horizontal movements of 4.5m at Wilmington oil field, California (Allen, 1973) and 4.5m vertical and 0.8m horizontal at Wairakei geothermal field, New Zealand, (Stilwell and others, 1975).

Lesser amounts of compaction and subsidence may be caused by fracture closing in response to decreased fluid pressures and, temporarily, by thermal contraction. Landsliding and tectonic movements are not discussed in this chapter because their occurrence depends highly on local conditions which are not necessarily associated with geothermal systems. However, tectonic movements at the rate of millimeters to centimeters per year may occur in geothermal systems because of their common location in tectonically active areas.

Table 4.1 Potential Severity of Subsidence Processes in Geothermal Areas

Resource Type	ΔP^* (kg/cm ²)	ΔT (°C)	Fluid Withdrawal	Fracture Closing	Earthquake Shaking	Thermal Contraction	Tectonic Movements
Magma	----	≤300	----	----	----	X	Variable
Hot Rock	----	≤200	----	----	----	X	Variable
Steam	30	~5	X	X	X	X	Variable
Hot Water	50-250	10-50	XX or XXX	X or XX	X or XX	X	Variable
Geopressured	250-400	10-50	XXX	X	X	X	Variable

Severity of potential subsidence:

XXX Significant (more than 1 m)
 XX Minor (less than 1 m)
 X Negligible (few mm or cm)
 ---- Not Applicable

*Approximate maximum drawdown to minimum enthalpy input requirements of generating systems; depends on both temperature and pressure. Full flashing assumed in initially liquid reservoirs.

4.2 COMPACTION DUE TO FLUID WITHDRAWAL

4.2.1 Introduction

Compaction results from a transfer of load from the pore fluid of a rock to its solid grain framework. This transfer takes place as the pore fluid is sucked or squeezed from the rock, causing the internal pore fluid pressure to decrease. The additional load applied to the grains tends to rearrange, distort, and break them, causing the rock to reduce in volume.

Compaction is a natural process which occurs in all sedimentary rocks at a very slow rate from the time of their deposition. As a stratum is gradually buried by continuously accumulating sediments, its pore space decreases at an ever-slowing rate. Although sediments retain only a few percent of pore space at the bottom of basins many kilometers deep, it has been suggested that they probably continue to compact very slowly as long as any pore space remains (Meade, 1968).

Induced compaction is basically an acceleration of the natural process. However, a more limited range of stress is involved because the sediments affected occur at depths of a few kilometers or less, and because these sediments have already partly adjusted to the stresses acting on them. Basic requirements for the occurrence of induced compaction and subsidence are a decline in pore fluid pressure, compressible rock, and a deformable overburden which is capable of supplying a constant load to the underlying fluid reservoir (Allen and others, 1971; Allen, 1973).

Subsidence and associated horizontal ground movements have occurred in many areas of groundwater, oil, gas production and in three geothermal

fields in New Zealand (Wairakei, Broadlands, and Kawerau; Stilwell, 1975). In general, fluid withdrawal is identified as the cause of subsidence in these areas because of a close association in time and space between fluid withdrawal and ground deformation. In most areas, the subsidence bowl corresponds closely to the margins of the pumping area, but this is not always the case; at Wairakei, New Zealand, the bowl is displaced from the main production area by about a kilometer.

Laboratory experiments have indicated that crystalline (igneous and metamorphic) rock also may compact by reduction of minute pore spaces and intracrystalline flaws and by the compression of fractures. However, the volumetric reduction in these rocks is so much smaller that it is considered negligible for most purposes. Therefore, this section is addressed primarily to the compaction of sediments.

In the following discussion, we examine the stresses which cause subsidence, some general physical and time considerations, the physical processes of compaction, and some potential influences on compaction and subsidence in geothermal areas.

4.2.2 Stresses in Compacting Rocks

Several types of stresses, related to fluid pressure gradients, the weight of interstitial water, and the weight of solid grains, exist within saturated porous rock. An understanding of the interplay between these stresses is vital to understanding the physical processes of compaction.

These stresses may be considered from two points of view: the static load representing the effective weight of overburden material, including water; and dynamic seepage stresses.

The earliest and simplest statement of the first approach was made by Terzaghi (1925) to describe the compaction of fine-grained beds at shallow depth which results from the construction of heavy buildings, dams, and other structures. More recently, Hubbert and Rubey (1959) extended Terzaghi's hypothesis to the problem of faulting in deeply buried rock. Nur and Byerlee (1971) and Garg and Nur (1973) have reviewed its applicability.

The Terzaghi theory is useful as a simple statement of the stress changes which lead to compaction. Basically, it considers the stress conditions before and after pumping, but not the dynamic processes by which the stress state is changed. However, the theory has several shortcomings. First, it describes only vertical stress components, whereas fluid pressure gradients also generate horizontal stresses; second, it was developed to describe a type of loading which differs from the loading caused by fluid withdrawal in magnitude, constancy, extent, depth, and rate of application (see Poland, 1969, for a full comparison). Third, consolidation may occur in excess of the predicted amount, but this excess (called "secondary consolidation") seems to disappear when improved methods of sample testing are used (Delflahe, 1975).

The principles of dynamic seepage stress (Scott, 1963), developed subsequently to the Terzaghi theory, have been used extensively by the U.S. Geological Survey in its publications concerning subsidence in the San Joaquin Valley of California (e.g., Lofgren, 1961, 1968; Lofgren and Klausing, 1969). In this approach, the compaction of fine-grained beds is attributed to seepage stresses which result from the frictional drag of moving water. The magnitude of these stresses varies with time. Unlike the Terzaghi theory, this approach is suitable for analyzing horizontal as well as vertical stress. However, because the Terzaghi theory

is conceptually simpler, it is presented here.

Stress calculations - Terzaghi related increases in the effective stress (grain-to-grain load) borne by the solid skeleton of a porous rock to reductions in load caused by fluid withdrawal, as follows:

$$p = p' + u_w \quad (4.1)$$

where

p = total stress due to overburden load, including the effects of both solid grains and interstitial water (or "geostatic stress")

p' = intergranular stress (or "effective stress")

u_w = pore fluid stress (also called "neutral stress" because it is incapable of decreasing the total volume of the sediment)

This equation applies when the major stress direction is vertical and the pore fluids are not moving. The stresses are on an average, or gross area basis; so that, for example, the intergranular stress p' applies over the total area, including the parts occupied by voids; it may be viewed as the mean of the integral over a horizontal plane section of the varying components of the stresses within the grains, caused by the weight of the partially buoyed overlying sediments. Further, since the grains probably will make contact at very small points, the local stresses there may be many times greater than p' .

The individual stress terms in Terzaghi's equation may be calculated in the following manner. Assuming static fluid conditions, consider the vertical stresses (or pressures) in a column of liquid and porous solid material with a unit plane area.

Let

ϕ = fractional porosity of medium (volume of pores/
total volume)*

ϕ_m = moisture above water table as a fraction of
total volume

ρ_s = density of solid grains

ρ_w = density of pore fluids

g = gravitational acceleration

A = horizontal area of a unit element of rock

Then, if we define a depth axis, z , we can compute the values of different stress components as a function of depth and the change in these stresses which would result either from lowering the water table or from decreasing the hydraulic head within a confined aquifer. As an example, the magnitudes of the stresses acting at the base of the aquifer in Figure 4.1(A) (depth $z_1 + z_2$) may be calculated as follows, for the initial position of the water table.

* The fractional pore space, ϕ , can also be expressed by the void ratio, e , which is defined as the volume of pores divided by the volume of solids. The porosity and void ratio are related as follows:

$$e = \frac{\phi}{1-\phi} ; \quad \phi = \frac{e}{1+e} \quad (4.2)$$

This measure of porosity is preferred for some purposes, particularly for graphing the results of compaction tests (discussed below) because only the numerator varies.

(A)

(B)

Figure 4.1 Pressure diagrams showing the relationships between effective stress, hydrostatic pressure and geostatic pressure. (A) shows the change in stress state which results from a water table lowering in an unconfined aquifer, and (B) the change from lowering the hydrostatic head in a confined aquifer (from Poland and Davis, 1969).

Weight of overlying solids:

$$W_s = \rho_s g(1-\phi)(z_1+z_2)A \quad (4.3)$$

Weight of water above the water table:

$$W_{wa} = \rho_w g \phi_m z_1 A \quad (4.4)$$

Weight of water below the water table:

$$W_{wb} = \rho_w g \phi z_2 A \quad (4.5)$$

The stresses associated with these forces will be designated σ_s , σ_{wa} and σ_{wb} .

Geostatic stress, due to all overlying materials:

$$p = \sigma_s + \sigma_{wa} + \sigma_{wb} \quad (4.6)$$

Hydrostatic stress, due to water below water table:

$$u_w = \rho_w g z_2 \quad (4.7)$$

Buoyancy stress on solid materials below water table:

$$\sigma_B = \rho_w g(1-\phi)z_2 \quad (4.8)$$

Effective stress: *intergranular*

$$p' = p - u_w \quad (4.9)$$

$$= \underbrace{\rho_s g(1-\phi)(z_1+z_2)}_{\sigma_s} + \underbrace{\rho_w g \phi_m z_1}_{\sigma_{wa}} + \underbrace{\rho_w g \phi z_2}_{\sigma_{wb}} - \underbrace{\rho_w g z_2}_{u_w}$$

The effective stress is stated in Equation 4.9 as the difference between the geostatic stress and the pore fluid pressure. However, it may easily be shown by rearrangement that the effective stress also equals the weight of solids and moisture above the water table, plus the buoyed weight of solids below the water table.

$$p' = \sigma_{sa} + \sigma_{wa} + \sigma_B \quad (4.10)$$

The initial values of hydrostatic and geostatic stress, computed above, are graphed in Figure 4.1(A) assuming a porosity of 0.40, grain density of 2.7 g/cm³, water density of 1.0 g/cm³, and fractional moisture content of .10 above the water table. In this presentation, the effective stress at any depth is denoted by the horizontal distance between the lines for hydrostatic and geostatic stress. Inspection of the graph and of Equation 4.1 indicates that the maximum transfer of load to the solid grain framework which may occur at any depth is equal to the hydrostatic stress.

In an unconfined aquifer, such as that shown in Figure 4.1(A), changing the elevation of the water table from position a (depth z_1), to position b (depth z_3), increases the effective stress below depth z_3 by removing the buoyant support for the solid grains in this interval. The increase in effective stress may be calculated by either of the following methods (the first is also appropriate for evaluating stress changes due to head decline in confined aquifers).

$$\Delta p' = \Delta p - \Delta u_w, \quad (4.11)$$

where

$$\Delta p = p_f - p_i \quad (4.12)$$

$$\Delta u_w = u_{wf} - u_{wi} \quad (4.13)$$

$$\Delta p' = \Delta \sigma_{wa} - \Delta \sigma_B \quad (4.14)$$

where

$$\Delta \sigma_{wa} = \sigma_{waf} - \sigma_{wai} \quad (4.15)$$

$$\Delta \sigma_B = \sigma_{Bf} - \sigma_{Bi} \quad (4.16)$$

This yields an increase in effective stress, per unit of depth between z_1 and z_3 , equal to

$$\Delta p'/z = \rho_w g(1-\phi-\phi_m) \quad (4.17)$$

This increment of effective stress is applied to all of the material below z_3 , including material below the aquifer system.

Unconfined aquifers are the source of some groundwater, the production of which may cause a lowering of the water table. However, oil, natural gas, brine, some groundwater, and geothermal fluids occur under confined conditions, as shown in Figure 4.1(B). Changes in fluid pressure within confined systems have a much greater effect on grain-to-grain stress than equivalent changes in the water table. For example, lowering the hydraulic head from a to b in Figure 4.1(B) would increase the effective stress within the confined aquifer by the amount:

$$\Delta p' = \rho_w g(z_3 - z_1) \quad (4.18)$$

This exceeds the increase in effective stress resulting from an equivalent change in the water table by a factor of $(1-\phi+\phi_m)$, or 70 percent using the assumed values for ϕ and ϕ_m .

In the general case, most aquifer systems experience simultaneous changes in the water table and the hydraulic head within confined aquifers. However, in most areas where voluminous extraction of oil, natural gas, or geothermal fluids occurs, the head drawdown in the confined aquifer far exceeds the pressure changes associated with the water table.

Although a hydrostatic pressure gradient has been used in the preceding illustrations, the same principles apply to geopressed systems. However, the initial effective stress is much smaller because the fluid is supporting part of the overburden weight. Thus, the potential exists for a much greater change in effective stress.

In summary, compaction may be viewed as resulting from an increase in the effective grain-to-grain stress caused by a decrease in pore fluid pressure.

4.2.3 Influence of Preconsolidation, Grain Size, and Time

Many physical properties of the fluid reservoir and associated materials influence the amount of compaction which may result from a given change in fluid pressure. The compressibility of a material, or unit change in some measure of volume per unit change in effective stress, reflects these many variables. Preconsolidation and grain size are two of the most important. The duration of the applied stress is also important because the compaction of clays and silts is time-dependent.

The compressibility of sediment changes with effective stress; thus, compressibility information is often presented in graphs relating void ratio and effective stress, in which the slope of the curve represents the compressibility. Some sample curves for various materials are shown in Figure 4.2.

Figure 4.2

Compression Tests on Clays, Silts, and Sands from Wilmington, California; Lake Maracaibo, Venezuela; and San Joaquin Valley, California (Corcoran Clay). (From Allen and Mayuga, 1969)

Preconsolidation - Figure 4.3, an idealized version of Figure 4.2, illustrates the concept of preconsolidation. The diagram shows successive compression (1), rebound (2), and recompression (3) curve segments, whereas most standard curves consist only of a single loading curve or loading-unloading cycle. The net compression for the first cycle (curves 1 and 2) is equal to the vertical distance between points A and B; deformation along the gently sloping portion of curve (1) was recovered as the load was removed. Therefore, we infer that deformation to the left of line AB is elastic and recoverable, while deformation to along AB is non-elastic and irrecoverable. The similarity in shape between the two loading curves, (1) and (2), indicates that non-elastic deformation does not occur unless the "preconsolidation stress," or greatest previous stress, is exceeded. Point A represents the preconsolidation stress for curve (1). Line AB is sometimes called the "virgin curve" because it represents compaction at stresses exceeding the preconsolidation stress. The effect on preconsolidation is apparent from the shape of the test curve in Figure 4.2 and from the behavior of aquifer systems, which compress much more when the preconsolidation stress is exceeded (Lofgren, 1968; Poland, 1969).

Grain Size - Grain size is one of the most important variables in compaction behavior (Meade, 1968) because it strongly influences compressibility and largely controls the mechanisms and rate of compaction.

The effect of grain size on compressibility is related to the way the porosity of sediments changes naturally with depth. The initial porosity of clayey muds at the time of deposition, 70-90 percent (Riecke and Chilingarian, 1974), decreases rapidly at shallow depth and more slowly thereafter (e.g., Athy, 1930; Hedberg, 1936; Dickinson, 1953). The initial porosity of sands is lower, 30-50 percent, but changes with depth

Figure 4.3 Schematic Variation of Void Ratio With the Logarithm of Effective Stress, (Modified after Riecke and Chilingarian, 1974)

at a more constant rate. The net effect of the contrasting behavior of sands and clays is that clays are more compressible at depths less than 600m and sands are more compressible at depths greater than 600m (Allen and Mayuga, 1969; Allen and others, 1971; Allen, 1973). For example, in compacting groundwater aquifers at depths from 200 to 600m (Poland, 1969), most of the compaction occurs in fine-grained clay beds (Lofgren, 1968; Poland, 1969). However, in deeper oil, gas, and geothermal reservoirs, a significant amount of compaction may occur in sands (Allen and Mayuga, 1969). Thus, it is possible that geothermal reservoirs may compact even if little fine-grained material is present.

Compressibility characteristics of sands and clays are summarized in Table 4.2. They result from the mechanisms of compaction on a grain-to-grain scale, which are different not only for sands and clays, but are also different for elastic and inelastic compaction.

Time - Compaction can proceed only as quickly as fluid is forced from the pores of the compacting material (Terzaghi and Peck, 1968). For sands, this process is relatively rapid, and compaction begins a few minutes after pumping begins (Peterson and Davis, 1969). However, clays and silts, whose permeability is lower by a factor of 10^3 to 10^{12} (Chilingarian and others, 1975; Riecke and Chilingarian, 1974) require weeks or years to adjust to the rapidly changing fluid pressures within adjacent sandy beds (Lofgren, 1968; Poland, 1969). This process of adjustment involves the gradual flow of water from the fine-grained into the coarse-grained beds, and is always more advanced at the edges than at the centers of the clayey or silty beds. The time required for complete readjustment is proportional to the square of their thickness (Poland, 1969).

Table 4.2.

Mechanism of Compaction in Sands and Clays.
The arrangement of items under "non-elastic deformation" corresponds roughly to increased effective stress.

Type of Deformation	Sands	Clays
ELASTIC	Elastic deformation of individual grains	Elastic deformation of individual particles or groups of particles (flocs)
NON-ELASTIC	Grain rearrangement by rotation and sliding	Grain rearrangement by development of preferred orientation
	Deformation of mica, other soft materials, and rock fragments	Breakage of electrical bonds between particles of a floc
	Grain fracturing (feldspar more susceptible than quartz)	Loss of chemically bound water
	Solution of minerals at contact points	Mineralogic changes involving further release of water
	Deformation of quartz and other hard grains	

Because of the differing response rates of sands and clays, it is common to observe a time lag between changes in the rates of pumping and the occurrence of subsidence. This delay may last for days or years, depending on the pumping history and the physical properties of the aquifer system (Lofgren, 1968; Poland, 1969). For the same reason, it is impractical to use short-term pumping tests to measure a field's subsidence potential; and it is even more difficult to predict subsidence rates, than the ultimate total amount of subsidence.

4.2.4 Other Influential Factors

In addition to fluid pressure changes, preconsolidation, grain size, porosity, depth, permeability, and the duration of increased effective stress, many other factors influence the compaction of sediments. These include grain shape, size uniformity, and composition; the nature of associated materials; stratification and hydraulic communication; temperature; overburden properties; and geologic structure. Seismic activity, for example, can temporarily increase the rates of compaction and subsidence (Poland and Davis, 1969), presumably by promoting grain rearrangement.

Many of the textural factors have been studied experimentally in work summarized by Meade (1968), Riecke and Chilingarian (1974), and in Volume 2, Research Report, Chapter 3. Unfortunately, little of this research was conducted under the temperature and pressure conditions found in geothermal systems. Therefore, the response of these systems to fluid withdrawal must be inferred from the behavior of groundwater and hydrocarbon systems, despite the fact that important differences may exist. Some of the features most likely to account for behavioral differences are summarized below.

Different reservoir materials - Whereas subsiding hydrocarbon reservoirs and groundwater aquifers consist of unconsolidated to semi-consolidation silt, sand, and clay, geothermal reservoirs may also contain cemented sandstone, volcanic flows, tuffs (sediments composed of volcanic particles), and bodies of crystalline (intrusive) rock. Hydrothermal alteration and cementation are likely to have modified the rock in irregular patterns.

Mechanisms of compaction - Sand compaction is likely to occur at the depths exploited (mostly between 1 and 3 km). Plastic deformation and solution of grains at the contact points may be more widespread because of the greater temperatures involved, perhaps rendering even sand compaction time-dependent (see Maxwell, 1960, 1964).

Extent of surface deformation - Because geothermal systems are relatively isolated from surrounding groundwater, the area of pressure reduction and subsidence may be very limited. If the area of pressure reduction exceeds the area of hydrothermal alteration, the less-indurated periphery of a field may subside more than the central production area (e.g., Stilwell and others, 1974).

Many of the above mentioned influences on compaction behavior are discussed in detail in Chapter 5, where indicators of subsidence potential are described.

4.3 FRACTURE CLOSING

A large body of evidence indicates that the volume of fluid-filled fractures changes with fluid pressure. Thus, fracture closing probably contributes to the pressure adjustment of fluid reservoirs, and may account for a large fraction of the adjustment if intergranular compaction is restricted by cementation. The evidence is drawn from the fields of wastewater disposal (Snow, 1968), foundation engineering (Serafim and del Campo, 1965; Benko, 1966; O'Neill and Lyons, 1974), rock mechanics (Bernaix, 1967; Birch, 1966) and mathematical modeling (Walsh, 1965). The extent of fracture closing should depend on the total fracture volume; the shape and orientation of individual fractures; the change in fluid pressure; and the deformation properties of the reservoir rock. Most geothermal reservoirs have high fracture porosity due primarily to tectonic stresses, but perhaps also due to heat waves associated with magnetic intrusion and sudden increases in fluid pressure associated with seismic shock waves.

At the present time, the only means for evaluating the net change in reservoir thickness which may be caused by fracture closing is by testing samples of the reservoir rock. However, only a few such studies have been performed. Using the axial strain measured by Batzle and Simmons (1976) for fractured samples of cemented rock from the Raft River and Salton Sea geothermal areas, thickness changes were computed for a variety of conditions (Table 4.3). Because the maximum calculated change in thickness was only 5 cm, it seems unlikely that the effect of fracture closing will be very great.

Table 4.3 Estimated Compaction Due to Fracture Closing (based on data of Batzle and Simmons, in press)

Reservoir Thickness (m)	Pressure Change (kg/cm ²)	Compaction (m)	
		Dunes	Raft River
500	25	.0005-.0014	.0035-.0040
500	50	.0010-.0028	.0070-.0080
500	100	.0020-.0056	.0140-.0160
1500	25	.0015-.0041	.0105-.0120
1500	50	.0030-.0082	.0210-.0240
1500	100	.0060-.0164	.0420-.0480

Axial strain per kg/cm² pressure change:

Dunes area, Imperial Valley, California, $40-110 \times 10^{-9}$

Raft River, Idaho, $280-320 \times 10^{-9}$

4.4 THERMAL CONTRACTION

Thermal contraction is theoretically a reversible consequence of geothermal production; however, the extent of recovery would depend on the amount of heat extracted and the availability of heat to replace it. For example, the heat extracted from hydrothermal systems and hot rock might well be replaced by heat flux from an underlying magma body, or over long periods of time by the establishment of "normal" geotemperature gradients. However, the loss of heat from magma, causing crystallization, probably would entail irreversible contraction at least over the time period of interest to man.

The magnitude of thermal contraction depends on temperature, the change in temperature, pressure, the thickness of the material affected, and its thermal contraction coefficient (Skinner, 1966). To illustrate its potential magnitude, some computations from the data of Skinner (1966; Table 4.4) are presented in Table 4.5. These figures represent only rough indications of potential behavior, because the temperature range and pressure at which the coefficients were determined are much less than those encountered in geothermal systems, and because the value of the coefficient is different during heating and cooling (Skinner, 1966). Actual ground movement would probably be less than indicated for several reasons. For hydrothermal systems, the proposed temperature changes probably represent maxima, and it is unlikely that such changes would be felt throughout the reservoir thickness. For all resources, but especially for hot rock and magma resources whose overburden probably consists of crystalline rock, it is unlikely that all of the subsurface compaction would be expressed at the surface as subsidence.

Table 4.4 Thermal Expansion of Rocks for the Temperature Interval 20-100°C, at 1 atm. Pressure (From Skinner, 1966)

Rock Type	Number of Determinations	Average Linear Expansion Coefficient	
		$\frac{1}{L} \frac{\Delta L}{\Delta T} \times 10^{-6}$	
Granites and rhyolites	21	8	± 3
Andesites and Diorites	4	7	± 2
Basalts, gabbros, and diabases	10	5.4	± 1
Sandstones	10	10	± 2
Quartzites	2	11	
Limestones	20	8	± 4
Marbles	9	7	± 2
Slates	3	9	± 1

The limits include nearly all the determined values

Table 4.5 Estimated Thermal Contraction (based on data from Table 4.4)

ΔT	Thickness	Rock Type	Thickness Change	Resource Type
5°C	500m	Sandstone	0.025m	Vapor-dominated
5°C	1500m	Sandstone	0.075m	Vapor-dominated
50°C	500m	Sandstone	0.25m	Liquid-dominated
50°C	1500m	Sandstone	0.75m	Liquid-dominated
100°C	500m	Granite	0.40m	Hot rock
100°C	1500m	Granite	1.20m	Hot rock
200°C	500m	Granite	0.80m	Hot rock
200°C	1500m	Granite	2.40m	Hot rock

4.5 TECTONIC MOVEMENTS

Horizontal and vertical tectonic movements related to natural, large-scale mountain-building processes may occur in geothermal areas at the rate of millimeters to centimeters per year. Such movements have been identified by repeat leveling surveys in the geothermal areas for which data is available: Imperial Valley, Long Valley, and The Geysers, California; and Raft River, Idaho (Lofgren, 1974, 1975). It is probable that similar movements are also occurring in many other areas because geothermal resources are usually located near the tectonically active boundaries between major crustal plates.

Tectonic movements may mask induced subsidence and horizontal ground motion associated with production. So that the impacts of production may be identified, it is important to design baseline leveling surveys (Lofgren, 1973) and gravity surveys (Volume 2, Research Report, Chapter 4) before production begins.

4.6 SUMMARY

The potential severity of the processes which may cause ground movements in geothermal areas is summarized in Table 4.1. Earthquake shaking, which promotes compaction, is shown in addition to the four processes of general importance: fluid withdrawal compaction, fracture closing, thermal contraction, and tectonic movements.

Compaction is thought to pose the greatest hazard, on the basis of its occurrence in many areas of fluid withdrawal and in three liquid-dominated geothermal areas. However, there may be important contrasts in the compaction behavior of geothermal and other resource areas because of temperature differences; differences in the reservoir rock and associated materials, including the effects of hydrothermal alteration; and relative isolation from surrounding groundwater systems.

On the basis of comparison with known subsidence areas and analysis of pertinent experimental results, the following conclusions can be made concerning the potential for subsidence in hydrothermal areas.

Vapor-dominated systems - The amount of subsidence is expected to be small because of the relatively small support initially provided by the steam and because of the induration of the reservoir rock (White, 1973; Lofgren, 1973).

Liquid-dominated systems (normally pressured) - Subsidence is considered a definite hazard in these areas, particularly if the reservoir contains beds of clay, silt, or shale, unless injection is practiced to prevent widespread reductions in fluid pressure (White, 1973; Lofgren, 1973).

Geopressured - Subsidence is considered likely in geopressured areas unless injection is practiced (Whiting, 1973) and may be very severe (Papadopoulos and others, 1975).

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CHAPTER 5
INDICATORS OF SUBSIDENCE POTENTIAL

5.1 INTRODUCTION

The amounts of compaction and subsidence which may result from geothermal production depend on many factors which influence the subsidence processes described in Chapter 4. These factors may be considered indicators of subsidence potential. The analogy method of subsidence prediction, described in Chapter 10, involves an assessment of these indicators at the site in question, and a comparison with the features of known subsidence areas. Although no single factor may be considered an irrefutable indicator of either stability or subsidence susceptibility, a preponderance of factors in one category provides a general indication of subsidence potential.

As a basis for comparison with sites to be evaluated, Tables 5.1, 5.2 and 5.3 list some characteristics of the major areas of subsidence due to groundwater, oil, gas, and brine withdrawal, and of the three subsiding geothermal areas in New Zealand. The basic characteristics of geothermal areas and known groundwater and hydrocarbon subsidence areas are compared in Table 5.4. These tables are further discussed in Chapter 2 of the Research Report, which also describes the pertinent features of each type of geothermal resource.

Table 5.5 summarizes the many factors thought to influence compaction and subsidence in geothermal areas. Because compaction due to fluid withdrawal will probably be the cause of most geothermal subsidence, and because hydrothermal resources are most likely to be affected, the table is largely directed toward these conditions. The factors include characteristics of the reservoir fluid, production history, recharge, physical properties of the reservoir and associated materials, reservoir geometry, overburden properties, and geologic structure. They are rated

TABLE 5.I COMPARISON OF PETROLEUM SUBSIDENCE AREAS

	WILMINGTON CALIFORNIA	LONG BEACH CALIFORNIA	INGLEWOOD CALIFORNIA	HUNTINGTON BEACH CALIFORNIA	GOOSE CREEK TEXAS	LAKE MARACAIBO VENEZUELA	PO DELTA ITALY	NIIGATA JAPAN
SURFACE DEFORMATION								
Subsidence								
Area Affected	>65km ² (1970)	31 km ²	11 km ²	37 km ²	~10 km ²	~600-700 km ²	>400 km ²	>800 km ²
Maximum Subsidence	8.8m (1928-1970)	0.75m (1925-1967)	1.73m (1911-1963)	1.22m (1933-1963)	1m (1918-1925)	3-3.3m (1926-1954)	~2m	0.8m (1900-1960)
Subsidence Rate	33-72cm/yr (1947-1958; before injection)	avg. 1.8cm/yr (1925-1967)	avg. 3.3cm/yr (1911-1963)	avg. 3.8cm/yr (1933-1963)	avg. 14cm/yr (1918-1925)	30cm/yr (1930's)	1-3mm/yr (1890-1950) max 30cm/yr	40-50cm/yr (1957-1959)
Horizontal Movement								
Maximum Movement	3.7m (1937-1970)	*	0.76m (1934-1963)	*	*	*	*	*
Rate	11cm/yr (1937-1970)		avg. 2.6cm/yr (1934-1963)					
Associated Faulting								
Type	Low angle	None	High angle, normal	None	High angle, normal	None	None	None
Location	Central		Peripheral		Peripheral			
Earthquakes	6 (1947-1961)							
Magnitude	2.4-3.3							
Time of Principal Occurrence	1947-1958+ (now halted by injection)	1925-1967	1911-1963	1933-1963	1917-1926	1926-1954+	1950-1960	1955-1960+
RESERVOIR MATERIALS								
Type, Age, Consolidation	Unconsolidated to semiconsolidated sand with interbedded clay and shale (marine), Miocene to Pliocene age	Similar to Wilmington	Similar to Wilmington	Similar to Wilmington	Unconsolidated sand and clay of Oligocene to Pliocene age	Interbedded sand, clay, and silt of Miocene age	Unconsolidated sand, sandstone with interbedded clay (littoral and lagoonal) Quaternary age	Unconsolidated sand, sandstone with interbedded clay, Cenozoic age
Porosity	20-35%							
Permeability	100-1500 mD							
Compaction Behavior	60% of compaction in sands, 40% in clays and shales					Compaction roughly equal in sands and clays		Cause of some subsidence prior to development is unknown
OVERBURDEN								
Type, Competence, Deformation Properties	Unconsolidated shale, sand, claystone, and siltstone of Pliocene and Pleistocene age	Similar to Wilmington	Similar to Wilmington	Similar to Wilmington	Similar to reservoir rock		Similar to reservoir rock?	Similar to reservoir rock?
REGIONAL GEOLOGIC STRUCTURE								
Folding, Faulting, Regional Stress	Broad anticline, flank dips 20-60°, with numerous transverse normal faults indicating compressive stress	Tightly folded anticline, high-angle reverse faulting indicating compressive stress	Anticline; faulting?	Anticline; faulting?	Gentle dome in Miocene and younger sediments; older deposits intensely faulted		Gently folded	
PRODUCTION								
Depth	600-2300m (most 600-1100m)	median 1690m	median 900m	median 930m	200-1400m		?(one well ~700m)	?-1000m
Fluid Type	oil, water, and gas	oil and water	oil; water and gas?	oil; water and gas?	oil, gas, and water	oil and water (?)	brine with dissolved methane	brine with dissolved methane
Production Rate	oil: 11-22x10 ³ m ³ /day (~70-140x10 ³ BBL/day ~9.4x10 ⁶ kg/day)				avg. total: 1.8x10 ⁶ m ³ /day (~11.1x10 ⁶ BBL/day ~1.5x10 ⁹ kg/day)		gas (1956): >550x10 ³ m ³ /day (~3.5x10 ⁶ BBL/day ~460x10 ³ kg/day)	gas (1956): 575x10 ³ m ³ /day (~3.6x10 ⁶ BBL/day ~480x10 ³ kg/day)
Total Production	oil + water: 222x10 ⁶ m ³ (~1.4x10 ⁹ BBL ~132x10 ⁹ kg) gas: 24x10 ⁹ m ³ (~20x10 ⁹ kg) total: 24x10 ⁹ m ³ (~156x10 ⁹ kg)				oil (plus water?) 1917-1926: >16x10 ⁶ m ³ (~100x10 ⁶ BBL ~14x10 ⁹ kg)		Total (1956), if water & gas: 1.1x10 ⁶ m ³ /day (~550x10 ³ kg/day)	Total (1956), if water & gas: 1.2x10 ⁶ m ³ /day (~75x10 ³ kg/day)
Maximum Pressure Decline	~77kg/cm ² (1100psi)				70-84kg/cm ² (1000-1200psi) (1917-1926) ~.001	~70kg/cm ² (1000psi)	?(~15kg/cm ² ~210psi) (1960)	
Subsidence: Head Decline	~.01						~.005	
Production from Compaction	39% (1928-1962, ignoring gas)				20% (1917-1926)			

Notes:

- 1) Dates in parentheses indicate period of measurement or year of report
- 2) Densities used for conversions, at 25°C and 1 atm: natural gas, 0.829 kg/m³; oil, 858 kg/m³; water, 1000 kg/m³

* Not measured

Sources: Van der Knaap and Van der Vlis, 1967; Poland and Davis, 1969; Yerkas and Castle, 1969; Mayuge, 1970; Allen, 1973; Kovach, 1974

TABLE 5.2 COMPARISON OF GROUNDWATER SUBSIDENCE AREAS

	SAN JOAQUIN VALLEY CALIF. (WESTERN AREA)	SANTA CLARA VALLEY CALIF.	HOUSTON-GALVESTON TEXAS	DENVER COLORADO	ELY-PICACHO ARIZONA	LAS VEGAS NEVADA	SAVANNAH GEORGIA	BATON ROUGE LOUISIANA	OSAKA JAPAN	MEXICO CITY MEXICO	TAIPEI BASIN TAIWAN	LONDON ENGLAND
SURFACE DEFORMATION												
Subsidence												
Area affected	>9,000km ²	600km ² (1969)	10,000km ² (1969)	~800km ² (1969)	?	500km ² (1969)	>130km ² (1969)	500km ² (1969)	280km ² (1951)	25+km ² (1969)	~100km ² (1969)	~275km ² (1969)
Maximum subsidence	9.1m	4m (1969)	1-2m (1969)	.4m (1962)	2.3m (1969)	1m (1969)	0.2m (1969)	0.3m (1969)	3-4m (1969)	8m (1969)	1m (1969)	0.7ft (?) (1969)
Subsidence rate	max 15-37cm/yr	max 22cm/yr	2mm-10cm/yr	avg 6mm/yr (1962)	1-40cm/yr	4mm-3cm/yr (1963)	max 4mm/yr		avg 12cm/yr (1885-1951)	4-50cm/yr (1969)		
Horizontal Movement	*	•	•	•	•	•	•	•	•	•	•	•
Associated Faulting	Fissuring due to hydro-compaction	None	None	None	Extensive fissuring peripheral to basin	None	None	None	None	None	None	None
Time of Principal Occurrence	1935-1970+	1920-1967+	1943-1964+	1890(?) - 1960(?)	1952-1967+	1935-1963+	1933-1955	1934-1965+	1928-1943, 1948-1965+	1938-1968+	7-1966+	1820(?) - 1931(?)
RESERVOIR MATERIALS												
Type, Age, Consolidation	Unconsolidated alluvial and lacustrine sediments of late Cenozoic age	Semi-consolidated alluvial and bay sediments of Pliocene and Pleistocene age	Unconsolidated sand and clay (fluvial) and shallow marine of Pleistocene to Miocene (?) age	Alluvial deposits (age?); late Cretaceous shale, coal, sandstone, siltstone (brackish and shallow marine)	Unconsolidated alluvial and lacustrine (?) sediments of late Cenozoic age	Unconsolidated alluvial sediments of late Cenozoic age	Soft, granular limestone with sand and marl; middle Eocene to Miocene age	Unconsolidated alluvial (?) sediments of Quaternary (?) age	Unconsolidated alluvial (?) sediments of Quaternary (?) age	Unconsolidated alluvial and lacustrine sediments of late Cenozoic age	Unconsolidated alluvial sediments of late Cenozoic age	Chalk aquifer overlain by thick clay
Porosity	28-61.2% (avg 40%)						High			84-90% in overlying bentonitic aquiclude		
Permeability	.001-.650 gpd/ft ²											
Mineralogy	montmorillonitic clay	montmorillonitic clay	montmorillonitic clay		montmorillonitic clay					montmorillonitic clay		
Compaction Behavior	Most compaction in fine-grained aquitards			About 3/4 of compaction in clays			Compaction in soft limestone, clay and marl			Both primary and secondary compaction, most compaction in overlying aquiclude		
OVERBURDEN												
Type, Competence, Deformation Properties	Unconsolidated alluvial and lacustrine sediments of Holocene age	Unconsolidated bay and alluvial deposits of Pleistocene and Holocene age	Unconsolidated sand and clay (fluvial) and shallow marine of late Cenozoic age		Similar to reservoir materials	Similar to reservoir materials, plus clay aquitard	Silty limestone		Similar to reservoir materials?	Unconsolidated silt and volcanic ash (lacustrine) of late Pleistocene age		
REGIONAL GEOLOGIC STRUCTURE												
Folding, Faulting, Regional Stress	Intermontane basin, small dips toward basin center	Intermontane basin, small dips toward basin center	Strata flat, gently dipping; normal faulting			Part of subsidence due to regional tilting, filling of Lake Mead				Intermontane basin, small dips toward basin center		
PRODUCTION												
Depth	90-900m	50-300m	50-600+m	7-760m	100-300+m	60-300(?)m		40-900(?)	10-200(?)m	Chiefly 10-50m	30-200(?)	90-? (1969)
Fluid Type	cold water	cold water	cold water	cold water	cold water	cold water	cold water	cold water	cold water	cold water	cold water	cold water
Production Rate	>3.4x10 ⁶ m ³ /day (~3.4x10 ⁹ kg/day) (1943-1959)	6.8x10 ⁷ m ³ /day (~6.8x10 ⁹ kg/day) (1950's)	8.7x10 ⁷ m ³ /day (~8.7x10 ⁹ kg/day) (1956)	7.6-19x10 ⁶ m ³ /day (~7.6-19x10 ⁷ kg/day) (1951-1961)	2.2-112x10 ⁶ m ³ /day (~2.2-112x10 ⁹ kg/day) (1937-1960)		8.7-24x10 ⁶ m ³ /day (~8.7-24x10 ⁷ kg/day)		1.1-11x10 ⁶ m ³ /day (~1.1-11x10 ⁷ kg/day)			
Total Production	>1.94x10 ¹⁰ m ³ (~1.94x10 ¹³ kg) (1943-1959)		4.32x10 ⁹ m ³ (~4.32x10 ¹² kg) (1943-1951)	1.12x10 ⁹ m ³ (~1.12x10 ¹² kg) (1883-1962)								
Maximum Pressure	15kg/cm ² (150m) (1969)	~5kg/cm ² (~50m) (1962)	10kg/cm ² (100m) (1962)	18kg/cm ² (180m) (1962)	3-6kg/cm ² (30-60m) (1969)	~3kg/cm ² (~30m) (1969)	~4kg/cm ² (~40m) (1969)			~3kg/cm ² (~30m) (1969)		4-10kg/cm ² (38-99m) (1936)
Decline												
Subsidence Head	.01-.08	.1-.08	.01	.002	.04	.03	~.003			.25		.07
Decline Ratio	29-50%		22%									
Production From Compaction	(1943-1959)											

* Not Measured

Sources: Poland, 1969; Poland and Davis, 1969

Table 5.3 Comparison of Geothermal Subsidence Areas

	Wairakei New Zealand	Broadlands New Zealand	Kawerau New Zealand
SURFACE DEFORMATION			
Subsidence			
Area Affected	65 km ² (1956-1970)	73 km ² (1969-1975)	~1 km ²
Maximum Subsidence	4.7m (1956-1974)	0.175m (1969-1975)	0.028m (1970-1971)
Subsidence Rate	Max. 40-45 cm/yr (1967-1974)	7.5 cm/yr (1969-1972)	Max. 2.8 cm/yr (1970-1972)
Horizontal Movement			
Maximum Movement	0.8m (1956-1974)	0.12m (1969-1975)	*
Rate	Max. -10 cm/yr (1970)	Avg. 2 cm/yr (1969-1975)	
Associated Faulting	None	None	None
Type			
Location			
Earthquakes			
Magnitude or Intensity			
Time of Principal Occurrence	1953-1976 +	1966-1976 +	1956-1976 +
RESERVOIR MATERIALS			
Type, Age, Consolidation	Pumice breccia with sandstone and minor siltstone, medial rhyolite sill, Pleistocene	Pumice breccia and tuff, Pleistocene, with medial siltstone and rhyolite aquitards, Pleistocene	Pumice breccia and ignimorite, with medial andesite sills, Pleistocene
Porosity	Extremely variable due to cementation	15-50% (highest in pumice breccia)	
Permeability	~50uD (intergranular), 100mD overall	Moderately high	
Compaction Behavior	Maximum subsidence outside area of greatest production. Local sills of volcanic rock may prevent transfer of load to underlying reservoir		
OVERBURDEN			
Type, Competence, Deformation Properties	Tuffaceous shale and sandstone with interbedded tuff and conglomerate, Pleistocene	Chiefly siltstone, mudstone, and rhyolite with minor sandstone, tuff and alluvium, Pleistocene	Pleistocene rhyolite flows and Holocene alluvium
REGIONAL GEOLOGIC STRUCTURE			
Folding, Faulting, Regional Stress	Sediments drape-folded over basement highs; normal faulting with small component of right-lateral movement, indicates tensile stress	Normal faulting, with small component of right-lateral movement, indicates tensile stress	Numerous normal faults, with small component of right-lateral movement, indicating tensile stress
PRODUCTION			
Depth	150-1360m	430-1200m	460-915m
Fluid Type	Hot water and flashed steam	Hot water and flashed steam	Hot water and flashed steam
Temperature	Maximum 260°C	Maximum 300°C+	Maximum 270°C+
Production Rate	1.3x10 ⁷ kg/day (1975)	Avg. 2.63x10 ⁷ kg/day (1973-1975)	Max. 1.6x10 ⁷ kg/day (1956-1970)
Total Fluid Withdrawal	930x10 ⁹ kg (1956-1974)		
Maximum Pressure Decline	25 kg/cm ² (1956-1974)		
Subsidence: Head Decline % of Production Yielded by Compaction	.02 (1956-1974)		

* Not measured.

SOURCES: Gridley, 1964, 1970; Stilwell and others, 1975.

Table 5.4 Comparison of Geothermal With Subsiding Hydrocarbon and Groundwater Areas

	GEOHERMAL (Hydrothermal & Geopressed)	HYDROCARBON (Subsiding)	GROUNDWATER (Subsiding)
Lithology	Highly variable. Reservoir usually sediment (volcanic particles may dominate), but may include fractured volcanic and coarsely crystalline rock	Sand with interbedded clay and shale	Chiefly sand with interbedded silt and clay; soft limestone and clay in two areas
Geologic Structure	Faulting common	Faulting and folding common (especially normal faulting and gentle folding)	Strata chiefly undeformed, may dip gently
Median Production Depth (m)	1500-2500	360-3900	200-900
Production Area (km ²)	10 ⁰ -10 ²	10 ¹ -10 ³	10 ² -10 ⁴
Production Rate ^{1,2}			
Mass (kg/day)	~10 ⁷	~10 ⁷ -10 ⁹	10 ⁵ -10 ¹¹
Volume (m ³ /day)	--	10 ⁶	10 ² -10 ⁸
Total Production ^{1,2}			
Mass (kg)		10 ¹⁰ -10 ¹¹	10 ¹² -10 ¹³
Volume (m ³)		10 ⁻⁷ -10 ¹⁰	10 ⁹ -10 ¹⁰
Pressure Decline ² (kg/cm ²)	Vapor- Dom. -25 (max)	Liquid- Dom. 50-250 (max)	Geo- Pressured 240-420 (max)
		70-85 [140-280] ³	3-18 [7-14] ³
Subsidence: Head decline ratio ² (m:m)		0.01-0.005	0.01-0.2, Tertiary-Quaternary unconsolidated, clayey sediments ³ Less than 0.005 marine carbonates and clays ³ 0.002, Cretaceous sediments (Denver)
Fraction of Production Yielded by Compaction ² (%)		20-39	22-50

¹ Includes both liquid and gas phases. Because of their differences in density, gas dominates the volume measurements and liquid the mass measurements.

² Based on comparative tables presented in this report for geothermal and subsiding hydrocarbon and groundwater fields (a few values only).

³ Based on Poland and Davis, 1969.

⁴ Based on values of available drawdown for hypothetical reservoirs in Papadopoulos and others (1975, Table 23), arbitrarily assuming final average pressure of 140 kg/cm² used in several production scenarios.

in terms of three categories of importance: major, intermediate, and minor. Those conditions are specified which tend to promote or to prevent subsidence.

The rating and choice of factors for inclusion was based on a review of subsidence processes in areas of groundwater, oil and gas production, and in the only geothermal areas known to be subsiding as a result of fluid withdrawal (Wairakei, Broadlands, and Kawerau, New Zealand). The opinions expressed are those of the authors, but reflect comparisons of subsiding areas made by Allen and others (1971), Allen (1973), Poland (1969), and Riecke and Chilingarian (1974). The characteristics of subsiding areas which emerge from these comparisons have also been discussed in Chapter 2 of the Research Report.

It is possible that fluid withdrawal may have significantly different effects in geothermal than in other resources areas because of differences in the physical properties of the rocks, in the natural hydrology, and in temperature and pressure. These considerations are discussed in detail in Chapters 3 and 4 of the Research Report.

The following discussion amplifies the conclusions expressed in Table 5.5.

5.2 RESERVOIR FLUID

5.2.1 Fluid Phase

The phase of formation fluids is a major factor in subsidence potential because of its influence on the magnitude of the buoyant support supplied to the solid grains, and the magnitude and rate of decrease in fluid pressure which results from production.

Steam provides much less buoyant support than water for the solid matrix of the reservoir because water is denser by a factor of 100 to 500, depending on temperature, pressure, and dissolved solids content. Thus, regardless of production, the reservoir rock in vapor-dominated areas must be stronger in order to resist deformation under its own weight. The difference in buoyant support provided by steam and water is not otherwise a factor in confined, single-phase systems, except to the extent that the density of the fluid changes during production. In two-phase systems, however, gradual lowering of the steam-liquid interface will greatly reduce the buoyant support in the zone of flashing.

The rate of change in reservoir pressure is dictated in part by the fluid phase (Chapter 11 and Research Report, Chapter 2). For equivalent rates of production, the decline in pressure will be fastest in all-liquid reservoirs, intermediate in all-vapor, and slowest in two-phase reservoirs.

5.2.2 Fluid Pressure and Density

The maximum change in effective stress which may occur at any level in an aquifer system is equal to the initial fluid pressure (Terzaghi, 1925). This pressure is a function of several factors: depth, fluid density (itself dependent on phase, temperature, and dissolved solids content); the degree of communication between the reservoir, adjacent aquifers and the

ground surface; and tectonic pressures. In normally pressured, liquid-dominated systems, the initial pressure is approximately hydrostatic, and in geopressured systems, it is much greater than hydrostatic.

5.2.3 Dissolved Solids and Temperature

The combined effects of dissolved solids and temperature are complex and probably vary from site to site. Although dissolved solids increase fluid density, in many areas this effect is offset by a concurrent rise in temperature (Ellis, 1975). High temperature alone facilitates compaction by promoting plastic deformation, mechanical failure, and solution of grains at their contact points (Maxwell, 1960, 1964). However, in geothermal areas, where high temperatures have persisted for periods on the order of 10^5 - 10^6 years, high temperatures and high dissolved solids promote physical and chemical changes in the structure of rock by solution, precipitation, and hydrothermal alternation. The net effect of these processes may be to strengthen or weaken the reservoir rock (see Section 5.5.6).

Thermal contraction of the reservoir is a reversible consequence of geothermal production whose magnitude depends on the temperature change, the linear coefficient of thermal contraction, and the reservoir thickness. The maximum change in reservoir thickness, based on typical values for these variables, is not expected to exceed several tens of centimeters (Chapters 3 and 4 of the Research Report).

5.3 FLUID PRODUCTION

5.3.1 Volume, Fluid Level and Pore Pressure

Changes in pore fluid pressure are virtually the most significant factor in compaction and subsidence (Lofgren, 1968; Poland, 1969). The larger the change in fluid pressure, the greater the load transferred to the rock matrix and the greater the compaction. Fluid levels are a measure of fluid pressure. In any single area, the change in pore pressure is proportional to the volume of fluid extracted. However, the pore pressure, not the volume or mass extracted, is the controlling factor.

In geothermal areas, production tends to be much greater in proportion to the size of the reservoir than in other fluid resource areas. For example, Stilwell and others (1975) state that production at Wairakei is about ten times as great as that at several North Sea oil fields. Therefore, the pressure changes in geothermal areas may be greater.

5.3.2 Formation Flashing

Flashing of liquid to steam in two-phase reservoirs tends to decrease the rate of pressure loss for a given rate of production. Therefore, fluid pressure decline is slower in two-phase reservoirs than in those containing all liquid or all vapor. In fields which contain a very high proportion of dissolved solids, such as the Salton Sea field in the Imperial Valley, it is sometimes desirable to prevent subsurface flashing in order to prevent mineral precipitation in the reservoir. However, it should be noted that such a production scheme would entail a more rapid loss of pressure in the reservoir than if flashing were allowed.

5.4 RECHARGE

5.4.1 Natural Recharge

The rate and location of fluid replacement can have a very strong effect on the magnitude and distribution of fluid pressure changes within a producing system. In subsiding areas, the rate of natural recharge is low in comparison to the rate of production (otherwise compaction would not occur). In geothermal areas, the rates of natural recharge probably vary, but are generally low. If recharge were very rapid, heat would be less likely to accumulate in usable concentrations. Recharge is probably lowest in vapor-dominated systems, which must be relatively isolated from surrounding cold water because they are underpressured with respect to their depth (White, 1973; Renner and others, 1975). Geopressured reservoirs must be well sealed in order to contain their abnormally pressured fluids. In liquid-dominated convection systems, recharge is probably localized. For example, in self-sealing systems, which are sealed at the top and sides by mineral precipitation, most recharge is from below (White, 1973).

The degree of communication between the resource fluids and surrounding cold groundwater will determine the area affected by pressure changes and, in turn, the shape of the subsidence bowl.

5.4.2 Injection

Injection is the major tool for halting or preventing subsidence. It is possible to inject at rates comparable to, or greater than, the production rate and actually to increase fluid pressures over their initial value (Allen and Mayuga, 1969; Chasteen, 1974; Einarsson, 1975). However, some problems may limit injection in geothermal areas. Potentially the most restrictive are the need for make-up water to replace that lost during the production cycle, and plugging due to precipitation or suspended particles.

5.5 RESERVOIR MATERIALS

5.5.1 Type

Generally speaking, the compressibility of sediments exceeds that of igneous or metamorphic rock because sediments have much higher porosities (Birch, 1966). In some areas, geothermal reservoirs consist of fractured igneous or metamorphic rock. Some of the reservoir characteristics listed in this section apply to this type of reservoir, but most are restricted to, or more significant in, sedimentary reservoir rock. Sand-sized grains are assumed to predominate in these reservoirs. Fine-grained sediments are considered not to form part of the reservoir and are classified as "associated materials".

5.5.2 Grain Shape

Sediments containing predominately angular grains are more susceptible to compaction because these grains fracture more easily than rounded ones (Roberts and de Souza, 1958; Meade, 1968). Particles of volcanic glass are extremely angular and susceptible to breakage.

5.5.3 Porosity

Other things being equal, the higher the porosity of a rock, the more compressible it is. On-site experience and experimentation have both shown this to be true for primary (intergranular) porosity (Meade, 1967; Birch, 1966). It also appears to be true for secondary (fracture and solution cavity) porosity, which may be reduced by partial or full collapse of fractures in response to increased effective stress (Chapter 3 of the Research Report; Batzle and Simmons, in press).

5.5.4 Consolidation and Cementation

The compressibility of sedimentary rock decreases very rapidly with increasing consolidation and cementation. The relative consolidation of sediments increases with depth and, to a small extent, with the incidence of seismic shaking. "Cementation of grains is considered to be overwhelmingly the most important single factor limiting mechanical sand compaction," (Allen and Chilingarian, p. 73, 1975). Because a variable degree of cementation probably has occurred at most geothermal areas, cementation is likely to be a major differentiating factor in the compaction behavior of geothermal, groundwater, and certain hydrocarbon fields.

5.5.5 Preconsolidation

This is a major factor in compaction behavior because compaction is very slight until the preconsolidation stress is exceeded (Lofgren, 1968; Poland, 1969). Its importance is especially great in geopressured systems, in which the reservoir materials bear only a fraction of the geostatic stress.

5.5.6 Hydrothermal Alteration

The effect of hydrothermal alteration depends on the type of chemical reactions which have occurred throughout the lifetime of the system, their spatial distribution, and the extent to which susceptible materials have been affected. Hydrothermal alteration generally indurates sedimentary rocks by creating a more interlocking texture (Somerton and others, 1965; Muffler and White, 1969; Hochstein and Hunt, 1970; Elders and Bird, 1974) and weakens igneous and metamorphic rocks by changing strong minerals to weak ones.

5.5.7 Admixed Clay Content

Interstitial clay acts as a lubricant in compacting sands, increasing their compressibility (Colazas, 1971; Allen and Chilingarian, 1975).

5.5.8 Sorting (Grain Size Uniformity)

Poorly sorted (or non-uniform) sands are more compressible than well sorted (or uniform) sands (Fatt, 1958; Roberts and De Souza, 1958; Rogers and Head, 1961).

5.5.9 Admixed Mineral Content

The presence of certain minerals increases the compressibility of sands. Admixed montmorillonite is more compressible than other clay minerals (Chilingar and Knight, 1960). A few percent of mica drastically increases compressibility, because the grains bend and break easily (Gilboy, 1928; McCarthy and Leonard, 1963). Feldspar is more susceptible to fracturing than quartz while soft minerals such as calcite and soft lithic fragments are more susceptible than quartz to plastic deformation (Meade, 1968).

5.5.10 Age

Age probably is comparatively less important in geothermal areas than in other fluid resource areas, because of the great variability in the nature of geothermal reservoir rock. Other things being equal, however, consolidation and cementation correlate with age. The cut-off used in Table 5.5 is the maximum age of compacting groundwater and hydrocarbon systems (Allen and others, 1971; Allen, 1973).

5.5.11 Thickness

The greater the thickness of reservoir rock in hydraulic communication, the greater the total volume of rock which is subjected to a change in fluid pressure. Communication strongly influences the behavior of aquifer systems, but it is extremely hard to assess. For this reason, highly simplified assumptions about communication, based on very limited information, are used in making most subsidence predictions.

5.5.12 Deformation Properties

The deformation properties of the reservoir materials, expressed in terms of elastic constants, compaction coefficients, yield stress, etc., are a basic measure of the net effects of many physical properties.

5.6 ASSOCIATED MATERIALS

5.6.1 Type

A wide variety of materials may be associated with geothermal reservoirs, depending on their geologic setting. Clays, siltstones and shales are relatively compressible. However, volcanic flows, shallow intrusions (bodies of igneous rock which crystallized below the ground surface) and welded tuffs (cemented sediments composed of volcanic particles) are much denser and less compressible. If interbedded with the reservoir materials, such rocks may tend to reduce downward transmission of effective stress.

5.6.2 Occurrence

Greater compaction may result if associated, fine-grained sediments are distributed in many thin beds than in few thick beds. Thin beds will adjust much more rapidly to changes in pore pressure in the adjacent coarse beds; the rate of adjustment may be a factor in the ultimate subsidence if the pore pressure in adjacent beds fluctuates with time. The distribution of these materials also determines the thickness of reservoir rock in hydraulic communication.

5.7 RESERVOIR GEOMETRY

5.7.1 Width of Producing Zone

The greater the reservoir width, the greater the tendency for the overburden to deform under its own weight and the additional stress resulting from production. According to the principles of engineering mechanics, the maximum displacement which may occur at the center of a slab or disc representing the overburden is proportional to the fourth power of its width (Timoshenko and Woinowsky-Krieger, 1959).

5.8 OVERBURDEN

5.8.1 Thickness

Two factors contribute to the significance of overburden thickness in determining the amount of reservoir compaction which is expressed at the surface as subsidence. In terms of engineering mechanics, the structural resistance to bending of a slab or disc representing the overburden is proportional to the cube of its thickness (Timoshenko and Woinowsky-Krieger, 1959). Thus, a very small increase in overburden thickness substantially reduces its tendency to deform. Second, expansion may occur within the overburden to compensate for the contraction of the reservoir materials (Allen, 1968). The thicker the overburden, the less compaction is likely to be transmitted to the ground surface.

5.8.2 Competence

Competence is a major factor in subsidence susceptibility because the presence of a deformable overburden is one of the prime requisites of subsidence (Allen and Mayuga, 1969; Allen and others, 1971). The more competent the overburden, the more it will resist both bending and expansion.

5.8.3 Deformation Properties

Deformation properties of the overburden, such as the elastic constants and yield strength, are a function of its competence, which is determined by the rock texture and composition.

5.9 GEOLOGIC STRUCTURE

5.9.1 Regional Stresses

Two types of stresses (other than fluid pressure) influence compaction: vertical (geostatic) stress due to overburden weight and horizontal tectonic stress due to large-scale crustal movements (Figure 5.1). These stresses are of the same order of magnitude and both should be considered in subsidence predictions. According to Hubbert and Willis (1957), these stresses differ by a factor of two or three, and either may be larger.

Compaction and subsidence are considered more likely in areas where the horizontal stress is tensional rather than compressive, on the assumption that tensile stress facilitates grain rearrangement (Allen, 1973). The magnitude and orientation of the principal stress directions may be determined by two methods: hydraulically fracturing buried rock by the injection of water at high pressures, in which case the fractures form perpendicular to the direction of greatest stress (Hubbert and Willis, 1957; Scheidegger, 1960, 1962; Kehle, 1964; Fairhurst, 1964); or by inference from geologic structures such as folds, faults, and fractures. The first method defines the present state of stress. The second defines the stress at the time of formation of the youngest geological features.

5.9.2 Folding

Allen (1973) has suggested that flat or broadly arched sediments with dips less than 25 degrees are relatively susceptible to bending in response to compaction of the underlying strata. In contrast, tightly

Figure 5.1 Stresses Generating Basic Geologic Structures

Maximum principle stress
Intermediate principle stress
Minimum principle stress

folded strata with flank dips greater than 25 degrees, are relatively resistant to such bending because of their inherent structural strength.

5.9.3 Faulting

Normal faulting, which results from tensional stress, is considered to indicate a greater potential for subsidence than reverse or thrust faulting, which results from compressive stress (Allen, 1973). Strike-slip faulting, due to shear stress, probably also contributes to grain rearrangement and compaction.

Faults may be reactivated by the stress changes accompanying fluid withdrawal, as has occurred at Kern Front oil field in California (Yerkes and Castle, 1969) and in the Houston-Galveston area of Texas, due to fluid withdrawal (Kreitler, in Vanston and others, 1976). In the latter area, the extent of subsidence at the surface has been restricted by faults which bound the aquifers and extend to, or near the surface (Brown and others, 1974).

5.9.4 Fracturing

Fractures contribute to subsidence in two ways: by increasing hydraulic communication, and by closing under increased effective stress (Chapter 3, Research Report). However, the data of Batzle and Simmons (in press) suggest that the latter mechanism should have a small effect.

5.9.5 Stratification

According to the principles of engineering mechanics, the resistance to bending of a reservoir and overburden composed of horizontally

layered rock depends in part on the number and thickness of layers of each rock type. If the total thickness is constant, the resistance to bending is less if each type of rock occurs in many thin layers than in a few thick layers. This is true if, as seems likely, the frictional contribution to bending resistance at the layer boundaries is less than the internal cohesive strength of the hard layers.

5.10 SUMMARY

The amount of compaction and subsidence which may occur in any geothermal area as a result of production depends on many factors which together determine the change in fluid pressure and the rock compressibility. These factors include the history of production and injection; natural recharge; hydraulic communication; fluid phase, density, and chemistry; rock porosity, permeability, grain size, grain shape, composition, cementation, and temperature; folding, faulting, fracturing and stratification.

The tables presented in this chapter provide a basis for estimating subsidence potential by analogy with known subsidence areas. For best results, however, this procedure should be combined with the analytical methods of prediction described in Chapters 11-13.

Table 5.5 FACTORS TENDING TO INFLUENCE GEOTHERMAL SUBSIDENCE

FACTOR TYPE (* major; † minor)	FACTORS WHICH MAY CONTRIBUTE TO SUBSIDENCE SUSCEPTIBILITY	FACTORS WHICH MAY CONTRIBUTE TO SURFACE STABILITY
1. RESERVOIR FLUID		
* Phase	All-liquid	Vapor-liquid mixture (vapor dominated, to a lesser extent)
Pressure	Geopressured (overpressured)	Low (below hydrostatic)
Density	High	Low
† Dissolved Solids	(see text)	
† Temperature	(see text)	
2. PRODUCTION FLUID		
* Volumes	Large	Small
* Fluid levels ¹	Large drops, long time, extensive areas	No drops
* Pore pressures ¹	Large drops, long time, extensive areas	No drops
Formation flashing	None	Extensive, continual flashing
3. GEOHYDROLOGY		
Natural recharge†	Low rates	High rates
4. RESERVOIR MATERIALS		
* Type	Sediments	Igneous or metamorphic
Predominant grain size	Coarse	-
Grain shape	Angular	Rounded
Porosity - Primary	25-40%	Very low
- Secondary	High	Low
* Consolidation/cementation	Unconsolidated, lacking cementation (loose or friable)	Consolidated, cemented
* Preconsolidation ²	None	Much
Hydrothermal alteration	Present	Absent
Admixed clay content (sorting) ³		
Admixed mineral content	High mica, montmorillonitic clays	None
Age	Miocene and younger	Older than Miocene (22 million years)
* Thickness (in communication)	Great vertical section	Small vertical section
* Deformation properties ⁴	Highly deformable	Slightly deformable
5. ASSOCIATED MATERIALS		
Type	Clays, siltstones, shales	Volcanic flows and shallow intrusions
Occurrence	Many thin strata of large total vertical thickness, interbedded with reservoir materials but not impairing communication between them (less susceptible if distributed in few thick strata)	
6. RESERVOIR GEOMETRY		
Width/thickness ratio ⁵	Large	Small
7. OVERBURDEN		
* Thickness	Small (< 3000 ft)	Great
* Competence	Incompetence, unconsolidated sediments	Competent, consolidated
* Deformation properties ⁶	Highly deformable	Slightly deformable
Density	High	Low
8. SITE GEOLOGY, STRUCTURE		
Folding	Gentle, broad, synclinal	Sharp, anticlinal (arched)
Flank dips	Less than 25°	Greater than 25°
Faulting	Normal, graben blocks	Reverse or thrust
Fracturing	Much, recent	Little, old, sealed
Regional stresses	Tensional	Compressional
Stratigraphy	(see text)	

1. Depend(s) upon formation properties, which may be studied by preliminary well tests.
2. Preconsolidated materials have previously experienced loads greater than their present load.
3. If high pressures did not always accompany the presence of admixed clays in geopressured zones, they will be preconsolidated.
4. Elastic constants, compaction coefficient, yield stress, etc.
5. Of the producing zone.
6. Can the overburden materials possible respond more slowly than the reservoir materials below

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CHAPTER 6
SUBSIDENCE INDICATORS FROM GEOPHYSICAL MEASUREMENTS

6.1 INTRODUCTION

6.1.1 Purpose and Scope

This chapter describes the use of geophysical methods to obtain information pertinent to subsidence prediction and modeling, and to measure compaction and subsidence. Other sources of related information, including core tests, drilling observations, and well tests, are described briefly. In particular, because of their frequent use in subsidence analyses, sample data are compared in applicability with data obtained from geophysical methods. Procedures for determining compaction coefficients are also described in detail, as background for the discussion in Chapter 12 of their use in subsidence models.

The information presented in this chapter is based on a literature review and discussions with various researchers in the fields of geophysics, subsidence, and geothermal exploration. Literature sources which may be consulted for a more complete description of geophysical methods and their use in geothermics are listed in Tables 6.1 and 6.2.

All of the topics covered in this chapter are discussed in Chapter 4 of the Research Report, to which the reader is referred for additional detail. The Research Report contains brief descriptions of the major geophysical survey and logging techniques, with examples of the format and interpretation of resultant data. In another section, alternative procedures are compared for determining the various rock and fluid properties listed in Table 6.3.

Table 6.1

**General References on Geophysical and
Laboratory Testing Techniques**

I. SURFACE GEOPHYSICAL SURVEYS

Dobrin, 1960, 1976
Grant and West, 1965
Griffiths and King, 1965
Heiland, 1946
Jakowsky, 1950
Nettleton, 1940, 1971, 1976
Parasnis, 1962, 1966, 1972
Society of Exploration Geophysicists, 1967

II GEOPHYSICAL WELL LOGGING

Allen, 1975
Barsukov and others, 1965
Dakhnov, 1962
Dresser Atlas, 1971
Lynch, 1962
Pirson, 1963, 1973
Society of Petroleum Engineers of AIME, 1971
Working Group on Nuclear Hydrology ..., 1971
Schlumberger Ltd., 1972, 1974

III LABORATORY TESTING

American Society for Testing and Materials, 1970, 1975
Teeuw, 1971

Table 6.2

**General Papers on the Use of Geophysics
in Geothermal Exploration**

Banwell, 1973

Banwell, 1975

Bodvarsson, 1970

Combs, 1972

Combs and Muffler, 1973

McNitt, 1975

Palmason, 1975

Ward, 1975

Geophysical Logging in the Geothermal Environment

Baker, Baker and Huguen, 1975

Baker, Campbell and Huguen, 1975

6.1.2 Chapter Organization

The remainder of the chapter is divided into five parts. The first describes the general operating principles, data format, interpretation, and use of standard geophysical survey and logging techniques. The second briefly describes other sources of information related to subsidence, including core tests, drilling observations, and well tests. In the third section, the use of geophysical data in subsidence analysis is discussed. Subsidiary topics include the choice of methods for measuring a particular property, the role of scale and accuracy in determining data use, and the availability of geophysical information in the geothermal environment. The fourth section describes the use of well logs and gravity surveys for measuring compaction and subsidence. In the final section, various methods for determining compaction coefficients are described in detail.

6.2 DESCRIPTION OF GEOPHYSICAL METHODS

Geophysical methods are used to determine the subsurface properties of rocks and their contained fluids. In these methods, certain physical properties of the earth are measured directly. Other properties of interest may then be deduced on the basis of established relationships. The properties most commonly measured are gravitational and magnetic attraction, the travel time of elastic waves, electrical resistivity, and radioactivity. Deduced properties are summarized in Table 6.3. For many of these properties, quantitative as well as qualitative interpretation is possible.

The geophysical methods are divided, on the basis of use, into two groups: surface surveys (some of which may also be conducted by air) and well logging techniques.

6.2.1 Surface Geophysical Methods

Geophysical exploration techniques detect variations in the physical properties of rocks below the ground surface, on the basis of measurements made at or above the surface. The measured physical properties include the relative strength of the earth's gravitation field (dependent on the subsurface density distribution), the absolute strength of the magnetic field (dependent on the magnetic properties of subsurface materials), the strength of natural or artificially induced electric fields (dependent on the resistivity distribution), the elastic properties, and the natural radioactivity of crustal materials. Methods for sensing radioactivity are used primarily for locating radioactive ores, and therefore are not described in this report. Multiple methods have been developed to detect some of the physical properties listed above, particularly the electrical properties. The main characteristics and uses of the major survey methods are summarized in Table 6.4.

Table 6.3 Information Deduced From Geophysical Methods

GEOPHYSICAL METHODS	INFORMATION DEDUCED																																							
	GEOLOGIC STRUCTURE					PETROPHYSICS															FLUID CHARACTERISTICS							SUBSIDENCE MEASUREMENT												
	Basement Depth	Basement Topography	Formation Contacts	Folds	Faults	Dikes, Sills	Major Stratification	Detailed Stratification	Correlation	Density	Porosity, Primary	Porosity, Secondary	Permeability	Lithology	Grain Size	Sorting	Mineralogic Composition	Relative Consolidation	Cementation	Hydrothermal Alteration	Fracturing	Elastic Constants	Compressibility	Compaction Coefficient	Fluid Phase	Abnormal Fluid Pressure	Water Saturation	Gas Saturation	Water Salinity	Aquifer Identification	Water Table Identification	Flow Rate/Direction	Specific Yield	Storage Coefficient	Net Mass Withdrawal	Maximum Subsidence Estimate	Casing Length Changes	Marker Spacing Changes		
Surface																																								
Gravity	X	X	X	X	X	X	O		X				O						O						O										X	X				
Magnetic	X	X	O	O	O	X							O						O																					
Seismic Refraction	X	X	X	O	X	X	X						X									X																		
Seismic Reflection	X	X	X	O	X	X	X						X									X																		
Electrical Resistivity	X				X								O												O															
Spontaneous Potential																															X									
Well Logs																																								
Spontaneous Potential							X	X		+		+	X	X		+									X	X		+	X	+										
Electrical Resistivity							X	X		+	X	+	X	X		+		X	X	X					X	X	+	X	+	+										
Acoustic (Sonic)							X	X		X		+	X	X	+	+		X	X	X	+	+	+	+	X	X	+	+	+											
Density (Gamma Gamma)							X	X	X	X		+	X		+	+	X	X	X			+	+	+	+	X		+												
Gamma Ray (Natural Gamma)							X	X		+		+	X	X		+												+	+	+	+	+	+	+					X	
Neutron							X	X		X		+			+	+									+		X	+	X	+	X	+	+	+						
Televiwer																					X																			
Mechanical Properties																						X	X	X																
Saraband							X	X		X		X	X	X													X													
Coriband							X	X		X	X	X	X	X													X													
Magnetic Susceptibility																																						X		

Symbols:

- X Method alone is adequate for qualitative or quantitative interpretation
- O Method alone is sometimes adequate for qualitative or quantitative interpretation
- + Method alone is inadequate for qualitative or quantitative interpretation and must be supplemented with at least one other method

Note: Symbol assignment is approximate

Table 6.4 Surface Geophysical Methods Useful for Subsidence Prediction

Method	Quantity Measured (Units)	Quantities Computed	Features Identified	Data Format	Depth Penetration and Volume Representation	Measurement Error
Gravity	Gravitational field strength (milligal)	Density contrasts of rocks, depths to zones of anomalous density	Geologic structure, including folds, faults, intrusions, depth to basement, basement topography, hydrothermal alteration; fluid phase	Contour map or cross section	Most influenced by material closest to station, but measurement affected by entire Earth	± 0.01 mgal (10^{-5} x Earth's field)
Magnetic	Magnetic field strength (gamma)	Susceptibility contrasts of rocks, depths to zones of anomalous magnetization	Geologic structure, including depth to basement, basement topography, dikes, sills	Contour map or cross section	Same as above.	± 1 gamma (10^{-4} x Earth's field)
Seismic Refraction	Travel time of refracted seismic waves (millisecond)	Depths to refracting horizons, horizontal speeds of seismic waves	Geologic structure where dips are small, folds, faults, depth to basement, basement topography	Cross section	Depends on wave energy, station spacing, seismic velocities. Usually, penetration less than spacing and path less than twice spacing	$\pm 2-3$ microseconds
Seismic Reflection	Travel time of reflected seismic waves (millisecond)	Depths to reflecting horizons, dips; may measure seismic wave velocities	Geologic structure where dips are small; folds, faults, depth to basement, basement topography	Cross section	Depends on same factors as above. Maximum penetration several km; path at least twice the penetration	
Electrical*						
Controlled-Source DC	Electric potentials resulting from applied electric currents; magnitude of applied currents (ohm-m)			Contour map or cross section	Depends on electrode configuration, resistivities. Penetration $\propto$ spacing. Path length less than twice spacing	
Controlled Source Electro-Magnetic	Electric potentials and induced magnetic fields resulting from applied electric currents; magnitude of applied currents (ohm-m)	Resistivity, depths to zones of differing resistivity	Limited information on geologic structure; fluid phase, detection of fracture systems, water salinity	Contour map or cross section	Depends on configuration, electromagnetic properties. Penetration 30 m to 3 km. Path length less than twice spacing.	
Natural AC (Telluric, etc.)	Electric potentials, and sometimes also induced magnetic fields, resulting from natural electric currents (ohm-m)			Contour map or cross section	Depends on configuration, resistivities. Penetration 200 m to more than 100 km. Path length less than twice spacing.	

* See Table 4.3 for additional detail.

Operation and interpretation procedures vary for the different methods. Gravity and magnetic measurements are made with portable, self-contained instruments. Seismic and electrical surveys, however, require an array of apparatus spread out over distances up to several kilometers. Some elements of this apparatus must be electrically connected.

The format of geophysical data depends both on the method used and the objectives of a particular application. Seismic data is always presented in the form of cross sections. However, gravity, magnetic, and electrical data may be presented as sections or as contour maps.

The interpretation of geophysical data involves two basic steps: correction for extraneous influences on the raw data, such as topography, elevation, and temperature; and the relation of observed variations to the subsurface distribution of the controlling physical property. This distribution is frequently a function of geologic structure.

The particular interpretation procedure depends on the method. Theoretical equations relating anomaly shape to spatial variations of physical properties can be solved analytically only for simple geometrical cases, in which the anomalous body is modeled as a sphere, cylinder, or plate. Computers are now used in most cases to model more accurately the distribution of controlling properties. A particular problem arises in the interpretation of gravity and magnetic data. Because both depth and the physical contrast of materials must be known to interpret the data, these methods do not yield unique solutions for subsurface structure. Additional geologic or geophysical information is required to choose the most reasonable of an infinite number of possible solutions. In most cases, such data is available from geologic mapping, exploratory drilling, or other geophysical investigations. The seismic methods are easy to

interpret in areas of nearly flat-lying, layered rock, but quickly become intractable in complex structures. The electrical surveys are the most difficult to interpret in terms of geologic structure, but are frequently performed in geothermal areas because of their sensitivity to temperature.

The volume representation of surface methods strongly affects their use in subsidence analysis. In general, these methods evaluate the properties of a volume, or linear path, several orders of magnitude greater than that evaluated by geophysical logs, which is in turn several orders of magnitude greater than that evaluated by laboratory tests on samples. Thus, the parameter values inferred from surface methods represent broadly based averages.

Single gravity and magnetic measurements are affected by the entire earth. It is the gradient of several measurements which specifies the depth of anomalous material, not the magnitude of any one measurement. Therefore, it is erroneous to talk in terms of a specific volume whose effect is most keenly sensed. However, for rocks of similar density or magnetic properties, those elements closest to the measurement station most strongly affect the measured value.

The seismic refraction and resistivity methods measure seismic velocity and apparent resistivity along a path consisting of one or several linear or arcuate segments. The path length, as a general rule of thumb, is between one and two times the station spacing (expressions for the actual length are presented in standard texts). This spacing may vary from a fraction of a kilometer to a few kilometers, depending upon the scale of subsurface information required.

In seismic reflection surveys, the wave travels along the two equidimensional sides of an isosceles triangle whose apex is on the reflecting surface underground, and whose basal corners are the sending and receiving stations. Thus, the path length may be more than 10 km.

The primary use of surface geophysical methods in subsidence analysis is to determine the geologic structure, or subsurface distribution of large rock formations. Structural features such as folds and faults, also thought to affect subsidence potential, may be identified by these methods. Some of the physical properties measured as an integral part of the methods, such as density, seismic wave velocity, and resistivity, may be used to calculate additional properties of rocks and their contained fluids. If this is done, the calculated values represent averages for very large volumes of material.

6.2.2 Geophysical Well Logging

The term "well logging" refers collectively to a group of methods for obtaining information about the geometry and condition of boreholes, the petrophysical characteristics of penetrated formations, and the nature of their contained fluids. The methods detect physical variations affecting the borehole surface or the materials within a distance of several centimeters to several meters from the borehole face. Therefore, the information obtained is distinct in scale and applicability from the data gathered in surface geophysical surveys.

A variety of logging devices have been developed to serve many different purposes: temperature and fluid pressure measurement; actual sampling of rock and fluid; recording hole diameter and orientation; imaging the borehole wall; and petrophysical and formation fluid analysis.

Geophysical logs are a subgroup of the broad group of well logs. Geophysical logs respond to the same physical properties as surface geophysical methods. However, magnetic logging is rarely performed. The properties commonly measured, from which petrophysical and fluid characteristics are deduced, are density, radioactivity, electrical, and elastic properties. Radioactivity methods have limited application in surface exploration, but are widely used in borehole investigations.

The main characteristics, use, and limitations of various logging methods are summarized in Tables 6.5 and 6.6. The tables include both geophysical and electromechanical methods. However, only the commonly used geophysical methods are discussed in this report. The tools are divided into four subgroups: electrical, radioactivity, acoustical, auxiliary (electromechanical and infrequently used geophysical logs) and computer analysis logs (developed by later analysis of basic geophysical logs). Each of the several logs listed within each division has a differing configuration or mechanism, and therefore obtains unique information about the penetrated rocks. The names used in this report are generic. However, each well log service company applies its own brand name to its variants of the basic tools.

The arrangement of equipment for well logging is shown in Figure 6.1. The basic elements in a logging include the sensing device (also called a "probe", "sonde", or "tool"), an electric cable or "wireline", a winch, and a recording system. All of these components are truck-mounted for convenient transport to the well site. The probe is lowered to the bottom of the well on the insulated cable. Some measurements are made with the probe held stationary. However, in most cases, the device is drawn upward as measurements are made and recorded in graphical form as a function of depth. Logging speed varies from 15 to 60 cm/sec (0.5

Table 6.5

Uses of Geophysical Logs

<u>Type of Equipment</u>	<u>Parameters Measured</u>	<u>Parameters That May Be Derived</u>	<u>Volume Investigated</u>
<u>Electrical Tools</u>			
*Spontaneous Potential (SP)	Voltages in the bore-hole mud	Lithology, water salinity, correlation	10-100 ft ³
*Induction	Conductivity (or resistivity) of formation fluids	Porosity, water saturation, boundaries of beds, abnormal pressure, fracture porosity	~100 ft ³
*Resistivity, focused	Resistivity of thin segment of formation	Definition of beds and the true resistivity of undisturbed formation waters	~100-2000 ft ³
*Resistivity, non-focused	Resistivity of formation fluids	Porosity, water quality, boundaries of beds, fracture porosity, abnormal pressure	few feet to 20,000 ft ³ ULSEL: 10 ⁶ -10 ⁹ ft ³
*Microresistivity	Resistivity of a thin section of the flushed zone	Resistivity of the flushed zone	few in ³
Microlog-Microcaliper	Resistivity of a few cubic inches of formation next to the bore-hole wall	Definition of porous and permeable beds, hole diameter	few in ³
Induction Casing Thickness Log	Relative conductivities of the casing (measured from sensing phase differences in a received magnetic signal)	Casing thickness	few in ³ of casing

* Denotes methods discussed in text

Table 6.5

-- Continued

<u>Type of Equipment</u>	<u>Parameters Measured</u>	<u>Parameters That May Be Derived</u>	<u>Volume Investigated</u>
Nuclear Magnetism	Magnetic polarization, relaxation time	Free fluid density, fluid identification	?
<u>Radioactivity Tools</u>			
*Gamma-Gamma Density	Compton scattered gamma radiation	Formation bulk density, porosity, lithology	Max. penetration 6 in.
*Gamma, Natural	Gamma radiation intensity (spectrum)	Lithology, correlation, permeability (qualitative)	~4 ft ³
*Neutron	Neutron moderation distance	Hydrogen density, porosity, lithology, water salinity and saturation, water table	~4-32 ft ³
Neutron Activation	Gamma radiation from decay of neutron activated elements	Elemental density (O, Si, Al, Mg), lithology	Penetration 1-2 ft
Neutron capture cross section	Thermal neutron decay time	Chlorine density, porosity, water saturation	Penetration 1-2 ft
Neutron/carbon	Gamma radiation from inelastic neutron scattering	Carbon density	Penetration 1-2 ft
Radioactive Tracers	Gamma radiation	Fluid movements	Borehole fluids
<u>Acoustical Tools</u>			
*Sonic Logs	Velocity of P&S waves, amplitude of S waves	Porosity, correlation, lithology, permeability, elastic constants, abnormal pressure, fractures	Penetration few inches to few feet

*Denotes methods discussed in text

Table 6.5

-- Continued

<u>Type of Equipment</u>	<u>Parameters Measured</u>	<u>Parameters That May Be Derived</u>	<u>Volume Investigated</u>
*Borehole Televiewer	Photograph of borehole wall	Fractures, formation dip collar location, casing shoe	Borehole surface
Cement Bond Log	P wave attenuation	Cement bond quality	Cement bond line
<u>Auxiliary Tools</u>			
Caliper	Hole diameters	Permeability, cement volumes	Borehole walls and/or mudcake face
Dipmeter	Resistivity of a thin section near the borewall at 3-4 places	Dip of the subsurface formations	Penetration very small
Directional Survey	Hole azimuth and direction	Bottom hole location	--
Flow Meter	Fluid flows	Flow rates, source, and injection or thief zones	Borehole fluids
Fluid Samplers	Borehole fluids	Water quality	4 gal. from formation near borehole
Formation Samplers	Cores	Porosity, density, lithology, correlation, heat conductivity	Wall rock sample 1-2½"
Gradiomanometer	Pressure gradient	Multi-phase fluid flow	2 ft interval of borehole fluid
Gravity Meter	Gravity differential	Density, porosity, hydrocarbons behind casing	10 ⁶ -10 ⁸ ft ³

Table 6.5

-- Continued

<u>Type of Equipment</u>	<u>Parameters Measured</u>	<u>Parameters That May Be Derived</u>	<u>Volume Investigated</u>
Temperature	Temperatures, absolute and gradient	Heat flow, cement tops, source and sink zones, fluid flow, behind casing	Borehole and immediately behind casing
Magnetic Susceptibility	Magnetic Susceptibility	Lithology, correlation, casing length changes	Small

Computer Analysis Logs*Mechanical properties

Shear modulus, bulk compressibility

Elastic moduli, compaction coefficients

*Saraband

Lithology, porosity, water saturation, permeability index

*Coriband

Same as Saraband, plus grain density and fracture porosity

(Modified after Baker, Campbell, & Huguen, 1975)

Table 6.6 Use Restrictions for Geophysical Logging Tools

<u>Type of Equipment</u>	<u>Max. Temp.¹ Degrees °C (°F)</u>	<u>Max. Pressure² psi (kg/cm²)</u>	<u>Min. Tool Diameter (inches)</u>	<u>Min. Hole Diameter (inches)</u>	<u>Other Borehole Restrictions</u>
Cables and Connectors	250 (480)				
<u>Electrical Tools</u>					
*Spontaneous Potential (SP)	260 (500)	20,000 (1,400)	2 3/4	4	Conductive mud, uncased
*Induction	260 (500)	20,000 (1,400)	2 3/4	4	Any fluid or dry, uncased
*Resistivity, focused	175 (350)	20,000 (1,400)	3 3/8	6 1/8	Conductive mud, small R_{mf}/R_w , uncased
*Resistivity, non-focused	260 (500)	20,000 (1,400)	1 1/2	3-6 1/8	Conductive mud, uncased
*Microresistivity	175 (350)	15,000 (1,050)	3 5/8	6 1/8	Conductive mud, uncased
Microlog-Microcaliper	175 (350)	15,000 (1,050)	3 5/8	6 1/8	Conductive mud, uncased
Induction Casing Thickness Log	145 (285)	10,000 (700)	3 1/2	4 1/2	Any fluid or dry, cased
Nuclear Magnetism	175 (350)	20,000 (1,400)	4 1/4	5 1/2	Any fluid or dry, uncased (can't use in highly magnetic formations)
<u>Radioactivity Tools</u>					
*Gamma-Gamma Density	205 (400)	20,000 (1,400)	1 11/16	2	Any fluid or dry, best uncased

* Denotes methods discussed in text

¹ Temperature conversions rounded to nearest five degrees.

² Pressure conversions rounded to nearest 50 kg/cm².

Table 6.6 -- Continued

<u>Type of Equipment</u>	<u>Max. Temp.¹ Degrees °C (°F)</u>	<u>Max. Pressure² psi (kg/cm²)</u>	<u>Min. Tool Diameter (inches)</u>	<u>Min. Hole Diameter (inches)</u>	<u>Other Borehole Restrictions</u>
Directional Survey	315 (600)	20,000 (1,400)	1 3/4	3	Uncased if magnetic referenced
Flow Meter	315 (600)	-- --	1 11/16	2	
Fluid Samplers	175 (350)	20,000 (1,400)	3 13/16	4 3/4	Cased, or uncased with suitable seal
Formation Samplers	270 (430)	20,000 (1,400)	4 3/4	4	Soft rock, uncased
Gradiomanometer	175 (350)	15,000 (1,050)	1 11/16	2	
Gravity Meter	150 (300)	-- --	4	5 1/2	
Temperature	315 (600)	30,000 (2,100)	7/8	2	
Magnetic Susceptibility		-- --			Uncased (seldom used)
<u>Computer Analysis Logs³</u>					
*Mechanical Properties	205 (400)	20,000 (1,400)		2	Any fluid, best uncased
*Saraband	175-205 (350-400)	15-20,000 (1,050-1,400)		2	Conductive mud, uncased
*Coriband	175-205 (350-400)	15-20,000 (1,050-1,400)		2	Conductive mud, uncased

* Denotes methods discussed in text

¹ Temperature conversions rounded to nearest five degrees.

² Pressure conversions rounded to nearest 50 kg/cm².

³ Restrictions are for component log with lowest tolerance, depend on choice of resistivity log.

(modified after Baker, Campbell, and Huguen, 1975)

Table 6.6 -- Continued

<u>Type of Equipment</u>	<u>Max. Temp.¹ Degrees °C (°F)</u>	<u>Max. Pressure² psi (kg/cm²)</u>	<u>Min. Tool Diameter (inches)</u>	<u>Min. Hole Diameter (inches)</u>	<u>Other Borehole Restrictions</u>
*Gamma, Natural	260 (500)	20,000 (1,400)	7/8	2	Any fluid or dry, cased or uncased
*Neutron	260 (500)	20,000 (1,400)	1	2	Any fluid or dry, cased or uncased
Neutron Activation	175 (350)	20,000 (1,400)	2 3/16	3 1/2	Any fluid, cased or uncased
Neutron capture cross section	175 (350)	20,000 (1,400)	1 11/16	2	Any fluid, best cased
Neutron/carbon	175 (350)	15,000 (1,050)	3 5/8	4 1/2	Any fluid or dry, cased or uncased
Radioactive Tracers	150 (300)	6,000 (400)	1 3/8	2	Any fluid, cased or uncased
<u>Acoustical Tools</u>					
*Sonic Logs	260 (500)	20,000 (1,400)	1 11/16	2	Any fluid, uncased
*Borehole Televiewer	150 (300)	20,000 (1,400)	3 3/8	4-22	Any fluid, cased or uncased
Cement Bond Log	190 (375)	20,000 (1,400)	1 11/16	2	Cased and cemented
<u>Auxiliary Tools</u>					
Caliper	150 (300)	20,000 (1,400)	1 1/4	40 max dia.	Any fluid or dry (conductive mud if based on resistivity), cased or uncased
Dipmeter	175 (350)	20,000 (1,400)	3 5/8	5 1/2	Conductive mud, uncased, little caving

* Denotes methods discussed in text

¹ Temperature conversions rounded to nearest five degrees.

² Pressure conversions rounded to nearest 50 kg/cm².

Figure 6.1 Arrangement of Equipment for Well Logging.
(From Baker, Campbell, and Huguen, 1975)

to 2.0 ft/sec), depending on the type of measurement to be made. Usually, several logs are run in each hole to maximize the data return for drilling costs.

The probe contains the instrumentation necessary to conduct the physical measurements and to prepare the logging signals for telemetering to the surface through the cable. For certain measurements, the formation or its environment must be energized by one or several "transmitters" placed in the probe in order to generate an appropriate field of force that is sensed by the detectors. Examples of these measurements are resistivity, acoustic velocity, induced gamma radioactivity, and neutron density and energy. For other measurements, no transmitter is needed, and the formation itself generates the field of force. Examples are the spontaneous potential and natural gamma radiation measurements.

A different probe is used to generate each type of geophysical measurement, subject to certain use restrictions shown in Table 6.6. The types of restrictions which must be considered in planning a logging program are casing presence, the kind of fluid in the hole, tool size, and ambient pressure and temperature. Of the logs discussed in this report (the major geophysical logs), only the radioactivity logs may be run in cased holes. The electrical resistivity and spontaneous potential logs must be run in a conductive mud (fresh water or oil emulsion based); the acoustic logs may be used with any fluid (any mud or fresh water); and the induction electric and radioactivity logs, the least restricted in terms of mud or casing, may be used in holes filled with any fluid or with air. Probe dimensions are a limiting factor in some small-diameter holes, and in the relogging of cased holes. Probe diameter ranges from 5 to 13 cm (2 to 5 in) and length from 1 to 6 m (3 to 20 ft).

The major logs are capable of operating reliably under the pressure conditions encountered in geothermal wells. However, the temperatures in some geothermal fields exceed present probe tolerances. In areas where the tolerance is not exceeded, temperature may still affect the measurements. These problems are discussed in more detail in a later section of this report.

Log data may be recorded in two formats: graphic and magnetic tape (for computer analysis). In general, the graphic logs consist of two parts: the heading, which gives identification and scales, and the record of formation characteristics versus depth. In many graphic logs, several characteristics are recorded, each identified by a different line pattern. Standard depth scales are 1:1,200 (100 feet of formation per inch of log) and 1:240 (20 feet per inch).

The interpretation of geophysical logs is an art which requires a high degree of skill. Because many different factors can influence the log deflection, it is important to choose with care the segment of the log that is used to evaluate any particular property. Improper selection can result in highly erroneous interpretations.

Factors which affect log deflections include the roughness (or "rugosity") of the borehole wall, tilt and excentering of the probe, changes in the formation properties which result from drilling (such as mechanical disturbance and shale hydration), interactions between the drilling mud and formation fluids, and adjacent bed effects. These factors influence the various logs to different degrees, and may vary in influence within different parts of the same borehole. Their influence may be estimated on the basis of practical experience, or in some cases measured with certain logs which are specifically designed for this purpose.

Because of the multitude of extraneous factors which may influence log deflections, the logs must be viewed as recording apparent rather than true values for the physical characteristics of interest. Log interpretation involves two basic steps: the derivation of actual from apparent values, called "physical interpretation"; and the derivation of petrophysical properties from the corrected values, called "formation evaluation". Determination of the target petrophysical properties often requires integration of data from several geophysical methods. Interpretation is accomplished with charts and nomograms, or by using empirical or simplified theoretical equations relating the various properties of interest.

In any quantitative application of logging data, including subsidence analysis, it is important to have a feel for the accuracy of the derived parameters. A great deal of research has been directed toward this problem by the major oil companies, much of it involving comparison of log-derived and core-measured properties. Unfortunately, many of the results have not been published and much of the existing literature is oriented toward hydrocarbon analysis. This literature is used infrequently by professional analysts because sample disturbance, variability of the borehole environment and of geologic materials, and the influence of specific test procedures on results preclude widespread comparisons. Therefore, the following discussion of interpretation accuracy is based on conversations with several workers in the field.*

In considerations of log accuracy, it is important to differentiate between the accuracy of the recorded log deflection and that of derived parameters. The accuracy of the deflection depends on instrument design

* Buzz Delano, Schlumberger Well Services, Ventura, California
Subir Sanyal, Geonomics, Inc., Berkeley, California
Paul Atkinson, Stanford University, Stanford, California

and calibration, and is assumed to be relatively good. However, several factors combine to decrease the accuracy of derived parameters: the impossibility of completely defining extraneous effects; inaccuracies in published well log interpretation charts, some of which are based on very few data points; the role of experience, including prior experience in a given geographic area, in improving interpretations; and the general subjectivity of log interpretation. The accuracy of interpretations is improved with computer analysis, because the computer can quickly compare analyses based on a variety of approaches, and can utilize a greater portion of the log data.

General consensus suggests the following accuracies for a few of the important logs and calculated parameters:

- Porosity (from density log) accurate to $\pm 1-3$ percent of total volume (often called "porosity percent"), or 10-20 percent of estimated porosity. The density log is one of the most accurate, and is dependable in all lithologies.
- Permeability (from computer analysis logs) accurate to a factor of 10.
- Acoustic wave travel times (from acoustic log) accurate to 10% or better under favorable conditions. More accurate in consolidated formations. May be impossible to measure, because of attenuation, in very poorly consolidated formations.
- Resistivity: Induction logs are much more reliable than older normal and lateral logs, which are influenced by many more extraneous factors.

The primary use of geophysical logs in subsidence analysis is for identifying petrophysical properties which influence compaction processes, or have been found to be associated with subsidence in other areas. Many pertinent fluid properties may also be deduced. Finally, correlation of strata between boreholes helps to define geologic structure.

6.2.3 General Importance of Geophysics

Geophysical methods are an extremely important source of information about the subsurface properties of rock and fluid. They are a major source of information about the interior of the earth below the depth that can be reached by drilling. In borehole applications, they provide a wealth of information at a cheaper cost than drilling, and they facilitate interpretation of the physical properties between boreholes.

Geophysical information is in some ways better and in others not as good as that obtained from other sources, including visual observation. It is easier to map geologic structures at the ground surface than to map similar structures at depth by geophysics. However, the logging techniques have much better resolution than the human eye, and often record significant variations in rock properties where a human would have noticed none. Another important attribute is the ability to measure pertinent rock and fluid properties in situ, thus avoiding the problems of sample disturbance and laboratory simulation of the sample environment.

6.3 OTHER SOURCES OF INFORMATION RELATED TO SUBSIDENCE

The geophysical survey and logging techniques are only two of several sources of information related to subsidence; the others are drilling observations, core tests, and well tests. Although there is some overlap in the types of information generated by each of the methods, in other ways the data they provide is unique. Brief descriptions of the other data sources are provided below, in order to promote an awareness of the possibilities for data integration.

6.3.1 Drilling Observations

Several rock and fluid properties may be deduced from observations of the drilling process, or from rock chips. For example, the bit penetration rate is a function of several properties including density, induration, and fluid pressure. Mud temperature can be used to estimate bottom hole temperature, and rock chips may be examined for various properties. However, these methods imprecisely define variations with depth because of mixing during circulation of the drilling mud. The main advantage of this type of information is that it may be used to modify drilling programs in progress.

6.3.2 Core Tests

Laboratory test procedures exist for measuring many rock and fluid properties, including all which are pertinent to subsidence analysis and which may be measured by geophysical methods. Core data is used for several purposes: calibration of geophysical instruments, comparison

with geophysical logs, in some calculations using geophysical data, and in independent calculations. However, the data has three significant limitations. First, small changes in test procedure can greatly alter the results. Second, the properties of the sample may have been substantially altered by mechanical disturbance and changes in moisture content. Third, differences between in situ and test conditions may affect the results.

6.3.3 Well Tests

Well tests measure dynamic properties associated with fluid flow, such as fluid pressure, hydraulic communication, and permeability. Although these properties can be estimated from geophysical logs, they can be determined accurately only by well tests.

6.4 USE OF GEOPHYSICAL DATA IN SUBSIDENCE ANALYSIS

6.4.1 Information Needed

The types of information required for subsidence analysis and prediction are discussed in detail in Chapter 9. To summarize, however, basically two classes of information are needed, depending on the type of analysis to be performed. For subsidence modeling as a minimum the deformation properties of the rock, expressed in terms of elastic moduli or compaction coefficients, must be known. The natural hydro-thermal system and production scheme must also be defined as fully as possible, to predict the stress changes to which the rock will be subjected. For the comparative-empirical approach, a broad knowledge of the geologic occurrence of the fluid resource is also needed. This geologic information may be used, if necessary, as a basis for inferring the physical properties of rock beyond the zones where they have been evaluated by geophysical methods. Table 6.3 indicates that geophysical methods can help to define many of the geologic, petrophysical, and hydrologic features pertinent to subsidence analysis.

6.4.2 Choice of Methods for Data Acquisition

As shown in Table 6.3, several alternative procedures may be used to determine most of the needed rock and fluid properties. The geophysical logging methods are particularly flexible in the types of information they provide. However, several logs must be run in order to fully utilize their capabilities for subsidence analysis. No one or two logs are capable of fully characterizing the formation properties, and some logs are considered significantly better than others for

evaluating certain properties. General texts on logging procedures provide a basis for these conclusions. The optimum use of several methods in subsidence analysis is also discussed by Allen (1975).

For example, the density log is considered best for measuring bulk density, porosity, and relative consolidation. The acoustic log is best for cementation. For lithology, either the spontaneous potential/resistivity or natural gamma/neutron combination is effective. Both the acoustic and density logs are required to determine elastic constants, compressibilities, compaction coefficients, and clay content (sorting). The neutron log, which responds primarily to formation water, provides several types of hydrologic information. A caliper log, to measure variations in borehole diameter, is usually run in conjunction with these logs to compensate for the effects of variable diameter on some of the log responses.

All of these logs are required for the Saraband and Coriband computer analysis logs (Schlumberger, 1974). These logs, presented in graphic and tabular form, result from computer analysis of the basic log data. In water-bearing formations, the following properties are computed: the fractional volumes of clay, shale, and sand; primary and secondary porosity; permeability index, and water saturation. The computer analysis logs are thought to provide a more accurate evaluation of these parameters than analysis of individual logs by hand, because a greater proportion of the log data can be used. The logs provide convenience in addition to accuracy. However, for some uses, it probably will be desirable to refer to the basic logs, even if computer analysis logs are available.

As noted above, the basic quantities used in petrophysical calculations may also be determined by sample testing, and, in some cases,

by surface geophysical surveys (e.g., density, resistivity, and elastic wave velocity). The main considerations in the choice of methods to determine a particular parameter, where multiple procedures are possible, are the scale and accuracy of the information provided. The following subsections are devoted to these considerations. Well testing and drilling observations are omitted from the discussion; the former procedure because it supplies information not duplicated in nature or quality by geophysical or laboratory testing methods; and the latter because the information provided is restricted in type and accuracy.

Scale - The scale, or volume representation, of sample test, logging, and survey methods differs substantially, and is a major consideration in the choice of methods to evaluate particular properties. The samples used in most tests measure a few centimeters in each dimension. The penetration of most geophysical logging methods, in contrast, varies from a few centimeters to a few meters. Therefore, the volume of material evaluated by logging methods varies from a few times to perhaps 10^5 or 10^6 times the volume of the samples. Surface geophysical surveys measure extremely large volumes of materials. Gravity and magnetic measurements are affected by the entire earth, although the effect of the material closest to the measurement station is greatest. The resistivity and seismic methods measure formation properties along paths composed of one or several linear or arcuate segments. In geothermal applications, the path length may range from a fraction of a kilometer to several kilometers.

In sample test, logging, or survey methods based on the propagation of elastic waves, the wavelength is another factor in the nature of the resultant data. In principle, elastic waves respond only to physical variations whose size is greater than half the wavelength. Because the wavelengths detected by each method vary from millimeters to kilometers, the information generated is inherently different. The logging and sample test procedures may detect many small variations in the properties of a formation which appears homogeneous to the longer seismic waves.

The same principle differentiates the measured values of other physical properties (density, resistivity, radioactivity) which are determined at greatly different scales. The smaller the volume representation of each measurement procedure, the greater the apparent variability.

It is largely as a result of differences in scale that survey methods are used predominantly to determine geologic structure, and sample testing and logging procedures are used for detailed petrophysical and hydrologic evaluation. These differences in usage apply to most subsurface investigations, in addition to subsidence analysis.

The physical continuity of the resultant data is another aspect of scale which is important in many applications. The geophysical survey methods provide information about large volumes of material which are physically continuous in all directions. The logging methods measure continuous variations in one dimension, depth. However, sample data is highly discontinuous. In many cases, the vertical spacing of the samples will be smaller than the horizontal spacing of adjacent wells, but at best, even in the vertical dimension, the samples represent only a small fraction of the total formation thickness. Interpretation of sample data is complicated by the possibility that the samples may not be physically representative of a very large fraction of the formation, and that variability between sampled points may preclude successful interpolation of physical properties. Sample data alone have failed to provide an adequate basis for subsidence prediction in the San Joaquin Valley, California (Lofgren, 1976) and for analysis of past subsidence at Wilmington, California (Allen, 1975a). The results suggest the advisability of combining data from the physically continuous (geophysical survey and logging) and physically discontinuous (sample-based) measurement techniques.

In general, the scale of the data must be suited to the task. The large-scale methods will provide broadly averaged values for information properties. The smaller-scale methods will record more local variations, but may not sense large features, such as fractures, which may influence overall deformation properties.

Accuracy - The accuracy of physical measurements, and of the interpretations based on them, also varies for sample tests, well logging, and geophysical surveys.

A broad review of the accuracy of many laboratory testing procedures was beyond the scope of this report. However, in general, the accuracy of test results suffers from three basic limitations. First, the properties of the sample may have been altered significantly during collection, storage, and transport. Second, the results may be affected by differences between in-situ and test conditions, such as temperature, pressure, stress, and isolation from surrounding materials. Third, small changes in the procedures used to perform some tests can greatly alter the results (American Society for Testing and Materials, 1970). The impact of these effects on laboratory measured compaction coefficients is discussed in a later section of this chapter.

The accuracy of geophysical logs has been discussed previously. In hydrocarbon areas, the error in most derived formation properties is estimated at 5 to 10 percent under good conditions (Subir Sanyal, 1976), and 1 to 3 percent in porosities (Dresser Atlas, 1971; Subir Sanyal, 1976; Buzz Delano, 1976). Previous familiarity with the geographic area contributes to analytical accuracy.

In geothermal areas, however, several problems arise which decrease the accuracy of log interpretation (Baker, Campbell and Huguen, 1975). These problems largely stem from the limited temperature tolerance of the tools (discussed below) and the inexperience of log analysts in geothermal areas. In very high temperature fields, the lack of certain basic measurements, because of tool limitations, may curtail analysis. Geothermal areas often contain types of rock which are unfamiliar to tool operators and log analysts alike. Therefore, tool malfunctions may go undetected. Further, few comparisons of geothermal log and core data have been performed. Finally, some formation parameters may depend on temperature, and interpretation schemes must be developed which compensate for this dependence. It is not known which interpretations are most affected by temperature, although research on this subject has been proposed (Subir Sanyal, oral communication, 1976). It must be emphasized that the magnitude of some of the preceding problems depends on temperature. The cooler geothermal fields are within the maximum temperature range encountered in hydrocarbon exploration (175°C, or 350°F), with which the logging industry has had some previous experience.

Surface geophysical survey data may be interpreted with very good accuracy by computer analysis. Information on both the subsurface distribution of different rock formations (geologic structure) and average values of formation properties may be obtained.

Interpretation of some surveys may be difficult in geothermal areas where the geologic structure is complex. The seismic methods are very difficult to interpret in rocks which have been severely folded, faulted, or intruded by magma. Geothermal areas often have experienced repeated intrusions of magma over long periods of geologic time, during which the direction of the earth's magnetic field may have reversed several times.

Therefore, separate bodies of igneous rock may have different directions of remanent magnetization, rendering difficult the interpretation of magnetic surveys. Electrical methods are popular for geothermal exploration because of their sensitivity to temperature. However, the effects of temperature and of other factors such as porosity and water salinity on these methods decreases their usefulness for interpretation of geologic structure. Other geophysical survey methods may be slightly affected by temperature, but these variations are not of great concern if the data is to be used primarily for structural evaluation.

6.4.3 Availability of Geophysical Information in the Geothermal Environment

Whether and when geophysical information becomes available for subsidence analysis in any geothermal area depends on several factors: the usefulness of individual methods for geothermal exploration and reservoir evaluation, their stage of use, and equipment limitations arising from the physical conditions of the geothermal environment, particularly temperature.

Subsidence analysis, as far as the geothermal exploration manager is concerned, is a secondary objective. However, because the occurrence, extent, and magnitude of subsidence are related to reservoir properties, the exploration objectives of reservoir location and evaluation should provide some geophysical basis, however limited, for subsidence analysis. Table 6.7 shows the timing of geophysical and laboratory test procedures in geothermal exploration.

Most standard geophysical surveys (gravity, magnetic, seismic, and resistivity) are performed eventually in most geothermal areas.

Table 6.7 Stages in Geothermal Exploration

Stage	Objective	Techniques	Comments
Literature Search	Locate and evaluate existing data		
Airborne Reconnaissance	Identify prospect areas	Infrared imagery *Aeromagnetic surveys	Limited usefulness
Regional Geologic and Hydrologic Surveys	Geographic delineation of thermal area	Geologic field mapping. Spring discharge measurements. Analysis of water well data	
Geochemical Surveys	Subsurface temperature, resource type	Water sampling and chemical analysis	
Geophysical Surveys	Identify drilling targets	*Resistivity surveys Microearthquake surveys Temperature gradient Heat flow	Useful for locating reservoir
		*Self potential surveys *Magnetic surveys *Gravity surveys *Seismic surveys	Useful for geologic structure; not always performed
Exploratory Drilling	Reservoir evaluation	*Geophysical logging	For common log combinations, see Table 4.18
Development Drilling		Sample testing Well testing Analysis of data obtained during drilling	

* Methods discussed in text

Sources: Banwell, 1970; Combs and Muffler, 1973; McNitt, 1975

Geophysical logging is also performed in most fields, although the combination of logs may vary depending on the preferences and budget of the company involved. However, in some fields, the use of logs may be restricted because of physical limitations.

The adequacy of present logging equipment for use in the geothermal environment was the subject of a recent workshop (Baker, Baker and Huguen, 1975) and a preliminary report (Baker, Campbell, and Huguen, 1975). The participants concluded that present equipment is not capable of operating reliably in geothermal areas. Limiting factors cited by the group include corrosive fluids, tool size, and the pressure/temperature tolerances of individual tools.

Corrosive fluids contribute generally to tool mortality, but were not considered a major problem. Tool size is a limiting factor to the extent that it may be desirable to re-log producing wells during the life of the field, in order to determine time variations of porosity and permeability. Table 6.6 summarizes the approximate temperature/pressure tolerances of each geophysical logging tool. Most of the tools are capable of withstanding pressures up to 20,000 psi (1,400 kg/cm²). This pressure is rarely exceeded at depths above 22,000 feet (6.7 km), and hence, has not posed a very large problem in the relatively shallow holes (less than 10,000 feet or 3 km) drilled to date for geothermal applications.

Temperature presents by far the greatest limitation to the use of logging tools in the geothermal environment. The tools are capable of operating reliably at the maximum temperatures encountered in oil and gas fields (175°C, or 350°F). However, at the higher temperatures encountered in many geothermal fields (see White and Williams, 1975, for

temperature ranges), the electronic components fatigue and eventually fail. Insulating dewar flasks are used to protect the few specially developed "hot hole" tools which are now available. However, the electrical cable which both supports and transmits data from logging tools is not capable of such protection, and is very vulnerable to high temperatures.

Whether or not geothermal boreholes can be logged depends on the relationship of their pressure/temperature conditions to the tolerance limits of individual logging tools. The temperature tolerance levels, which are the more limiting, are not precisely known because the performance of a particular tool depends strongly on its preparation and the skill of the crew operating it. Current practice in geothermal areas is to log holes whose maximum temperature is below the tolerance limits. In hotter holes, the number of logs which may be used is restricted. In some cases, only the cooler portions of exploratory holes have been logged. In others, the formation is artificially cooled before logging by the circulation of cold fluid.

In summary, it is apparent that the availability of geophysical logs in geothermal boreholes may be restricted, depending on the maximum downhole temperature. However, many geothermal fields are below the limiting temperature of approximately 260°C (500°F). Logging capabilities in geothermal areas may be improved during the next decade due to federal funding support. The government's goal is to achieve a temperature capability of 500°C (930°F) by 1986.

6.5 MEASUREMENT OF COMPACTION AND SUBSIDENCE BY GEOPHYSICAL METHODS

One of the main objectives of this geothermal study is to assess the usefulness of geophysical methods for measuring compaction and subsidence. A review of applicable methods indicates that a few are suitable for this purpose. A discussion of these methods follows.

6.5.1 Identification of Compacting Intervals

Compacting intervals presently are identified, and the compaction measured, with implanted objects or devices (the various procedures are described in detail by Chilingarian and Wolfe, 1975). Some of these methods involve the use of geophysical logs to measure changes in casing length and the spacing of radioactive marker bullets (magnetic susceptibility and natural gamma logs, respectively). However, in several studies, the logs alone have proved to be essentially useless, at least in the areas investigated.

A study of electric logs from Wilmington Oil field, California, attempted to measure changes in the thickness of individual beds caused by compaction (Stanford Research Institute, 1949). Pairs of logs from adjacent wells, one drilled early in the subsidence history and one drilled several years later, were compared. However, the observed thickness changes were judged to be insignificant and undifferentiable from lateral stratigraphic thickness changes. Continued study of the use of electric logs for compaction detection was not recommended.

Ben Lofgren and other staff members of the USGS Office of Subsidence Research concluded that acoustic and density logs are not useful for

detecting compaction in the San Joaquin Valley, California (Ben Lofgren, oral communication, March 1976). However, due to its ability to detect volume changes of 1-3 percent (Dresser Atlas, 1971; Delano, 1976; Sanyal, 1976), it is nevertheless possible that the density log may be useful in some cases. An advantage of this log for successive measurements is that it may be used in cased holes.

6.5.2 Subsidence Detection by Repeat Gravity Surveys

Although geophysical logging methods may be used to detect compaction, gravimetry is the only geophysical technique known to be capable of detecting subsidence. The procedure has been described in several recent papers (Hunt, 1970, 1975; Hunt and Hicks, 1975). Studies which estimate subsidence from gravity data have been completed at two New Zealand geothermal fields: Wairakei (Hunt, 1975) and Broadlands (Hunt and Hicks, 1975).

The approach is based on changes in gravitational acceleration which are observed during successive surveys. In areas of fluid withdrawal, observed changes in gravity may be caused either by subsidence or by net fluid withdrawal (production exceeding combined injection and natural recharge) or both. Subsidence tends to increase the observed value of gravity and net fluid withdrawal to decrease it. Therefore, subsidence may be occurring even if there is no apparent change in gravity, if the effects of subsidence and net fluid withdrawal are balanced. The absence of such a change, when net fluid withdrawal is suspected, is reason to suspect subsidence.

If the net fluid withdrawal could be measured by some independent means, fairly precise estimates of subsidence could be obtained. However,

because gravity variations over geothermal fields are usually used to measure net fluid withdrawal, such estimates are not generally possible. If net mass withdrawal is assumed to be zero, and all of the change in gravity is attributed to subsidence, an estimate may be obtained if the maximum amount of subsidence occurring between successive surveys.

In practice, other factors in addition to net fluid withdrawal and subsidence can affect gravity values. These factors include variations in topography, depth to water table, and relative elevation of gravity measurement stations. Allowing for such extraneous effects, the gravity approach is capable of detecting subsidence on the order of a few centimeters in magnitude (Lofgren, 1976).

Subsidence alone increases the observed value of gravity by 0.308 mgal/m, or 0.0930 mgal/ft. Approximate expressions for calculating subsidence, derived in Chapter 4 of the Research Report, are given below for two simplified reservoir shapes (slab and disc). The geometrical assumptions are sketched, and the variables defined, in Figures 6.2 and 6.3. The method assumes that all of the compaction occurring in the reservoir is expressed at the surface as subsidence, and that no compaction or dilation occurs in the overburden. The initial and final reservoir densities, which appear in the expressions, reflect changes caused both by compaction and by net fluid withdrawal.

The change in gravitational attraction for the infinite, slab-shaped reservoir is constant at any point on the ground surface and does not depend on reservoir depth. For the disc-shaped reservoir, because of edge effects the expression depends on reservoir depth and applies only to gravity values measured at the intersection of the ground surface and the disc axis. Minor topographic effects on gravity, due to the development of a subsidence depression, were ignored in the derivation.

Figure 6.2

Variables Used to Calculate the Change in Gravitational Attraction of a Slab-shaped Reservoir.

Figure 6.3

Variables Used to Calculate the Change in Gravitational Attraction of a Disc-shaped Reservoir.

For ρ in g/cm^3 and all other dimensions in meters,

$$\Delta g_{\text{slab}} = 4.19 \times 10^{-6} (\rho_f T_f - \rho_i T_i) + 0.308 \Delta T \quad (6.1)$$

$$\begin{aligned} \Delta g_{\text{disc}} = 4.19 \times 10^{-6} & \left\{ \rho_f \left[T_f + (d^2 + r^2) - r^2 + (T_i + d)^2 \right]^{1/2} \right. \\ & \left. - \rho_i \left[T_i + (d^2 + r^2) - r^2 + (T_i + d)^2 \right]^{1/2} \right\} + 0.308 \Delta T \quad (6.2) \end{aligned}$$

For ρ in g/cm^3 and all other dimensions in feet,

$$\Delta g_{\text{slab}} = 1.38 \times 10^{-5} (\rho_f T_f - \rho_i T_i) + 0.0939 \Delta T \quad (6.3)$$

$$\begin{aligned} \Delta g_{\text{disc}} = 1.38 \times 10^{-5} & \left\{ \rho_f \left[T_f + (d^2 + r^2) - r^2 + (T_i + d)^2 \right]^{1/2} \right. \\ & \left. - \rho_i \left[T_i + (d^2 + r^2) - r^2 + (T_i + d)^2 \right]^{1/2} \right\} + 0.0939 \Delta T \quad (6.4) \end{aligned}$$

6.6 DETERMINATION OF COMPACTION COEFFICIENTS

The methods of determining compaction coefficients are described in detail below, to provide a background for the later discussion, in Chapter 12, of their use in simplified subsidence models.

Compaction coefficients may be determined by five methods: in situ measurement; consolidation (or compaction) tests; calculation from elastic constants or from the acoustic and density logs; and back-calculation from observed subsidence. The in situ measurement techniques, developed for engineering investigations, will not be described here because their maximum penetration is about 200 feet (American Society for Testing and Materials, 1970). The other approaches have various advantages and disadvantages, depending on the underlying assumptions and sources of error. These differences must be kept in mind when using the resultant data.

6.6.1 Laboratory Testing

The theoretical basis for laboratory measurement of compaction coefficients is the assumption that compaction behavior depends only on the effective stress; that is, on the difference between internal fluid pressure and external frame stress, and not on the actual stress magnitudes. Therefore, the behavior of the reservoir rock can be simulated by applying suitable stress differences (Teeuw, 1971).

The general test procedure involves loading a small specimen of soil or rock incrementally and measuring its deformation over time. During this process, the pore fluid pressure is maintained at a constant, atmospheric level by allowing the fluid to be squeezed into a manometer

as the sample compresses. Effective stresses in the actual reservoir are simulated by the difference between the constant fluid pressure and the increasing external pressure. The compaction test yields a plot of void ratio versus the logarithm of the effective stress (called an "e-log p" plot), from which the compaction coefficient for the appropriate stress interval is calculated by the following method (see Research Report):

$$C_m = \frac{e(p_2) - e(p_1)}{(1+e(p_2))(1+e(p_1))} \quad (6.5)$$

Three different test procedures are used to measure compaction, each of which has its own advantages and disadvantages. These are the uniaxial (oedometer), modified triaxial, and hydrostatic tests (Teeuw, 1971).

The oedometer and triaxial cells (Figure 6.4) simulate the reservoir boundary conditions of uniaxial compression and zero lateral displacement. In both tests, the sample (a few centimeters in diameter and height) is compressed vertically between pistons. In the oedometer cell, lateral constraint is provided by the solid cylinder wall. In the triaxial cell, constraint is provided by constant readjustment of the pressure in the surrounding fluid reservoir. In both types of apparatus, the sample is enclosed in an impermeable sleeve and capped by permeable discs which allow excess pore fluid to escape into a manometer.

Error can be introduced into both the oedometer and triaxial tests by improper shaping of the sample. In both tests, it is important that the upper and lower surfaces of the sample be flat and parallel to the piston surface, as any deviation will result in too large compactions over the low pressure range of the test. Shaping of the sample sides is not a problem

UNIAXIAL COMPACTION CELL (OEDOMETER)

HYDROSTATIC COMPACTION CELL

TRIAXIAL COMPACTION CELL

Figure 6.4

Laboratory Apparatus Used for Measuring Compaction,
(From Teeuw, 1971)

in the modified triaxial test because an elastic sleeve, which conforms to the sample, is used. However, samples must fit perfectly into the rigid-walled oedometer, or the condition of zero lateral displacement will not be met. Shaping is not a problem with clays and loose sands, but with consolidated rock it is very difficult to avoid a gap between the sample and the oedometer wall. This makes interpretation of the test results tenuous at best. Therefore, the modified triaxial test is slightly more favored as a method for measuring uniaxial compaction. Another advantage of the method is that it provides an independent measurement of Poisson's ratio.

The hydrostatic loading test (Figure 6.4) has been widely used to measure the compressibility of consolidated rock. In this test, pressure is applied to the sample through the surrounding fluid reservoir, causing it to compress in all directions. Because the sample is enclosed in a tight-fitting jacket, no shaping problem exists. In addition, the measurement is simple and rapid.

Unlike the uniaxial and modified triaxial tests, which measure uniaxial compaction as a function of pressure, the hydrostatic test measures volume compressibility as a function of pressure. The volume compressibility, C_b , also called bulk compressibility, is defined as:

$$C_b = \frac{1}{V_p} \frac{dV}{dp} \quad (6.6)$$

The compaction coefficient may then be calculated from the bulk compressibility (Teeuw, 1971)*:

$$C_m = \frac{1}{3} \left(\frac{1+\nu_b}{1-\nu_b} \right) C_b \quad (6.7)$$

* Another expression used by Teeuw (1973, Equations 3 and 4) to related C_m and C_b is dimensionally incorrect.

For most rocks, using an average value of 0.30 for v_b will introduce an error of ± 10 percent (Teeuw, 1971). An advantage of testing programs which combine both modified triaxial and hydrostatic tests is that the former provide independent measurements of v_b , which may be used instead of the average value to decrease the margin of error.

Comparing the three test procedures, Teeuw (1971) found that all produced the same results for hard, well-cemented rocks. For friable rocks, however, the modified triaxial and hydrostatic tests yield comparable results, but much greater compaction occurred in the oedometer tests. Therefore, Teeuw recommends that testing programs be designed so that most tests be performed with the hydrostatic cell. A few tests should be made with the triaxial cell, to check the hydrostatic measurements and to provide an independent evaluation of Poisson's ratio.

Use of laboratory compaction data - To date, rather poor results have been obtained in attempts to model past subsidence using laboratory-measured compaction coefficients. Such studies have been carried out for the San Joaquin Valley (Ben Lofgren, oral communication, 1976), and for the Wilmington oil field by Dan Kosloff at UCLA (Dennis Allen, oral communication, 1976). However, in both cases, a poor correspondence was obtained between the actual and simulated subsidence. There are two major reasons for this difficulty. The first is the impossibility of reproducing, in the laboratory, the in-situ behavior of compacting materials. The second is the problem of extrapolating a few laboratory measurements, made on very small samples, to a much thicker column of sediments.

Laboratory compaction behavior differs from in-situ behavior because of differences in the natural and artificially applied stress fields, disturbance of the sample during its collection and transportation, and

changes in the natural moisture content. These problems are especially severe with loose or poorly consolidated sands, which are common in many subsiding areas. In addition, variations in the test procedure can also significantly affect the results (American Society for Testing and Materials, 1970). It would be useful to try to quantify, and correct for, some of these effects.

The problem of extrapolation is also difficult to resolve. The density of available compaction coefficient measurements is probably greater, in general, in areas which have already experienced a great deal of subsidence than in those with little or none. Even in areas with comparatively numerous measurements, however, the data represent only a very small fraction of the total sediment thickness.

Geophysical logs may be useful for extrapolating between sample points. However, the process is subjective and, as Ben Lofgren (1976) notes, difficult to apply in areas such as the San Joaquin Valley where a great deal of lithologic variation occurs between samples.

6.6.2 Calculation from Elastic Constants

Another approach for determining compaction coefficients in calculation from Young's modulus, E , and Poisson's ratio, ν (see Research Report):

$$C_m = \frac{(1+\nu_b)(1-2\nu_b)}{E(1-\nu_b)} \quad (6.8)$$

This indirect approach suffers from the possibility of error in the methods used to measure E and ν . Sources of error whose effect is probably slight are variations of elastic properties with stress and with the

frequency of elastic waves used to measure the constants. However, if the rock is elastically anisotropic, a large error may be introduced if E and ν are calculated using interconnecting relationships for the elastic properties of isotropic materials, or if E and ν are not measured in the vertical direction. Percent variations in E and ν with orientation have been reported which are as great as 37 to 17 percent respectively, (Research Report, Chapter 4).

If elastic waves are used to measure the constants, the volumetric generality of the resulting values will depend on the wavelength. In general principle, elastic waves may sense only those physical inhomogeneities which are larger than half the wavelength. Wavelengths which might be used to determine elastic properties range from less than a millimeter to 5,000 meters, depending on the method used, the particular instrument, and the seismic velocity of the material (Research Report, Chapter 4). Surface seismic surveys, which employ relatively widespread station spacings and long wavers, yield elastic constants which reflect the average characteristics of relatively large volumes of rock. Acoustic logging, which uses a shorter wavelength, records smaller-scale variations in rock properties and measures the properties of a smaller total volume. Laboratory techniques for measuring the elastic constants use the shortest waves, measures the smallest volume, and yield the least representative results.

The accuracy of compaction predictions based on this approach depends on the accuracy and volumetric representation of the elastic constants. Constants determined from seismic surveys, particularly from surveys in which instruments are used which sense very low frequencies, may have an averaging effect perhaps comparable to that obtained in back-calculation of compaction coefficients (see below). The use of laboratory

measured constants would involve problems of interpolation between sampled points. Elastic constants can be determined as a continuous function of depth from the acoustic and density logs, using certain assumptions. However, it would be pointless to use these constants to compute compaction coefficients, as a more direct approach exists.

6.6.3 Calculation from Acoustic and Density Logs

The following expression (Schlumberger Limited, 1974) relates bulk compressibility to the travel time of elastic waves, Δt , as measured by the acoustic log, and formation bulk density, ρ_b , measured by the density log:

$$\begin{aligned} C_b &= 2.24 \times 10^{-10} \frac{(1-\nu_b)(\Delta t)^2}{(1+\nu_b)\rho_b} \text{ (psi)}^{-1} \\ &= 3.19 \times 10^{-9} \frac{(1-\nu_b)(\Delta t)^2}{(1+\nu_b)\rho_b} \text{ (kg/cm}^2\text{)}^{-1} \end{aligned} \quad (6.9)$$

where

C_b = bulk compressibility

ν = Poisson's ratio

Δt = acoustic wave travel time, in microseconds/ft,
from acoustic log

ρ_b = bulk density, in g/cm³, from density log

The bulk density must be stated in g/cm³, and the travel time in microseconds/ft.

Poisson's ratio may be determined by several methods. The following approach (Schlumberger Limited, 1974), which also utilizes the acoustic and density logs, is based on empirical data for Tertiary sediments in the Gulf Coast:

$$v_b = 0.124q + 0.27; \quad (6.10)$$

$$q = \frac{\rho_b - \rho_f - \rho_{ma}(1 - \phi_z)}{\rho_c \phi_z - \rho_f} \quad (6.11)$$

where

ρ_b = bulk density, from density log

ρ_f = fluid density, measured or estimated

ρ_{ma} = density of sand grains, measured or estimated

ϕ_z = porosity, calculated from acoustic log
(see Research Report Chapter 4 for procedure)

Luckily, when the preceding expression for C_b is substituted into Equation (6.7), Poisson's ratio drops out, and the compaction coefficient is stated very simply in terms of density and travel time:

$$\begin{aligned} C_m &= 2.24 \times 10^{-10} (1/3) \frac{(\Delta t)^2}{\rho_b} \text{ (psi}^{-1}\text{)} \quad (6.12) \\ &= -.19 \times 10^{-9} (1/3) \frac{(\Delta t)^2}{\rho_b} \text{ (kg/cm}^2\text{)}^{-1} \end{aligned}$$

6.6.4 Back-Calculation from Observed Compaction

In areas where some compaction (or subsidence) has already occurred, an average coefficient for the entire compacting interval may be calculated if the initial thickness, z , the shortening, Δz , and the average pressure

change, Δp , are known. This average coefficient can then be used to predict future compaction of the interval as a whole. The expression used is (see Chapter 12),

$$\Delta z = C_m \Delta p z \quad (6.13)$$

The advantage of this approach is that the resulting coefficient reflects the behavior of the entire interval, averaging the effects of strata for differing lithologies. It circumvents the problem of extending the results of a limited number of compaction tests, made on samples which may differ in unknown ways from adjacent materials, to an entire column of sediments. Ben Lofgren (1975), was better able to simulate subsidence in the San Joaquin Valley, California, by back-calculation than by extrapolation from a limited number of laboratory measurements.

The approach has two basic disadvantages. First, it requires some previous compaction, and therefore is unsuitable for use in virgin areas. Second, if the compacting interval contains fine-grained beds, the observed shortening at the time of measurement, on which the coefficient is based, may not represent the ultimate total readjustment to the latest pressure change in the coarse-grained beds. This effect would make the resulting compaction coefficients low and would result in an under-prediction of subsidence.

6.6.5 Comparison

In the absence of any means for obtaining information on the compaction properties in the area of interest, it may be helpful to scan available information on other areas which are similar in lithology (general rock type), and the mode of sediment deposition. Some information of this type is presented in Chilingarian and Wolfe (1975) and in Research Report Chapter 4. An informal collection of compaction coefficients has also been compiled by Joseph F. Poland, at the U. S. Geological Survey Office of Subsidence Research, in Sacramento, California.

6.6.6 Summary

A variety of procedures exists for determining the compaction coefficients of the depth intervals likely to experience compaction in geothermal areas. It appears that, barring limited availability of the requisite geophysical data, laboratory facilities, core samples, and measured magnitudes of past subsidence, the major considerations in the choice of an approach for a specific situation should be the volumetric representation and physical continuity of the resulting coefficients.

In terms of volumetric representation, the methods may be divided into three groups: very large (back-calculation from observed subsidence and calculation from elastic constants measured by seismic surveys); intermediate (calculation from acoustic and density logs) and very small (any procedure involving sample tests, either direct measurement of compaction coefficients or laboratory measurement of elastic constants). All the procedures yield compaction properties for physically continuous volumes of material except those based on sample tests. Interpolation between sampled points is a problem, especially in areas of lithologic variability, which may not be able to be resolved.

A third consideration in the choice of approach is the stress range for which the compaction properties are measured. Only compaction tests define the variation in these properties over a full pressure range. The other approaches define compaction properties at existing stress levels, and only in areas with observed compaction is it certain that this stress exceeds the preconsolidation stress.

However, the art of predicting or modeling subsidence is in its infancy at this time. The physical continuity and volume representation of compaction data may have a greater effect on the accuracy of interpretations than on the stress magnitude. In any locality, it would be advisable to compare predictions made on the basis of as many approaches as possible.

6.7 CHAPTER SUMMARY

Many geologic, petrophysical, and hydrologic characteristics of fluid resource areas, which are pertinent to subsidence prediction or modeling, may be deduced by a variety of methods. These include geophysical survey and logging techniques, core tests, drilling observations, and well tests. The types of subsidence-related information which may be obtained from the different methods overlap to some extent. However, in some ways, each class of methods provides information which is unique in quality or convenience. The geophysical methods are emphasized in this discussion because they provide a relatively wide range of information on the in situ properties of rock and fluid. In addition, geophysical methods are the only means for acquiring information about subsurface formations which are distant from boreholes and surface exposures, and for acquiring many types of information about the unsampled intervals of boreholes. Sample test results are also frequently used in subsidence analysis and are contrasted where appropriate with the geophysical methods.

The types of subsidence-related information which may be deduced from geophysical methods are summarized in Table 6.3. The table indicates that several alternative logging procedures are available for determining many of the rock and fluid properties listed. However, because no one or two logs are capable of fully characterizing rock formations, and because certain logs are generally recognized as best for deducing certain properties, several logs must be run in each hole to exhaust the possibilities of well logging as a source of subsidence-related information. Surface geophysical surveys can also provide raw data on some physical variations, which can be used to interpret several other rock and fluid properties. In addition, laboratory procedures are available for measuring the properties of core and fluid samples.

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Because of procedural differences, data obtained from surface geophysical surveys, well logging, and sample tests varies in scale and accuracy, and therefore in applicability. The geophysical survey methods, which provide broadly averaged values of physical parameters for very large volumes of rock, are best suited for determining geologic structure. In contrast, well logging and sample tests provide more varied types of information at a finer scale, and therefore are best suited to the interpretation of rock and fluid properties on a detailed scale. Well logs measure continuous physical variations with depth, at a scale intermediate between geophysical surveys and samples tests. Well log analysis is a subjective art. Under favorable conditions, an accuracy of 5 to 10 percent in deduced parameters may be attained, but in geothermal areas, the accuracy is poorer because of inexperience and unknown temperature effects on the log response. Sample tests measure the properties of very small, discontinuous volumes of rock. Although laboratory test conditions and procedures can be carefully controlled, the results must be interpreted with caution because the procedures can influence the results and do not reflect in situ conditions. In general, the data sources must be matched to the scale and accuracy of the task at hand. Comparison of results based on several methods is recommended.

The normal use of geophysical methods for reservoir location and evaluation should provide at least some basis for subsidence analysis in all areas. The particular combination of data which is available will depend on the local geology and hydrology and the budget of the companies involved. Most standard geophysical surveys are performed eventually in most geothermal areas, and several well logs are usually run. However, the quality and availability of log data in geothermal areas will be poorer than in hydrocarbon areas until the temperature limitations of the logging tools are corrected, and basic experience in log interpretation in thermal areas is acquired.

Geophysical methods are not widely used for the detection and measurement of subsidence or compaction. However, two logs are used to detect changes in the length of casing and spacing of radioactive markers. A maximum estimate of subsidence may be obtained from successive gravity surveys.

In summary, in subsidence analysis the geophysical methods may be used to determine a wide range of rock and fluid properties. This information may be used both for subsidence modeling and for subsidence prediction by a comparative-empirical approach. The use of geophysical information improves subsidence analyses by providing a broader data base.

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CHAPTER 7
GEOHERMAL RESERVOIR MODELS

7.1 INTRODUCTION

Although the focus of this Handbook is on subsidence evaluation, the role of the geothermal reservoir in understanding and in predicting subsidence is so important that it must be given considerable attention. The exact nature of that role will be more clearly detailed in Chapter 11, where a quantitative mathematical model will be presented. At this time, we note that the ultimate cause of subsidence associated with geothermal development is reduction in the reservoir pore pressure caused by fluid withdrawal. Thus, to evaluate properly the potential for subsidence of a geothermal development, we must be able to relate the operating policy, i.e., the rate of fluid withdrawal, to the reduction in reservoir pressure, and that relationship is provided by a quantitative model.

The purpose of this chapter is to indicate the state-of-the-art in modeling geothermal reservoirs and to provide a guide to existing models. Presented first will be a brief discussion of relevant phenomena that should be represented by a quantitative model for a geothermal reservoir. Presented second is a brief summary of numerical methods that can be used to solve the equations representing the physical phenomena; and presented lastly is a brief discussion of how to choose a particular geothermal reservoir model for a specific application, among the various types of models available at present.

7.2 PHYSICAL PHENOMENA AND MODELING REQUIREMENTS

Viewed as a physical system, the geothermal reservoir is a porous geological formation whose interstices are occupied by an aqueous fluid. The concept of a porous medium was discussed in Chapter 3. The fluid may be steam, water, or a two-phase mixture, and in addition it may contain dissolved solids.

Reservoir models are primarily concerned with the thermodynamic and hydrodynamic behavior of the fluid occupying the interconnected pore space. The thermodynamic variables of interest are the pressure, temperature, and phase relationships. Hydrodynamically, the velocity fields and pressure gradients are of interest.

Most generally, these quantities are determined by solving sets of time-dependent partial differential equations in three spatial dimensions representing heat, mass, and momentum balances, in conjunction with equations of state for the fluids, and correlations for fluid properties. The fundamentals are discussed by Bird and others (1960), and Slattery (1972). Specific applications to geothermal reservoirs are given for example in Brownell and others (1975), and Mercer and others (1974).

There is a large petroleum reservoir modeling literature, and an entry into this literature is provided by the proceedings of the 1976 symposium of the Society of Petroleum Engineers on numerical simulation. More detail on existing reservoir models is provided in Volume 2, the Research Report.

7.3 NUMERICAL METHODS

A reservoir model is a set of mathematical relations representing the physical processes of the reservoir. In general, implementing the reservoir model involves solving a set of nonlinear, partial differential equations (NLPDE), usually by a numerical method on a digital computer. NLPDE's can be solved by various numerical methods. In particular, there are finite-difference methods (Collatz, 1960), the method of "best approximation," e.g., weighted residuals or variational methods (Finlayson, 1972; Rachford, 1976; Strang and Fix, 1973), or functional analysis methods, (Rall, 1969, 1971; Collatz, 1966). Until about 1970, reservoir modelers had used finite-difference methods almost exclusively. Recently, finite element and more general variational methods have become more popular (Rachford, 1976). At the recent (1976) 4th Symposium on Numerical Simulation, the papers were about evenly split between the two methods.

A word of warning is in order concerning the use of numerical methods. As shown in an example by Collatz (1960), a perfectly plausible numerical method may converge to a wrong solution (nonsolution). Numerical analysis provides a methodology for analyzing particular numerical methods and insuring that the numbers resulting from the computer program are indeed a solution of the NLPDE's and of the model. The analysis of the specific numerical method used in a reservoir modeling study is indeed quite important, and if ignored, the risk of generating an expensive nonsolution is significant.

7.4 CHOOSING GEOTHERMAL RESERVOIR MODELS

In Table 7.1 we have summarized available information on three fluid-heat flow models and seventeen geothermal models. There is a great diversity among the twenty models listed, mainly in terms of the degree of completeness for the physical phenomena treated. The dates of these references clearly correlate to the historical evolution of the state-of-the-art; consequently, the older models should be thought of as prototypes to the later more advanced models. Many recent models are still under development and the documentation may be meager. We have provided information in Table 7.1 on the model developer, the available documentation, as well as such descriptors as the model type, fluid phases considered, number of physical dimensions, heat flow mechanism, and numerical methods used. The reference numbers refer to Table 7.2. More detail on these models is provided in Volume 2, the Research Report.

In Chapters 11 and 13, we will present lumped, single-phase and two-phase geothermal reservoir models. These models are quite easy to use, but sacrifice the resolution achieved by higher dimensional models. For a particular problem at hand, we recommend starting with such a model; and if required, graduate in a hierarchical fashion to a more complex sophisticated model. Chapter 10 describes such a hierarchical approach.

In choosing among the models listed in Table 7.1, prime factors concerning their potential usefulness are such items as the existence of user's documentation, the comprehensive nature of the physical processes treated, the amount and type of data needed to run the model, the computer memory and calculation time required, the degree the computer code has been debugged and/or used by others, and finally the degree the model has

Table 7.1 Summary of Geothermal Reservoir Models

Developer(s)	Model Name	Model Type	Fluid Phases	Dimensions	Heat Flow	Numerical Method	Computer Model	References (Table 7.2)
Edwards	Trump	Fluid-Heat Flow	One	1-3	Conduction & Convection	-	Yes	1-5
Edwards	Trump	Ditto for porous media	One, compressible	1-3	Conduction & Convection	-	Yes	7
Lasseter	Shaft (1)	Ditto for porous media	One	1-3	Conduction & Convection	-	Yes	8
Lasseter, Witherspoon, & Lippman	Shaft (2)	Geothermal Reservoir	Two (Uniform Composition)	1-3	Conduction & Convection	Integrated Fin. Diff.	Yes	9, 10
Sorey	Schaff	Geothermal Reservoir	One (Liquid)	1-3	Conduction & Convection	Mixed Fin. Diff. Fin. Elem.	Yes	11
Mercer & Faust	-	Geothermal Reservoir	One (Liquid)	2	-	Fin. Elem.	Yes	12, 13, 14
Pinder	-	Geothermal Reservoir	Two	3	-	Fin. Elem.	Yes	15
Faust	-	Geothermal Reservoir	Two	1-2	-	Fin. Elem./ Fin. Diff.	Yes	16, 17
Toronyi	-	Geothermal Reservoir	Two	2	-	-	Yes	18, 19
Atkinson	-	-	Two	-	-	-	Yes	20, 21
S-Cubed	Quagwr	Geothermal Reservoir	Two	2-3	Conduction & Convection	Fin. Diff.	Yes	22, 23
Trescott	-	Geopressured Reservoir	-	-	-	-	Yes	24
Intercomp	Geoth & [Shaft (2)]	Geopressured Reservoir	Two	2-3	Conduction & Convection	Fin. Diff.	Yes	25
Intercomp (Inera)	-	Waste Disposal	One	2-3	Conduction & Convection	Fin. Diff.	Yes	
Donaldson	-	Natural Hydrothermal	-	-	-	-	No	26
Whiting & Ramey	-	Geothermal Reservoir	Two	Lumped Parameter	-	-	No	27
Harlow & Pracht	-	Hot Dry Rock	One (Liquid)	-	-	-	No	28
Brigham & Morrow	-	Geothermal Reservoir	Two	3 x lumped Parameter	-	-	No	29
Kassoy	-	Natural Hydrothermal	-	-	-	-	No	30
Gringarten & Sauty	-	Natural Hydrothermal	(One)	(Two)	-	-	No	31

Table 7.2

Reference Key of the Reservoir Models
in Table 7.1

1. Edwards, 1972	16. Faust and Mercer, 1975
2. Schauer, 1973	17. Mercer and Faust, 1975
3. Gabrialson, 1967	18. Toronyi, 1974
4. Lobel, 1971	19. Toronyi and Farouq Ali, 1975
5. Edwards, 1969a	20. Kruger and Ramey, 1974
6. Edwards, 1969b	21. Kruger and Ramey, 1973
7. Edwards, 1969c	22. Pritchett and others, 1975
8. Lasseter, 1972	23. Garg, and others, 1975
9. Lasseter, 1975a	24. Trescott, 1974, 1976
10. Lasseter, 1975b	25. Coats and others, 1974
11. Sorey, 1975	26. Donaldson, 1968
12. Mercer, 1973	27. Whiting and Ramey, 1969
13. Mercer and Pinder, 1974	28. Harlow and Pracht, 1972
14. Faust and Mercer, 1976	29. Brigham and Morrow, 1974
15. Mercer and others, 1974	30. Kasoy, 1975
31. Gringarten and Sauty, 1975	

been validated. The state-of-the-art is such that none of the present models rank satisfactorily on all these factors; and consequently choosing a model for a special application study has to be done with great care. Finally, there is the problem that the chosen model may not be available to the public.

7.5 SUMMARY

In this chapter we have provided an introduction to geothermal reservoir models. We have discussed the physical phenomena to be modeled and the numerical methods for solving the model. We have presented the results of a survey of geothermal models and has also discussed the criteria for choosing a model for a particular use.

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CHAPTER 8
SUBSIDENCE MODELS

8.1 INTRODUCTION

The purpose of this chapter is to introduce subsidence models and to provide a survey of the state-of-the-art. Subsidence models use knowledge of the solid mechanics of geological materials to calculate the deformation resulting from the change in pore pressure. The field of solid mechanics studies the relationship between the forces on a material and its deformation.

Since the pressure distribution will often be determined by a reservoir model, this chapter and Chapter 7 compliment one another. As with the reservoir models, we shall first discuss the physical phenomena and requirements placed on mathematical models to predict subsidence (Section 8.2). We then discuss modeling the flow deformation interaction (Section 8.3) and the choice of a subsidence model (Section 8.4). The reader shall note that more detailed information on subsidence models is provided in Volume 2, the Research Report.

8.2 PHYSICAL PHENOMENA AND MODELING REQUIREMENTS

Distinct from subsidence is the phenomena of compaction. As illustrated in Figure 8.1, compaction is the reduction in volume of a particular stratum, which in this case is the geothermal reservoir. Subsidence on the other hand, is the downward movement of the ground surface as a result of that compaction.

Reservoir compaction occurs because of an increase in effective stress felt by the rock matrix, caused by a decrease in pore pressure. If we view the porous medium as a composite material, then it is clear that the fluid bears a portion of the stress exerted by the overburden on the reservoir. By removing fluid, the pore pressure is reduced, and rock matrix material experiences an increase in stress.

With regard to mathematically modeling compaction, one must formulate a theory of stress for the composite material (the porous medium) and then determine a constitutive relation for the response of the material to a change in stress.

Terzaghi (1925, cf. Terzaghi and Peck, 1967) introduced a simple, but useful theory, of effective stress. He defined effective stress as the difference between the stress in the fluid and the total stress exerted by the overburden. The hydrostatic stress in the fluid has the same magnitude as the pore pressure. Decreasing the pore pressure increases the effective stress, and the material compacts as a response to the increase in effective stress. Terzaghi's concept of effective stress as generalized to three dimensions (Scheidegger, 1973) is generally thought to be quite adequate for geothermal reservoir analysis.

Figure 8.1. A Schematic Geological Model of Subsidence and Compaction

The change in effective stress within the reservoir can also affect the stress in the overburden. We may view the situation in terms of a change in the stress boundary condition at the boundary between the two regions. This reservoir compaction is then propagated through the overburden and results in subsidence at the surface. In summary, the change in effective stress caused by a reduction in pore pressure may be viewed as causing compaction in the reservoir and subsidence at the surface.

In order to compute the equilibrium deformations associated with this stress change, we must use a theory of solid mechanics. Historically, the constitutive relation assumed is a classic elastic material (Biot, 1941) and the resulting model is referred to as poroelasticity.

Current thinking (see Volume 2, Research Report) is that some form of non-associated, visco-plastic constitutive relation is required. Since the current models rely almost exclusively on poroelasticity assumptions, we will continue the discussion in terms of the corresponding constitutive equations.

In geothermal subsidence analysis, an overburden model is required for a complete analysis; however, for groundwater subsidence analysis, such a model is not needed, due to the shallow depths. For this component of the analysis, one can probably use classical elasticity assumptions.

The reservoir compaction problem, considering only mechanics, consists of the simultaneous solution of equilibrium relations, the stress-strain relations, the boundary conditions, and the discontinuity conditions. To solve this problem in three dimensions using a realistic amount of geological detail, requires sophisticated numerical techniques. The numerical method currently in use is the finite element method (see Chapter 7).

8.3 MODELING THE FLOW-DEFORMATION INTERACTION

In order to relate subsidence predictions to geothermal fluid withdrawal rates, the relationship between the compaction model and an appropriate reservoir model must be established. Two models are called coupled if the solution of each model is required to specify the other. In general, the flow and deformation models are coupled. Thus, the most general choice would be to solve simultaneously a three-dimensional, transient reservoir model and a three-dimensional, transient compaction model. Such a course is rarely followed because of the computational complexity and the difficulty of determining all the material constants (Gambolati and Freeze, 1973).

A simplification of the model-coupling complexities that is often followed is to solve the reservoir flow equations separately in order to obtain a pressure distribution within the reservoir. The calculated pressure field is then used to calculate reservoir deformation. A somewhat refined version of this approach, interactive calculation, is first to calculate the pressure and flow fields for a small pressure increment, and then to calculate the deformation of the reservoir before performing additional flow calculations.

Another common approach, which has its roots in soil mechanics, is to simplify the combined equations for reservoir deformation and flow so that a single equation for reservoir pressure results (Gambolati and Freeze, 1973). Besides the expected hydrodynamic relations, this equation contains a new term reflecting the effect of reservoir compaction. The deformations themselves are calculated from the pressure field via one-dimensional models. This approach is convenient for calculating an approximate pressure distribution when deformations are of secondary interest. The associated deformation models are limited to one-dimension.

8.4 SUMMARY OF SUBSIDENCE MODELS

Subsidence models have been developed for studying the effect of withdrawing several types of geofluids: groundwater, petroleum, and geothermal fluids, as well as to study natural subsidence. In Table 8.1 we have summarized a survey of three simple models and fourteen advanced models designed to simulate subsidence caused by geofluids withdrawal. Classified by application, these models include four groundwater, seven oil and gas, six geothermal subsidence models, and two miscellaneous type models. Other proprietary subsidence models were known to exist in the oil companies, but are not included in this survey. Advanced, computerized subsidence models have appeared only recently (the 1970's). The geothermal subsidence models, are quite complex and recent developments have been stimulated by interest in alternate energy sources. These models have first been reported in 1975, and none have been validated in applications as of July 1976.

Characteristic information on these models is tabulated in Tables 8.1 and 8.2. The data presented includes the developers and available references, the model type, fluid phases considered, physical dimensions considered, numerical method used, computer requirements, and constitutive relations assumed. The criteria for choosing a model are the same as in Section 7.5. More details on the principles of subsidence modeling are given in the Research Report. Again, the important features to consider when choosing a model, is its documentation, degree of validation, and whether it has been debugged and/or used by others.

Table 8.1 SUMMARY OF SUBSIDENCE MODELS

DEVELOPER(S)	MODEL NAME	MODEL TYPE	FLUID PHASES	DIMENSIONS		NUMERICAL METHOD		COMPUTER MODEL	CONSTITUTIVE RELATIONS	REFERENCES
				FLOW	DEFORMATION	FLOW	DEFORMATION			
Sandhu & Wilson		General subsidence			2-3		Fin. Elem.		Many	1
Jacquín & Poulet		Natural subsidence	One (liquid)	2	1			Yes		2,3
Gambolati		Groundwater subsidence	One (liquid)		1			No	Terzaghi	4,5
Gambolati, et. al.		"	"	2	1	Fin. Elem.	Fin. Diff.	Yes	Two α -values	6,7
Helm	COMPAC	"	"	1	1	Fin. Diff.	Fin. Diff.	Yes	Two α -values	8-12
Narasimhan	TRUST	"	"	3	1	Integrated Finite Diff.		Yes	Terzaghi	13,14
		(var. sat'n)								
McCann & Wilts		Oilfield subsidence	(One)	-	3	-	-	No	Elastic	15
Geertsma		Oil or gas subsidence		-	2-3	-	-	No	Elastic	16
Geertsma & van Opstal	ASKA	"		?	2-3		Fin. Elem.	Yes	Elastic	17
Frazier & Archambeau	FRI	Oilfield subsidence	One (liquid)	2	2	(Fin. Elem?)	Fin. Elem.	Yes	Elastic	18,19
Finol & Farouq Ali		"	Two	2	2			Yes	Elastic	20
Paris & Farouq Ali		"		?				Yes		
Kosloff & Scott	PANDORA	"	One	No	2-3	No	Fin. Elem.	Yes	Plastic cap model	21
S-cubed	AGRESS	Geothermal subsidence	Two	2-3	2-3	Fin. Diff.	Fin. Elem.	Yes	Many	22-24
Lippman & Narasimhan	SUBSIDE	"	One	2-3	1	Integrated Finite Diff.		Yes	Terzaghi	25,26
Papadopoulos		Geopressured geothermal subsidence	One	2	1	-	-	No	Elastic sand, plastic clay	27
Safai & Pinder		Geothermal subsidence	One	2	2				Visco-elastic	-
Intercomp*		"	Two	2-3				Yes		-
Kassoy et. al.*		"	Two					Yes		-

* Planned.

Table 8.2 Reference Key for Subsidence Models

1. Sandhu and Wilson, 1970
2. Jacquin and Poulet, 1970
3. Rieke and Chilingarian, 1974
4. Gambolati, 1970a
5. Gambolati, 1972b
6. Gambolati and Freeze, 1973
7. Gambolati and others, 1974
8. Witherspoon and Freeze, 1972
9. Helm, 1972d
10. Helm, 1975b
11. Helm, 1975c
12. Helm, 1974a
13. Narasimhan, 1975a
14. Narasimhan, 1974b
15. McCann and Wilts, 1951
16. Geertsma, 1966
17. Geertsma and van Opstal, 1973
18. Rimey and others, 1973
19. Archambeau, 1974
20. Finol and Farouq Ali, 1975
21. DiMaggio and Sandler, 1968
22. Brownell and others, 1975
23. Pritchett and others, 1975
24. Garg and others, 1975a
25. Narasimhan and Witherspoon, 1975
26. Lippman, et al., 1976b
27. Papadopoulos, 1975

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PART B
SUBSIDENCE EVALUATION PROCEDURES

- Chapter 9: Subsidence Prediction for Geothermal Areas**
- Chapter 10: The Analogy Method for Evaluating Subsidence Potential**
- Chapter 11: A Fundamental Geothermal Reservoir Model**
- Chapter 12: A Lumped Model for Reservoir Compaction**
- Chapter 13: Geothermal Field Operating Policies for the Mitigation of Subsidence as Derived From Reservoir Engineering Principles**

CHAPTER 9
SUBSIDENCE PREDICTION FOR GEOTHERMAL AREAS

9.1 INTRODUCTION

This chapter serves as an introduction to "Subsidence Evaluation Procedures," Part B of this Handbook. We distinguish two different situations in which subsidence predictions may be required. In the first, detectable man-induced subsidence has occurred at a site of interest, and in the second, it has not. Two types of methods are currently available to evaluate subsidence: the analogy method and analysis method. The analysis method uses mathematical models to predict subsidence for a given plant operating policy. The analogy method relies on a subjective analysis and comparison of geological and hydrological features of the site under study with corresponding features of other sites that have undergone development and operation in the past. These two types of methods to evaluate subsidence may be used either independently or as complements to each other, but the latter procedure makes the best use of the available information.

We will next discuss the fundamentals of subsidence evaluation, followed by a discussion of the procedures for evaluating subsidence potential and the difficulties with these procedures. We provide an overview of the use of models and then we discuss the expected accuracy of the predictions. Chapter 10 discusses the analogy method for predicting subsidence. Chapters 11 through 13 are devoted to the analysis method. Chapter 11 discusses a so-called "lumped" or averaged single-phase reservoir model; Chapter 12 presents a fundamental model to evaluate reservoir compaction; and Chapter 13 discusses a model to evaluate the pressure drop in a two-phase reservoir, but it is focused on discussing plant operating policies to mitigate subsidence.

9.2 FUNDAMENTALS OF SUBSIDENCE EVALUATION

9.2.1 Fundamental Difficulties

There are two fundamental difficulties in making an evaluation of subsidence potential. The first is the variety of disciplines whose mastery is necessary for understanding of the subsidence behavior for any given resource. The breadth of topics covered in Part A and the Research Report are indicative of this point. The second major difficulty is the complex characters of the physical situation. The detailed knowledge required for a truly precise prediction is staggering; namely, a comprehensive set of data describing the geological structure, rock properties, and reservoir properties.

9.2.2 Quantities of Interest

Two different quantities are of interest in making subsidence predictions: the magnitude of subsidence (u) and the rate of subsidence ($\frac{\partial u}{\partial t}$). The prediction of subsidence rates, is more difficult and has less reliability than merely predicting the ultimate subsidence.

Predicting subsidence rates requires, the additional understanding of time delays in the response of certain geological layers in communication with the reservoir. The compaction of fine-grained sediments with low permeability is not immediate upon reduction of the pressure in adjacent sands.

9.2.3 Causality

Since we are dealing with man-induced subsidence, the question of distinguishing between natural and man-induced subsidence arises. Natural subsidence rates in some areas may be quite high, e.g., millimeters to centimeters per year, and it is very important to distinguish the stimulating source of deformations observed at the surface. One method is to perform at least two baseline leveling surveys at intervals of a few years, prior to significant fluid production. This approach is being undertaken for a number of areas by the U.S. Geological Survey (Lofgren, 1973). Since gravimetric surveys can also detect subsidence, it is also useful to run baseline gravimetric surveys in preparing a data base for later subsidence analysis.

9.2.4 Use of Prior Man-Induced Subsidence

When some man-induced subsidence has already occurred at the site of interest, a far better basis for making predictions is available, provided sufficient data is collected during the initial production and deformation period. One advantage is that the surface deformation observed represents an integrated total response to the pore pressure changes throughout the reservoir, which may be composed of a variety of different materials with different behaviors and which are very hard to sample and represent individually. This advantage may not be as straightforward, since the responses of the various materials in hydraulic communication within the producing reservoir may have very different deformation response rates, depending upon their permeabilities (low for clayey sediments) and thickness.

An even greater advantage would be obtained if underground observations of the vertical distribution of ground movements had been made by such methods as radioactive bullet logging or possibly collar logging (Allen and Mayuga, 1970; Allen, 1973). Compaction measurements by collar logging depend upon the formation's gripping the well-casing sufficiently tight so that there is little relative slippage during deformation. An array of borehole extensometer recorders (Lofgren, 1970), measuring changes in surface to bottom hole distances for a variety of depths, would provide similar information on differential compaction, but in less detail.

9.3 PROCEDURES FOR EVALUATING SUBSIDENCE POTENTIAL

9.3.1 Procedures

In this section, we introduce two somewhat different recommended procedures for evaluating subsidence potential for a particular site. These procedures, outlined in Figures 9.1 and 9.2, differ depending upon whether man-induced subsidence has been observed or not. Note that the study of natural ongoing subsidence is assumed to have been undertaken in a separate baseline study, discussed in Section 9.2.

Both procedures are similar in that they begin with a tabulation of all available information which may be required by the analogy method or by the analysis method (models). Thereafter they make subsidence estimates and predictions using each of the available methods, with opportunities to collect more data as needed. Finally, an estimate of subsidence potential is made by comparing the model predictions with the analogy results. This final comparison estimate must be made in the full light of all the estimator's accumulated familiarity with the particular resource, and keeping in mind all the assumptions made in the use of models.

9.3.2 Data Requirements

Methods for obtaining the required information on reservoir fluid properties; production, geohydrology; reservoir adjacent and overburden materials; and site geology are discussed in Chapters 5 and 6.

In the analysis method, the amounts of data required by the models will greatly depend upon the complexity of the models used. Sensitivity

Figure 9.1 Subsidence Estimation Procedure to be Used Prior to Any Occurrence of Subsidence

Figure 9.2 Subsidence Estimation Procedure to be Used After Subsidence Has Occurred

analysis methods (see Research Report) may be used to identify the data most crucial to model accuracy. The amount of time and effort represented by the additional data needs of alternative models will undoubtedly have a strong influence upon the selection of the models to be used in these procedures.

In both the procedures (Figures 9.1 and 9.2), the user returns to the beginning of the analogy approach whenever he collects more data. The intent is to keep the two methods, to be compared in the last step, on as equitable a basis as possible.

9.3.3 Operating Policies

There are two practical ways in which the relationship between reservoir exploitation and reservoir deformations may be studied. The first is to specify the wellhead production-reinjection regime; from this compute the well bottom conditions; and hence solve interactively for the reservoir pressures, flows and deformations. The second is to specify the reservoir pressure condition from which may be computed both the production-reinjection regime needed to produce the specified pressures and the resulting deformations. An advantage of the latter is that when predicting deformations from known pressure histories, we dispense with the complexities in computations relating withdrawal to reservoir pressure. However, such computations are required to enable subsidence predictions for future production; particularly so, if the interaction between deformation and pressure is non-negligible.

Many reservoirs are controlled by their well flow rate operating conditions, and not by conditions within them. In addition, it is the production rate, rather than the reservoir pressure, which is directly

controlled in most reservoirs. Since the production rate is much easier to control, it is the natural control variable. Thus, the recommended procedure illustrated in Figures 9.1 and 9.2, have assumed the first approach, wherein production is related to deformation.

9.3.4 History Matching

The flowchart procedure of Figure 9.2 recommended after subsidence has occurred, uses the history of observed subsidence at a site to make better analogies, and to perform history matching with any model predictions representing the physical processes. As the field is developed and more subsidence occurs, the procedure should be repeated. The additional information available will improve the accuracy of the model and analogy results, and thereby our understanding of the physical process involved in subsidence. This increased understanding will enable better subsidence predictions for the future.

9.4 DIFFICULTIES WITH THESE ESTIMATION PROCEDURES

Most of the difficulties with these procedures arise from the infinite variations existing in geological environments. Theoretically, every different piece of rock will behave differently in a different environment. Some of the specific difficulties of this type include the variations of natural recharge rates with fluid drawdown, the viability and acceptability of reinjection, and the representation of entire layers by core samples at point locations.

Other major difficulties center around the rheologic (deformation) properties of the reservoir and associated materials. For instance, core samples for the weakest materials, which are the most susceptible to deformation, are the hardest to obtain and test; and tests of the deformation properties of rock samples are hard to perform in the laboratory at the temperatures and pressures which exist in the sample's original environment.

In addition, relatively very little is known about the deformation properties of rocks below the top few feet of the ground, the domain of the discipline of soil mechanics. The final rheological difficulty is that most of the constitutive models, particularly for multiple dimensions, are based upon unproven theories, and this comment holds even for soil mechanics.

These difficulties are illustrated by an example cited by Ben Lofgren (1976) of the U.S.G.S. subsidence research unit. A model of subsidence in the San Joaquin Valley was tuned "to perfection" using many compaction tests on cores and eight years of fluid pressure and subsidence history; predictions were nevertheless in error by one order of magnitude.

It should be noted that this comparison was for groundwater withdrawal, which may be much closer to the surface than geothermal fluid withdrawal.

9.4.1 The Importance of Individual Circumstances

The individual geological circumstances and resource type of any potential subsidence site are obviously important to subsidence estimates. Peculiar site-specific features are of even more concern at hydrothermal sites, because unique features are often associated with such sites: convection cells, self-sealing caps created by hydrothermal alteration, and tectonic and seismic activity with fissuring and faulting. While these factors must be included in a general sense, their significance can vary greatly with the type of geothermal resource under consideration. It is very important to keep these individual circumstances well in mind when making estimates of subsidence potential. Having made all the broad comparisons suggested in the preceding procedures, each case should still be examined carefully for important anomalous features.

9.5 THE USE OF HANDBOOK MODELS

Chapters 11 and 12 contain a set of lumped, fundamental models for the estimation of subsidence and reservoir pore pressure. In the precise sense of the dictionary, these models are simplified in that they reflect in an uncomplicated way, the fundamental physics of the natural processes. These models serve two purposes: they provide a means to understand clearly the physical processes and they do provide aggregate or averaged subsidence estimates. Although the models are not comprehensive multidimensional representations of all the natural phenomena, they do contain the essential physics. Thus, exercising these models provides a means of understanding the relationship among the key variables.

With regard to subsidence evaluation, these models are designed to provide estimates without the use of complex computer software. The results of these models should be viewed as being of a preliminary nature. Consequently, if the simplified models give results which indicate that significant subsidence is possible, then more comprehensive models (see Chapters 7 and 8) should be consulted before arriving at a definitive prediction.

In essence, the recommended approach is to use a hierarchy of models to evaluate subsidence potential. Beginning with simplified models, successively more comprehensive models are consulted (as necessary) to refine the estimate of subsidence.

9.6 EXPECTED ACCURACY

No predictions of subsidence, made before or during the early stages of subsidence, have proven accurate. With the best models, techniques, and data in reasonable amounts, present and near-term technologies will be doing very well to achieve accuracies for subsidence predictions within the range of ± 100 percent.

The history of subsidence predictions for the Wilmington Oil Field is of interest in this regard. Early studies variously predicted from 10-16 feet of ultimate subsidence, which was surpassed even before the reports were completed, leading to revised predictions in the range of 60-70 feet. None were accurate until about 75 percent of the ultimate subsidence (29 feet maximum experienced) had run its course (Allen, 1973). Hopefully, however, much has been learned about subsidence from the Wilmington experience, and better predictions should therefore be made for any future similar occurrence.

In the area of assessment of model accuracies, much remains to be done. Geophysical models in general are subject to a variety of systematic and non-systematic errors (Schainker, et al., 1975), a subject too broad for detailed discussion in this Handbook. It suffices to say that a model prediction may diverge significantly from the behavior of the modeled physical process, due to neglected phenomena (systematic errors) and errors in model parameters (which propagate non-systematic errors into the model predictions). In one relevant study, an analytical comparison of consolidation theories concluded that three-dimensional theory affords a higher degree of reality than either the conventional one-dimensional or pseudo three-dimensional consolidation theories (Schiffman, et al., 1969); however, the data needed to support the application of

multidimensional theories is correspondingly much greater than the data needed for lower dimensional theories. If a comprehensive set of data is not available, the accuracy and cost to implement multidimensional theories may be unsatisfactory.

The expected accuracies mentioned above leave plenty of room for improvement; however, it must be stressed that the available methods still represent a useful capability to determine the potential order of magnitude of subsidence. To be able to state that the subsidence potential of a given site, for a given production-reinjection regime, is say, either three inches, three feet, or thirty feet, is still a very useful capability, and is of great assistance to the assessment task of evaluating potential environmental impacts.

9.7 SUMMARY

In this chapter we have provided an overview of subsidence prediction for geothermal areas with emphasis on the analogy and analysis methods. We have presented two procedures for evaluating subsidence, differentiated by prior occurrence of man-induced subsidence. We have also discussed the inherent difficulties with making predictions of geological phenomena and the expected accuracy of the present estimation procedures.

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CHAPTER 10
THE ANALOGY METHOD FOR EVALUATING SUBSIDENCE POTENTIAL

10.1 INTRODUCTION

In the analogy method for the evaluation of subsidence, the potential for subsidence of a particular site is determined by comparison of the characteristics of that site with the characteristics of sites already known to have subsided. The reasoning assumed is that if the site of interest has many common characteristics with a subsiding site, then it too is likely to subside. Compared to the analysis method, the analogy method is subjective and intuitive. The use of this method depends heavily on the information associated with compaction processes and indicators of subsidence potential, discussed in Chapters 4 and 5, respectively.

10.2 THE ANALOGY METHOD

10.2.1 Sites With Analogues

The key to the analogy method is the determination of the presence or absence of the factors tending to influence subsidence (see Table 10.1). The factors are descriptive of such site characteristics as the reservoir fluid, production scheme, natural recharge, properties of the reservoir materials, properties of materials associated with the reservoir, reservoir geometry, properties of the overburden, and the site and regional geology. The factors are presented in two categories: those contributing to subsidence susceptibility and those contributing to surface stability.

After gathering as much detailed information as is available on the specific site, all the indicators are evaluated to determine whether they tend to promote or to prevent subsidence. If the factors contributing to subsidence susceptibility outweigh those contributing to surface stability, then there is a likelihood that subsidence will occur.

It is to be noted that while none of these cited factors are individually necessary for subsidence to occur, the combined occurrence of a number of factors is a strong indicator of subsidence potential.

Furthermore, when making analogies with subsidence in groundwater producing areas and oil fields, great care should be exercised, for such areas may differ from geothermal fields in a number of fundamental ways. These differences will usually include depth of burial, rock competency, structure, and age (see Chapters 4 and 5).

Table 10.1 FACTORS TENDING TO INFLUENCE GEOTHERMAL SUBSIDENCE

FACTOR TYPE (* major; † minor)	FACTORS WHICH MAY CONTRIBUTE TO SUBSIDENCE SUSCEPTIBILITY	FACTORS WHICH MAY CONTRIBUTE TO SURFACE STABILITY
1. RESERVOIR FLUID		
* Phase	All-liquid	Vapor-liquid mixture (vapor dominated, to a lesser extent)
Pressure	Geopressured (overpressured)	Low (below hydrostatic)
Density	High	Low
† Dissolved Solids	(see text)	
† Temperature	(see text)	
2. PRODUCTION FLUID		
* Volumes	Large	Small
* Fluid levels ¹	Large drops, long time, extensive areas	No drops
* Pore pressures ¹	Large drops, long time, extensive areas	No drops
Formation flashing	None	Extensive, continual flashing
3. GEOHYDROLOGY		
Natural recharge†	Low rates	High rates
4. RESERVOIR MATERIALS		
* Type	Sediments	Igneous or metamorphic
Predominant grain size	Coarse	-
Grain shape	Angular	Rounded
Porosity - Primary	25-40%	Very low
- Secondary	High	Low
* Consolidation/cementation	Unconsolidated, lacking cementation (loose or friable)	Consolidated, cemented
* Preconsolidation ²	None	Much
Hydrothermal alteration	Present	Absent
Admixed clay content (sorting) ³		
Admixed mineral content	High mica, montmorillonitic clays	None
Age	Miocene and younger	Older than Miocene (22 million years)
* Thickness (in communication)	Great vertical section	Small vertical section
* Deformation properties ⁴	Highly deformable	Slightly deformable
5. ASSOCIATED MATERIALS		
Type	Clays, siltstones, shales	Volcanic flows and shallow intrusions
Occurrence	Many thin strata of large total vertical thickness, interbedded with reservoir materials but not impairing communication between them (less susceptible if distributed in few thick strata)	
6. RESERVOIR GEOMETRY		
Width/thickness ratio ⁵	Large	Small
7. OVERBURDEN		
* Thickness	Small (< 3000 ft)	Great
* Competence	Incompetence, unconsolidated sediments	Competent, consolidated
* Deformation properties ⁶	Highly deformable	Slightly deformable
Density	High	Low
8. SITE GEOLOGY, STRUCTURE		
Folding	Gentle, broad, synclinal	Sharp, anticlinal (arched)
Flank dips	Less than 25°	Greater than 25°
Faulting	Normal, graben blocks	Reverse or thrust
Fracturing	Much, recent	Little, old, sealed
Regional stresses	Tensional	Compressional
Stratigraphy	(see text)	

1. Depend(s) upon formation properties, which may be studied by preliminary well tests.
2. Preconsolidated materials have previously experienced loads greater than their present load.
3. If high pressures did not always accompany the presence of admixed clays in geopressured zones, they will be preconsolidated.
4. Elastic constants, compaction coefficient, yield stress, etc.
5. Of the producing zone.
6. Can the overburden materials possible respond more slowly than the reservoir materials below

10.2.2 Sites With Few Analogues

For proposed geothermal sites with few available analogues, the information base for use of the analogy method is certainly inadequate. One approach, would be to produce high flow rates from a well in a nearby area where conditions are as similar as possible to the proposed site, but where any resulting subsidence could do no environmental damage. Ground movements observed there could then provide a useful basis for analogies with the proposed site.

This approach, however, has severe limitations, that make it impractical. First, a suitable site for such an experiment is likely to be available only in very limited cases. Second, experience suggests that this method may not be totally reliable; for some areas which on first examination appear similar, may in fact, be very different. Finally, such tests could only be run for relatively short periods, during which the slower responses of affected fine-grained materials (clays, siltstones, shales) would probably have little change to be manifested.

10.3 LIMITATIONS OF THE ANALOGY METHOD

10.3.1 Case Histories

The analogy method can be viewed as providing a necessary condition for subsidence, but not a guarantee that it will occur. The history of several known subsidence areas and the success of several past attempts at subsidence prediction illustrate the problems inherent in making estimates based on analogy. For instance, greatly differing amounts of subsidence in two closely-spaced California oil fields indicate that apparent stratigraphic similarity is not necessarily a reliable basis for prediction. Twenty-eight feet of subsidence have occurred in intercalated sands and shales at the Wilmington Oil Field, but "many fields yielding oil from deposits of similar age and from an equivalent depth range, of approximately similar lithology, and with comparable decrease in fluid pressure have not experienced subsidence of more than a few feet," (Poland and Davis, 1969). The Long Beach Oil Field, only one or two miles from the Wilmington field, subsided a mere 2-1/2 feet. This differential subsidence must have been caused by some macroscopic or microscopic contrast in the physical properties of sediments at the two locations. Allen (1973) attributes the behavior to tensional regional stresses at Wilmington, facilitating rearrangement of sediment grains, and compressive stresses at Long Beach. The many important similarities between the Wilmington and Long Beach oil fields suggest that, if the comparative-empirical method of estimating subsidence has any merit at all, it should have been successful there.

As an example of the opposite conclusion, the subsidence history of four water wells in the Houston-Galveston area of Texas indicates that identical amounts of subsidence can occur by chance even in areas of

differing stratigraphy. The amount of subsidence in relation to fluid pressure decline was exactly the same at all four wells, despite the fact that one well is 25 miles updip from the others and penetrates older sediments (Poland and Davis, 1969).

In summary, it is apparent that empirical subsidence estimates based on a subjective comparison of regional and site geology may be used with some success to determine whether significant subsidence is likely to occur in a given area. In the opinion of one subsidence expert (Allen, 1973) the analogy method should be capable of distinguishing between sites with expected subsidence greater or less than one foot.

10.3.2 Expected Accuracy

As discussed in Section 9.6, the present state-of-the-art does not allow for great accuracy in subsidence predictions. An estimate, accurate to within one- to two-orders of magnitude should be considered good.

10.4 SUMMARY

We have presented the analogy method for the evaluation of subsidence, which relies heavily on the background information presented in Chapters 4 and 5. The analogy method is a subjective method, and it requires a suitable site for comparison. The analogy method is limited, but in the opinion of experts in the field, it does provide a valuable, additional tool to the analyst investigating subsidence.

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CHAPTER 11

A FUNDAMENTAL GEOTHERMAL RESERVOIR MODEL

11.1 INTRODUCTION

This chapter is the first of two chapters wherein we present models of the fundamental processes for single-phase and two-phase geothermal reservoirs. The purpose of developing these models is to provide a relationship between fluid withdrawal and reservoir pressure and temperature, specifically focused on subsidence evaluation. To this end we focus attention on the average reservoir pressure and consider so-called lumped models, wherein all the spatial variation in pressure and temperature is aggregated, and the reservoir is considered to exist at a single average pressure. Despite this simplification, these models provide significant insight into reservoir behavior for the study of subsidence.

The models to be presented are built upon the work of Whiting and Ramey (1964), Martin (1976), and Brigham and Morrow (1974). The models are based upon thermodynamic relations and hydrodynamic phenomena are treated implicitly by the assumptions for the behavior of the two-phase reservoir (see Chapter 13).

A detailed discussion of reservoir models is provided in the Research Report and only a single-phase reservoir model will be presented in this chapter. Because a two-phase reservoir model strongly impacts the study of operating policies, it will correspondingly be described in Chapter 13.

In the following sections we will first discuss the effect of reservoir phase on the pressure history of the reservoir. We will then present a lumped model for a single-phase reservoir and lastly, illustrate the use of this model on data for the Wairakei, New Zealand geothermal site.

11.2 RESERVOIR FLUID PHASE AND SUBSIDENCE

As discussed in Chapter 3, the geothermal fluid may be water, steam, or a two-phase mixture. We shall focus attention on reservoirs that are initially liquid-dominated, for liquid-dominated reservoirs appear to be the most numerous, important for commercial development, and they exhibit the greatest potential for subsidence.

An operating line for a geothermal reservoir consists of a sequence of states, described by pressure and temperature, through which the reservoir evolves during exploitation. In Figure 11.1, we have plotted an operating line for a reservoir beginning as pressurized water (Point A). This operating line assumes no reinjection. As fluid is withdrawn, the reservoir follows essentially an isothermal path until the saturation pressure is reached (Point B). The operating line then follows the saturation curve until all the liquid is vaporized (Point C). In its final stages, the reservoir is a gas phase reservoir.

We observe the important fact that during its lifetime the reservoir has experienced three distinct operating regimes. It has been a liquid reservoir, a two-phase reservoir, and a gas-phase reservoir.

We now wish to examine qualitatively the relationship between pressure decline and cumulative mass withdrawal for each operating regime. We note that by specifying the rate of withdrawal as well as the cumulative mass, we also specify the time scale of reservoir operation. Figure 11.2 depicts the reservoir pressure versus the cumulative mass withdrawn, with time as an implied variable. Of particular interest is the slope of these curves, which dictates the reduction of pore pressure for an increment of mass ($\frac{dp}{dm}$). We note that this slope is largest in the single-phase liquid regime, and smallest for the two-phase regime.

Figure 11.1 Reservoir Operating Line

Figure 11.2 **Schematic Pressure Decline History for Hydrothermal Sites**

11.3 SINGLE-PHASE RESERVOIR

The model presented in this section, developed in Chapter 8 of the Research Report, is valid for a single-phase liquid or a single-phase gas reservoir. The model is based on volume and mass balances for an isothermal reservoir. In terms of the mass fraction produced, the model is

$$X_p = 1 - V_o/V_p(T,P) \quad (11.1)$$

where

$$X_p = M_p/M_o \quad (11.2)$$

T is the temperature of the reservoir

P is the pressure of the reservoir

M_o is the fluid mass in the reservoir at initial conditions P_o and T

M_p is the fluid mass produced for reservoir pressure P ($P < P_o$)

X_p is the fraction of the original mass in-place

V_o is the specific volume of the fluid at the initial conditions

V_p is the specific volume of the fluid at pressure P

To use the model, an equation of state, $V_p(T,P)$, for the fluid is required. There are a number of ways to obtain this function. Some representations are comprehensive, in the ranges of temperature and

pressure covered, but complicated in the form of the expression. Other equations of state are simple in form, but limited in applicability. Below, we describe four methods of obtaining the equation of state.

First there is the use of the data provided in tabular form in the steam tables (Keenan, Keyes and others, 1969; Meyer and others, 1968). A second method is to program the comprehensive, but complicated, empirical formulas provided in these references. Denoting that equation of state by $V_p^+(T,P)$, the model becomes

$$X_p = 1 - V_o / V_p^+(T,P) \quad (11.3)$$

Equation (11.3) would, of course, require a digital computer for implementation.

A simplified equation of state is Tait's isotherm (Moelwyn-Hughes, 1964; Yi, 1967).

$$V = V^* \left\{ 1 - A \ln \left[1 + \frac{(P_o - P^*)}{B} \right] \right\} \quad (11.4)$$

where P^* and V^* are reference conditions, and A and B are fitted to the data cited above. The parameters A and B are functions of temperature, although B is not strongly so. Using this equation of state, the reservoir model becomes the following:

$$X_p = A \ln \left[\frac{B + P_o - P^*}{B + P - P^*} \right] \quad (11.5)$$

This model is easily programmed on a scientific calculator.

An even simpler equation of state than Tait's, that can be used for moderate pressure ranges is the linear expression below.

$$V = V^* + \frac{\partial V}{\partial P} [P - P^*] \quad (11.6)$$

If the reference pressure is the same as the initial pressure and we let β be defined as

$$\beta = - \frac{\partial V}{\partial P} \frac{1}{V^0} , \quad (11.7)$$

then the reservoir model is simply

$$X_P = \frac{\beta(P^0 - P)}{1 + \beta(P^0 - P)} \quad (11.8)$$

Again the model is amenable to the use of a scientific calculator.

To summarize, we have presented a lumped relationship between reservoir pressure and mass withdrawal. Furthermore, we have discussed four ways to use the model in conjunction with the four equations of state provided by: (1) the steam tables, (2) complex, empirical equations of state, (3) Tait's isotherm, and (4) a linear equation of state. Either of the four versions of this model may be combined with a compaction model (Chapter 12) to evaluate the potential for subsidence at a specific site of liquid withdrawal. In the following sections we will illustrate the use of this model.

11.4 USE OF THE RESERVOIR MODEL

In this section we will discuss the use of the reservoir model to calculate production histories. We will clarify the calculation procedure and discuss the estimation of the initial mass in-place (in the reservoir).

In calculating the production history, we are interested in the reservoir pressure as a function of the cumulative mass withdrawn. The model equation (11.1), is, however, more advantageous for the use of pressure as an input and production fraction as the output. As illustrated in Figure 11.3, given the pressure, we may calculate explicitly the fraction produced; however, if we are given the fraction produced, then we perform an iterative calculation to determine the reservoir pressure.

As long as the entire history is of interest, rather than only point values, we may take advantage of the explicit form, and use pressure as the specified input variable. After the profile is generated, its future use is independent of the perspective from which it was calculated.

The model may be used to generate a profile of fraction produced versus pressure without knowledge of the initial mass in-place, M_o . However, to generate production histories and to perform history matching, M_o is required. Obviously, knowing M_o , the mass produced (M_p) is related to the fraction produced, X_p ,

$$M_p = X_p M_o \quad (11.9)$$

There are several methods of estimating the original mass in-place. A method with much physical appeal is to use geological information to calculate the available pore volume of the reservoir and then to use

Explicit Solution

Implicit (Iterative) Solution

Figure 11.3

Input Variables and Solution Procedures

the density at the initial conditions to calculate the mass in-place.
Thus,

$$M_o = \phi \bar{V}/V_o \quad (11.10)$$

where ϕ is the porosity of the reservoir and $\bar{V}$ is its total volume.

A second method of estimating M_o is to fit a set of actual production data using a technique of parameter estimation, such as least squares.

In Figure 11.4, we have provided a flowchart for the use of the reservoir model. Note the feedback loop which provides for updating the estimate of M_o . In the next section we illustrate the use of this model.

Figure 11.4 Flowchart for the Use of the Reservoir Model

11.5 RESULTS FOR A SINGLE-PHASE RESERVOIR

To illustrate the lumped single-phase model presented in the previous section, we shall compute the production-pressure curve corresponding to conditions in the Wairakei field. The Wairakei reservoir initially contained all liquid, and experienced a transition into two-phase behavior about 1965 (Stilwell and others, 1975).

Figure 11.3 contains the actual production history for Wairakei (Stilwell and others, 1975). We first note that the general form of the curve follows that presented in Figure 11.2. The change in slope occurs very near the saturation pressure (486 psia) for 240°C, and the slope in the single-phase regime is greater than in the two-phase regime.

Following the algorithm given in Figure 11.4, we specify the initial temperature to be 240°C and the initial pressure to be 769 psia. Two equations of state are used in this example, but primarily the results rely on the correlation, V_p^+ , of Meyer and others (1968).

The production profile which evolves down to the saturation line is calculated explicitly using Equation (11.3). The fraction of the initial mass in-place at the saturation line is .0024. In an attempt to match the reservoir history, the amount in-place, M_o , is estimated from the data to be $M_o = 1.6 \times 10^{14}$ kg.

The dotted line in Figure 11.5 represents the results of using this value of M_o , reservoir model Equation (11.3) to predict the production curve. Considering the lumped nature of representing the phenomena, this model is quite accurate. Using the linear equation state, and a value of $\beta = 9.0132 \times 10^{-6} \text{ (psia)}^{-1}$, Equation (11.8) agrees to two significant figures with model (11.3).

We now compare the estimate above to estimates made from geological considerations. The Waiora formation (Browne, 1976) has been modeled as a disc with a radius of 0.5 km and a thickness of 3.0 km. If the porosity is assumed to be 0.2, then the mass of liquid initially in-place is 1.85×10^{12} kg. Thus, using the model (11.1) to interpret the production data suggests that the Wairakei field behaves as if it contained two orders of magnitude more water initially than would be indicated by geological inferences.

In summary, by using one free parameter, the total liquid mass initially in-place, we have satisfactorily performed a history matching for the Wairakei reservoir data using the lumped model. The inferred value of this parameter however, is greater than expected from geological information.

Figure 11.5

Actual Production History for Wairakei
(Stilwell, 1975)

11.6 SUMMARY

This chapter has presented a lumped model for a single-phase geothermal reservoir. This model is applicable to either water or steam reservoirs. For water reservoirs, we illustrate the use of two simple equations of state, which result in easily used expressions for the reservoir model. We have compared the lumped model to data for the production history of the Wairakei, New Zealand field. Considering the lumped nature of the model, the agreement was satisfactory.

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CHAPTER 12
A LUMPED MODEL FOR RESERVOIR COMPACTION

12.1 INTRODUCTION

In this chapter we present a lumped model for the evaluation of reservoir compaction. The model to be presented does not represent the state-of-the-art in the solid mechanics of geological materials; however, it serves the purpose of a simplified model described in Chapter 9. The model clearly indicates the key variables in subsidence and allows tractable estimation of reservoir compaction. Finally, the results of the model can justify the use of a more comprehensive subsidence model, as in the hierarchical approach of Chapter 9, if the results indicate substantial reservoir compaction.

In general, reservoir compaction is studied via the subject of the mechanics of geological materials (cf. Jaeger, 1961). A key concept in understanding compaction is that of effective stress described earlier (see Chapter 5). The increase in effective stress is equal to the change in pore pressure. We now wish to relate reservoir compaction to the change in pore pressure. One approach, as indicated in Chapter 8 and the Research Report, is to solve a set of differential equations numerically.

The approach taken in this chapter is not so detailed however. We shall study reservoir compaction via a lumped model which is based upon the uniaxial compaction coefficient, an empirically determined property of the reservoir.

In the sections which follow, we introduce the lumped compaction model, discuss the compaction coefficient, provide a sample calculation, discuss modeling subsidence reservoir interaction, discuss the usefulness of the compaction model, and present estimates of subsidence.

12.2 THE COMPACTION MODEL

The simplified compaction model presented in this chapter is based on a linear measure of fractional compaction called the uniaxial compaction coefficient C_m . This coefficient can be defined as the formation compaction, dz , per unit change in the effective stress σ .

$$C_m = \frac{1}{z} \frac{dz}{d\sigma} \quad (12.1)$$

C_m is in units of (pressure)⁻¹. The compaction coefficient is a property of the reservoir material. It is a function of the effective stress. Chapter 6 discusses the experimental determination of C_m . Using the compaction coefficient, the change in reservoir thickness ΔH can generally be related to the change in effective stress by the integral

$$\Delta H = \int_0^H \int_{\sigma_1}^{\sigma_2} C_m(\sigma, z) d\sigma dz \quad (12.2)$$

The all important pore pressure reduction enters the model through

$$\sigma_2 = \sigma_1 + \Delta p \quad (12.3)$$

For constant, C_m , formula (12.2) reduces to the simple product

$$\Delta H = C_m \Delta p H \quad (12.4)$$

Thus, it is clear that three variables influence compaction: (a) the vertical extent of the reservoir, (b) the magnitude of the relevant deformation property C_m , and (c) the reduction in reservoir pressure.

While the latter two influences are usually considered to be primary in causing compaction, an unexpectedly large reservoir height can result in compaction even when C_m and Δp are moderate.

We use the term reservoir in a broad sense to refer to all strata experiencing fluid withdrawal, either directly or through communication with the information of the operating horizon. For several layers, we need merely sum over the number of compacting layers for ΔH_T , the total compaction. For the simplest case wherein C_m is a constant for each stratum, s , we have

$$\Delta H_T = \sum_{s=1}^S \Delta H_s = \sum_{s=1}^S C_{m,s} \Delta p_s H_s \quad (12.5)$$

12.3 THE COMPACTION COEFFICIENT

The uniaxial compaction coefficient is computed from the bulk compressibility C_b via

$$C_m = \frac{1}{3} \frac{(1+\nu_o)}{(1-\nu_o)} C_b \quad (12.6)$$

where ν_o is Poisson's ratio for the porous medium. The porous medium is in reality a composite material consisting of rock grain and fluid-filled pores. Since it is sometimes easier to determine Poisson's ratio for the rock matrix material, ν , Geerstma (1957, 1973) has proposed an alternate version of (12.6) in terms of ν and a correction factor β .

$$C_m = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)} (1-\beta) C_b \quad (12.7)$$

If $\beta = 0$, the relation obtained would hold for solid rock with Poisson's ratio ν . The factor β , thus, accounts for the porous nature of the material.

It remains to establish the relationship between C_b and the effective stress. Although the relationship is established experimentally, it has been found that a convenient functional form for the data is

$$C_b = a\sigma^b \quad (12.8)$$

where the constants a and b are determined from the data.

We now assume that C_m is independent of z . Substituting (12.8) and (12.6) into (12.2), we find that ΔH is given by

$$\Delta H = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)} (1-\beta) (\sigma_2^{b+1} - \sigma_1^{b+1}) \frac{a}{b+1} H \quad (12.9)$$

In terms of Equation (12.4) the compaction expression is

$$\Delta H = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)} (1-\beta) a \sigma^b \Delta P H \quad (12.10)$$

where σ is the average effective stress over the pressure interval.

It is convenient to recognize that (12.10) can be decomposed so that the expression

$$C_D = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)} (1-\beta) (\sigma_2^{b+1} - \sigma_1^{b+1}) \frac{a}{b+1} \quad (12.11)$$

is a dimensionless quantity which is the ratio of compaction to reservoir thickness. C_D is also represented by the expression in brackets of Equation (12.10).

12.4 USE OF THE COMPACTION MODEL

In Figure 12.1 we have provided a flowchart for the use of the compaction model. The procedure is designed for evaluation of the compaction of the reservoir by pressure-drop increments. The first step in the procedure is to gather data on the compaction coefficient and Poisson's ratio.

The second step is to specify either a given amount of production or pressure-drop and then to calculate the other quantity using a reservoir model. Provided for this purpose is a single-phase reservoir model (provided in Chapter 11) and a two-phase reservoir model (provided in Chapter 13). If the connection between production and compaction is not of interest, only the pressure-drop need be specified. Presented next in the flowchart of Figure 12.1, is the calculation of effective stress and compaction for each pressure-drop increment.

Also illustrated in the flowchart is a procedure to correct the porosity based on the reservoir compaction. This procedure, discussed in Section 12.6, will not normally be required.

The result of the above calculations is the compaction versus pressure-drop, and through a reservoir model the compaction is related to the fluid mass produced.

Figure 12.1

Flowchart for the Use of the Compaction Model

12.5 AN EXAMPLE OF COMPACTION CALCULATIONS

Professor S. Biehler (1976) at the University of California, Riverside, has pointed out that the central portions of the Imperial Valley may contain up to 10,000 feet of soft sands often referred to as "mush." In Table 12.1, we have tabulated data for a reservoir composed of these soft sands, centered at 1 km. Data for C_b , i.e., a and b , corresponding to California unconsolidated sands, are derived from data presented in Rieke and Chilingarian (1974).

In Table 12.2 we have tabulated the results for a set of reductions in pore pressure, Δp , caused by extraction of geothermal fluids. The third column gives the compaction ratio C_D of reservoir thickness. The fourth column indicates the compaction if the reservoir is 500 feet thick. The compaction for any other reservoir thickness H may be obtained by multiplying C_D by H .

We see that for a reduction in pore pressure of only 100 psia, the 500 foot thick reservoir compacts by almost three feet. For a pore-pressure drop of 700 psia, the compaction is over 17 feet. Whether such subsidence will actually occur or not depends in large part upon whether fluid will be withdrawn from such sands.

Table 12.1 Data for Unconsolidated Sands

v	$=$	.20
β	$=$	.1
a	$=$	.01192
b	$=$	-.62672
σ_1	$=$	1755 psia

Table 12.2 Compaction Estimates for Situations Similar to Imperial Valley

Δp (psia)	σ_2 (psia)	C_D (-)	ΔH (ft)*
100	1855	.00543	2.72
200	1955	.01067	5.33
300	2055	.01575	7.87
400	2155	.02068	10.33
500	2255	.02546	12.73
600	2355	.03011	15.05
700	2455	.03465	17.32

* for $H = 500$ feet

12.6 MODELING THE INTERACTION OF COMPACTION AND RESERVOIR BEHAVIOR

In this section we discuss how the two simplified models may be coupled in order to study the effect of reservoir compaction on the reservoir pressure drop. The reservoir model in the previous section uses a stepwise calculation. In order to account for the effect of compaction on the fluid, we take small increments in pressure and correct the porosity at each stage (see Figure 12.1).

Since we have assumed a one-dimensional reservoir with uniform porosity and cross section, let us write ϕ at step N as

$$\phi_N = \frac{H_p}{H} \quad (12.12)$$

where H_p is the height of the pores $H_p = V_p/A$. If we assume that all compaction results in loss of pore volume, then the new porosity

$$\phi_{N+1} = \frac{H_p - \Delta H}{H - \Delta H} \quad (12.13)$$

For small pressure changes, $H - \Delta H \approx H$ and we have

$$\phi_{N+1} = \phi_N - C_D \quad (12.14)$$

The effect of decreasing the porosity at each step is to increase the pore pressure. Thus, compaction has an aspect of negative feedback concerning the ratio of mass produced to subsidence. This fundamental tendency of compaction to increase pore pressure is referred to as a "rock drive" in the petroleum engineering literature (cf. Martin, 1975).

At Wairakei, where extensive subsidence has occurred, rock drive is small and not important: a 500 meter thick reservoir has subsided 4.5 meters; thus, the change in porosity given by C_D is

$$C_D \cong 4.5\text{m}/500\text{m} \cong .01$$

Thus, the change in porosity due to compaction is less than one percent, which is less than the uncertainty in the porosity and can justifiably be neglected for this site.

12.7 USEFULNESS OF THE COMPACTION MODEL

By its lumped nature, the compaction model presented in this chapter treats all points within the reservoir as being the same. Thus, the results of the compaction calculation indicate an average compaction. The model input, the pore pressure, is also a lumped quantity, and the possibility exists that regions in a real reservoir will have a much greater reduction in pore pressure and hence, a compaction which is greater than the averaged or lumped compaction estimated by the Handbook model presented.

12.8 PREDICTING SUBSIDENCE

12.8.1 Subsidence Model

To this point we have been concerned with reservoir compaction, and we have presented a lumped model for that phenomena. However, in order to relate compaction to subsidence, we must provide an overburden model. In the analysis of the consistency of modeling assumptions presented in the Research Report, the overburden model determined to be consistent with the lumped compaction model presented earlier is one that assumes all compaction is propagated to the surface as subsidence. Thus, for this Handbook, we recommend an overburden model that equates subsurface compaction to surface subsidence. This results in an estimate of average subsidence. As discussed in the previous section, there may be points where subsidence exceeds this average value. However, this average is a pessimistic bound on the average of the true subsidence.

12.8.2 Hierarchical Approach

Appropriate to the hierarchical approach discussed in Chapter 9, the subsidence estimated utilizing the above lumped models is subject to refinement. If the average subsidence estimated, is significant, considering that it may be exceeded at specific locations, then more comprehensive models for reservoir compaction and overburden deformations should be considered.

12.9 SUMMARY

In this chapter we have presented a lumped model for reservoir compaction based upon the uniaxial compaction coefficient. Then we have discussed the computation of the compaction coefficient from bulk compressibility measurements; presented a set of sample calculations for the Imperial Valley, California; and discussed the interaction of compaction and reservoir behavior and found that it is not significant at this time. Consistent with the lumped reservoir and compaction models, the lumped overburden model used is one that equates surface subsidence to subsurface compaction. In accord with the hierarchical approach discussed in Chapter 9, more sophisticated models, such as those summarized in Chapter 8, should be consulted if the lumped Handbook models presented here predict significant subsidence.

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CHAPTER 13

GEOTHERMAL-FIELD OPERATING POLICIES FOR THE MITIGATION OF SUBSIDENCE AS DERIVED FROM RESERVOIR ENGINEERING PRINCIPLES

13.1 INTRODUCTION

13.1.1 Purpose

The major focus of this chapter is on determining ways of operating the geothermal field that will cause the least subsidence. At first glance minimizing subsidence and exploiting a hydrothermal resource seem to be contradictory goals, for the removal of hydrothermal fluids from the reservoir must cause a pressure drop, and that decrease in pore pressure is the cause of subsidence. Thus, in order to minimize subsidence and extract fluids, we must determine methods of operating the field, operating policies, that allow the simultaneous removal of fluid and maintenance of pressure.

13.1.2 Basis of Operating Policies

The operating policies to be formulated are based upon understanding the fundamental physical processes in the hydrothermal reservoir. These key processes include the thermodynamic behavior of water and the dynamics of phase-transition. In fact, the operating policies follow from a qualitative understanding of the physics of the reservoir; however, in order to obtain quantitative results we have formulated a mathematical model incorporating that understanding.

In discussing reservoir modeling, thus, this chapter is a continuation of Chapter 11. The model is for a geothermal reservoir containing two fluid phases, and as in Chapter 11, the spatial variation of variables is lumped. The lumped, two-phase model, however, is an order of magnitude more complicated than the single-phase model.

13.1.3 Chapter Overview

We next present a preliminary perspective on operating policies. Some assumptions behind the postulated physical mechanisms are given, and we then discuss the hypothetical stages of reservoir operation. We next present the algorithm for implementing the model implied by the physical mechanism and some example calculations based on conditions similar to the Wairakei, New Zealand field. Finally, we discuss the strategies of reservoir operation.

13.2 PERSPECTIVE ON OPERATING POLICIES

We now consider the physical mechanisms which maintain pore pressure as fluid is withdrawn. The first mechanism is volumetric expansion of the fluid as the pressure is reduced; this topic was treated in Chapter 11. The second mechanism is the so-called "rock drive," the reduction in available pore volume due to reservoir compaction. Rock drive was discussed in Chapter 12. The final mechanism, the one which provides the best hope of subsidence control and mitigation, is the volumetric expansion associated with phase change from water to steam. This mechanism will be treated in detail in this chapter.

13.2.1 Injection

Independent of the physical mechanisms responsible for subsidence, at present the best control policy, is the injection of fluid into the reservoir. In formulating a policy of injection (or reinjection)* the control strategies relate to the specific magnitude of such variables as the well spacing, well-depth, and well flow rate. While a concrete realization of these policies requires specific details on the reservoir, certain general rules or principles can be successfully applied. These rules have as their basis, the prolongation of reservoir life and follow good reservoir-engineering practice. Briefly stated, they are as follows:

Rule 1: For a given well spacing, the depth of the injection well should be significantly below the producing zone. Such a rule applies to single-phase systems as well as two-phase systems. For two-phase systems, well depth should be well below the liquid vapor-interface. Thus, fluid injection takes place in the liquid phase (if it exists) and consequently, the injectant does not cool off the producing zone.

* The term reinjection is used for those cases where fluid previously removed from a reservoir is returned to the reservoir.

Rule 2: With the goal being complete reinjection of withdrawn fluid, the fraction of fluid which is reinjected should be maximized, subject to operating constraints of the geothermal plant. For example, if the above ground generating facility is open cycle, only a twenty percent return of fluid may be possible, whereas if the facility is closed cycle, nearly a hundred percent return is perhaps achievable.

The basis of these rules will become clearer after the presentation of the physical model and the calculations based upon it.

13.2.2 Injection in a Liquid Phase Reservoir

We now briefly consider the effect of fluid injection on a liquid phase reservoir, which was partially treated in Chapter 11. Water at a lower temperature than the reservoir fluid is injected to maintain fluid pressure by replacing fluid mass. The cooler temperature of the injectant has two effects. The cooler injectant occupies a smaller volume than the same mass of produced fluid; thus, even if the reinjection rate equals the withdrawal rate, the reservoir pressure will decline. Second, reinjection cools the reservoir; hence, the lumped temperature is lower and the saturation line is reached at a lower pressure and at a later stage in the production history of the reservoir. We will return to this point in Section 13.7.

13.3 SOME CONSIDERATIONS OF THE FUNDAMENTAL PHYSICS OF A TWO-PHASE RESERVOIR

The basis of a segregated two-phase lumped model is found in the work of Martin (1975) and Brigham and Morrow (1974). The fundamental criteria for this type of model is that the geothermal fluid has segregated fluid phases; namely, the liquid and vapor phases occupy distinct regions in the geothermal reservoir, where the liquid region is below the vapor region. The validity and physical realization of this type of model, and consequently its usefulness, depend in large part on the physical processes of gravity segregation and the thermal process of convective heat transport.

Other assumptions incorporated into the model are as follows:

1. The porosity is uniform throughout the reservoir
2. The thermal and physical properties of the rock are uniform
3. The reservoir rock is in thermal equilibrium with its adjacent fluid
4. Thermal equilibrium exists throughout each phase, i.e., there is no spatial variation in the heat content of each phase
5. Boiling occurs only at a steam water interface

The first and second assumptions are for mathematical convenience, and they are consistent with the degree of model sophistication used, insofar as the model presented involves no small scale spatial dependence. However, the two-phase lumped model does include "global" spatial dependence in that the steam and water are treated separately. The phases are not assumed to be all mixed, nor are they assumed to be in thermal equilibrium.

The question of thermal equilibrium is addressed in the third and fourth assumptions. The essence of these assumptions is that the steam region^{*} and the water region are separately in thermal equilibrium. In other words, we are saying that at any time, the rock temperature above the interface equals the steam temperature and similarly, the rock temperature below the interface equals the water temperature. Thus, the steam and water are assumed not to coexist at the same temperature, and the temperature of each of these phases is assumed to be equal to an average value (or lumped) over the spatial dimensions of interest.

The assumption of thermal equilibrium rests upon the rate of heat transfer in each phase. In the liquid region, the heat transfer mechanism is very fast and is typically accomplished by convective heat exchange, brought on by boiling and subsequent mixing, stimulated by the spatial density difference between the top and bottom of the water region, cf. White and others (1971), and Donaldson (1970) for details.

In the steam region mixing is not stimulated by a thermal density difference. Nonetheless, the production of steam from the upper portion of the reservoir does cause a forced convective heat exchange to take place and thermal equilibrium does occur fairly rapidly. It should also be noted that the rate of fluid withdrawal nearly equals the rate of vaporization thus causing an equilibrium condition to alternately take place.

In the fifth assumption listed above, which is a consequence of the fourth assumption, we address the question of spatial temperature variation at the steam-water interface and recognize that an idealization

^{*}We denote the steam (or water) region as that portion of the reservoir rock coexisting with the steam phase (or water) phase (see Figure 13.1).

is used herein. We assume that the steam-water interface is of infinitesimal, but finite, thickness and that temperature experiences a jump condition across the interface. In reality, the steam-water interface is a transition region wherein both phases coexist. Across this region, temperature and steam quality vary continuously. Since this transition region can not be distinguished with the lumped model, we assume the idealization above in order that the lumped temperature of each phase properly reflects the correct average state of the reservoir.

13.4 THE HYPOTHETICAL STAGES OF THE PHYSICAL MECHANISM

Having discussed the underlying assumptions of the model, we now present the physical mechanism assumed for the model. For exposition purposes we shall present the model in terms of a thought experiment.

The reservoir is initially at conditions i . Upon an incremental decrease in the reservoir pressure, the reservoir adjusts by progressing through two hypothetical stages (see Figure 13.1). Between Stage i and Substage i_1 , an increment of water vaporizes, as the water region now is at pressure $P_i - \Delta P_i$. The temperature of the water region decreases to a temperature specified by the saturation curve for water. The amount of water vaporized depends upon the change in enthalpy (or heat content) of the water region. Vaporization, thus, provides the means of transferring heat energy (enthalpy) from the rock to the water, to the steam region.

In Substage i_2 we now have more steam than can be held in the gaseous portion of the reservoir. This steam excess is to be removed as fluid production, ΔX . To compute the temperature of the steam region, and the mass produced, we use heat and mass balances on the steam region.

After removal of the excess steam, we arrive at Stage $i+1$. Thus, we have related a production, ΔX , to an increment in reservoir pressure.

It is interesting to note that although we are producing steam from the steam region, the mass and energy is being provided by the vaporization from the water region. The phase change is crucial, both to energy transfer and to maintaining the reservoir pressure.

Figure 13.1 Schematic of the Temporal Staging of an Idealized Reservoir

To gain an appreciation of how this mechanism works, let us consider the volume change in vaporization at 240°C and 486 psia. Based on steam tables, the volume change dramatically increases by a factor of 48.4. As the temperature decreases, the increase in fluid volume upon vaporization is even larger and the pressure maintenance mechanism becomes more powerful.

Thus, vaporization in the two-phase geothermal reservoir provides a dramatic mechanism of pressure maintenance. As a side-light, this type of vaporization mechanism does not occur in groundwater or petroleum reservoirs, and highlights why pressure drop and subsidence analyses are quite unique for geothermal systems.

13.5 ALGORITHM FOR THE RESERVOIR MODEL

We now provide the computational procedure to go from step i to step $i+1$ in the two-phase reservoir.* We begin with a reservoir of total volume $\bar{V}$, porosity ϕ , liquid region volume V_1^+ and steam regions V_1 . The respective water and steam temperatures are T_1^+ and T_1 , corresponding to reservoir pressure P_1 .

The algorithm is as follows:

Step 1: Specify ΔP_1 . Then $P_{i+1} = P_1 - \Delta P_1$ (13.1)

Step 2: Calculate $\mathcal{T}_{i+1}$ from steam-water saturation curves. As in same curves, if $\mathcal{T}_{i+1}$ is defined by the function β , then

$$P_{i+1} = \beta(\mathcal{T}_{i+1}) \quad (13.2)$$

is solved iteratively to determine $\mathcal{T}_{i+1}$.

Step 3: Calculate the mass of water vaporized $(X_s)_{i+1}$ as follows:

$$\begin{aligned} (X_s)_{i+1} &= \left(\frac{1}{v_s} V_s \right)_{i+1} = \left[\left\{ \frac{1}{v_r} V_r \mathcal{H}_r \right\}_i - \left\{ \frac{1}{v_r} \mathcal{H}_r \right\}_{i+1} \right] \left\{ V_r \right\}_i \\ &\quad + \left\{ \left(\mathcal{H}_w \right)_i - \left(\mathcal{H}_w \right)_{i+1} \right\} \left\{ \frac{1}{v_w} V_w \right\}_i / \\ &\quad \left[\left(\mathcal{H}_s \right)_{i+1} - \left(\mathcal{H}_w \right)_{i+1} \right] \end{aligned} \quad (13.3)$$

* The theory justifying the equations in this procedure are developed in Volume 3, the Research Report.

† In general, non-script variables are evaluated at conditions within the water region, e.g., $(V_s)_{i+1}$ is the specific volume of steam associated with the water region at $\mathcal{T}_{i+1}$ and P_{i+1} .

where v_w is the specific volume of water, v_w is the pore volume occupied by the water, and $\mathcal{H}_w, \mathcal{H}_s$ are the water and steam enthalpies respectively. The subscript r , indicates rock properties.

Step 4: Compute the estimated steam, M_s

$$M_s = \left(\frac{1}{v_s} v_s \right)_i + (X_s)_{i+1} \quad (13.4)$$

Step 5: Compute bulk steam temperature T_{i+1} by iterative solution of

$$T_{i+1} = \left[A - (X_s)_{i+1} (H_s)_{i+1} \right] / B \quad (13.5)$$

where

$$A = \left\{ \frac{1}{v_r} v_r H_r \right\}_i + \left\{ \frac{1}{v_r} \mathcal{H}_r \right\}_{i+1} (v_{r_i} - v_{r_{i+1}}) + \left\{ \frac{1}{v_s} v_s H_s \right\}_i + \left\{ \frac{1}{v_s} v_s \mathcal{H}_s \right\}_{i+1} \quad (13.6)$$

$$B = \frac{1}{v_r} C_{p_r} (v_{r_i} + v_{r_i} - v_{r_{i+1}}) \quad (13.7)$$

The quantities A and B are known at this step, but $(H_s)_{i+1}$ is a function of T_{i+1} .

Step 6: Compute the mass produced, M_p

$$M_p = \left(\frac{1}{v_s} \Delta v_s \right)_{i+1} = M_s - \left(\frac{1}{v_s} v_s \right)_{i+1} \quad (13.8)$$

The respective volume for steam, water, or rock, at any point in the algorithm can be evaluated by straightforward use of the volume balance and the definition of porosity.

The algorithm may be implemented using the steam tables (Keenan, Keys, and others, 1969; Meyer and others, 1968) and a scientific calculator. For repeated calculations, development of a simple computer program is justified.

The algorithm discussed above can be initialized at any defined or measured state of a two-phase reservoir. It is generally applicable as a first-order representation of the behavior of a two-phase geothermal system and will give results with a minimal amount of computational effort. For more refined calculations and to assess geometric effects on reservoir behavior and the resultant subsidence, a more comprehensive model as described in Chapter 7 can be consulted.

13.6 EXAMPLE CALCULATIONS

In this section we present results for the lumped, two-phase segregated reservoir model, presented above. As an illustrative example, we have calculated the behavior of a reservoir as it evolves from a state where the entire pore-space is occupied by a saturated liquid at 240°C, 465.67 psia. This calculation gives a clear idea of how the phenomena of phase change affects the reservoir operation.

The conditions chosen (see Table 13.1 for some of the reservoir parameters) are similar to the pressure and temperature characteristics that occurred in the Wairakei, New Zealand field at the time of the reservoir transition to the two-phase regime. Thus, these results may be considered as a continuation of the reservoir studies presented in Chapter 11.

Table 13.1 Reservoir Parameters

Porosity,	ϕ	= .2
Density,	ρ_R	= 162 lbs/ft ³
Heat Capacity,	C_{P_R}	= .2 BTU/°F-lb

13.6.1 Phase Relationships

In Figure 13.2 we display the fraction of the reservoir in the steam region as a function of reservoir pressure and in Figure 13.3 we display the pressure versus temperature curves for the water and steam regions. Naturally, as the reservoir is developed, and as fluid is withdrawn the steam region of the reservoir increases. The temperature

Figure 13.2 Pressure Versus the Fraction of Reservoir Volume in Steam Region

Figure 13.3 Temperature Pressure Profiles for Steam and Water Regions

history of the respective phases is somewhat surprising. The profiles diverge as the reservoir is developed, and as the reservoir becomes increasingly vapor-dominated, the steam phase becomes more superheated.* That we have a superheated vapor phase in a two-phase reservoir with substantial liquid may seem surprising, but this result is consistent with recent observations that vapor dominated reservoirs do contain a segregated liquid region (White and others, 1971). We observe that at 50 psia the steam has 94°F of superheat.

13.6.2 Production History

In Figure 13.4 we display the theoretical production history of the reservoir. The results shown are in terms of a reservoir with unit volume; thus, production is given in terms of kilograms of fluid produced per cubic meter of reservoir volume. To perform a history matching with the Wairakei production data of Stilwell and others (1975), we assume that 400×10^9 kg have been produced at 413 psia. Thus, we calculate a reservoir volume of $3.07 \times 10^{10} \text{ m}^3$. We note this estimate agrees more closely with that of Browne (1976), within a factor of two, than did the volume estimate of Chapter 11, using a single-phase assumption for the reservoir.

As confirmed in Table 13.2, the important derivative $\frac{dP}{dM}$ decreases as the reservoir becomes more vapor-dominated. As shown in Table 13.3 this effect is a result of the near balance between production and vaporization, and the fact that more differential vaporization occurs at lower pressure.

* Superheated steam is steam above the saturation temperature at specified pressure.

Figure 13.4

Pressure Versus Normalized Production

Table 13.2 Selected Values of $\frac{dP}{dM}$ From Figure 13.4

P (psia)	$\frac{dP}{dM}$ (psia/kg) (m ³)
398.6	5.94
297.1	5.56
195.6	4.85
108.5	3.82
50.5	2.69

Table 13.3 A Comparison of Vaporization and Production Data

Pressure (psia)	Water Vaporized $\left(\frac{\text{kg}}{\text{m}^3}\right)$	Production $\left(\frac{\text{kg}}{\text{m}^3}\right)$
471.1	2.45	2.37
398.6	2.49	2.45
297.0	2.63	2.61
195.6	2.97	2.89
108.6	3.78	3.80

13.7 OPERATING STRATEGIES AS DERIVED FROM THE PHYSICAL MODEL

In order to operate a geothermal reservoir, some magnitude of pressure drop must certainly result. To mitigate subsidence, we want to operate the geothermal plant in such a way as to minimize this pressure drop. One criteria involved in this minimization is the derivative $\frac{dP}{dM}$, which represents the magnitude for a change in pressure for an incremental change in fluid mass. As noted in Section 11.2, the magnitude of this derivative is less for two-phase systems than for single-phase systems. Thus, with the objective of mitigating subsidence, it is clear that a two-phase reservoir is more advantageous than a single-phase reservoir.

13.7.1 Liquid-Dominated Reservoirs

For liquid-dominated reservoirs, a feasible policy is to operate the system to achieve a two-phase reservoir as quickly as possible in relation to the development of the field. Based on the saturation curve this result can be accomplished by simply withdrawing the fluid with no reinjection. As discussed in Section 13.2, reinjection tends to lower the reservoir temperature; hence, the two-phase region is reached at a lower pressure. For that reason, reinjection is discouraged.

It should be noted that this strategy considers the long-term subsidence potential of a liquid-dominated field, rather than just the short term subsidence potential. Furthermore, in a practical sense, the geothermal brine must be safely disposed.

13.7.2 Two-Phase Reservoirs

For two-phase reservoirs, we recommended in Section 13.2 that fluid be produced from the steam region and that reinjection take place in the

water region. It is now clear that these two rules provide several advantages. First, reinjection interferes least with the produced fluid. Second, reinjection simultaneously helps maintain reservoir pressure and extracts energy from the rock. Finally, by producing steam, we are able to use a simpler, less expensive power plant at the surface facility. For example, complex power plants are not needed to process steam, as compared to those power plants needed to process highly contaminated hot water brines. Since a liquid-dominated reservoir will sooner or later evolve to a two-phase reservoir that produces steam, complicated, expensive power plants (designed to handle hot water contaminated with salts) should have a definite lifetime, coinciding with the transition to a well-developed two-phase reservoir.

13.7.3 Steam-Dominated Reservoirs

For steam-dominated systems, (e.g., the Geysers, California), the recommended operating policy is to locate the depth of the small, but important liquid region, and subsequently inject water into that region. Such a policy will prolong the lifetime of the geothermal resource by maintaining pressure in the field as well as enhancing the amount of energy extracted, since vaporization of the water injectant is an efficient means of extracting the energy from the hot rock.

13.8 SUMMARY

In this chapter we have focused on operating policies to mitigate subsidence. These policies are derived from fundamental physical principles and a conceptualization of hydrothermal reservoir mechanisms.

The operating policies discussed include the following: In terms of the overall life of the field, it may be advantageous to develop liquid-dominated reservoirs so that the transition to the two-phase regime occurs as early as possible in the production history of the resource. For two-phase reservoirs, fluid extraction should take place from the steam region and reinjection should be in the water region, well below the flash zone. For steam dominated resources, the expected water zone in the resource should be located, and water should be injected into that zone.

To quantify the conceptualization of appropriate hydrothermal physics, we have translated the conceptualization into mathematical equations, and we have exercised the resulting mathematical model to obtain numerical results for a situation similar to the Wairakei, New Zealand reservoir. The trends indicated by the numerical results were consistent with observational data. In particular, in studies for the steam-dominated two-phase system the model results did predict a superheated steam region above a saturated liquid.

We began this Handbook by presenting background information on geothermal subsidence and proceeded to provide methods of evaluating the subsidence potential of geothermal resources. We have now culminated the Handbook with this final chapter providing operating policies to mitigate subsidence. As a final remark, we indicate again that more details on each of the topics presented here can be found in Volume 2, the Research Report.

13.9 REFERENCES

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