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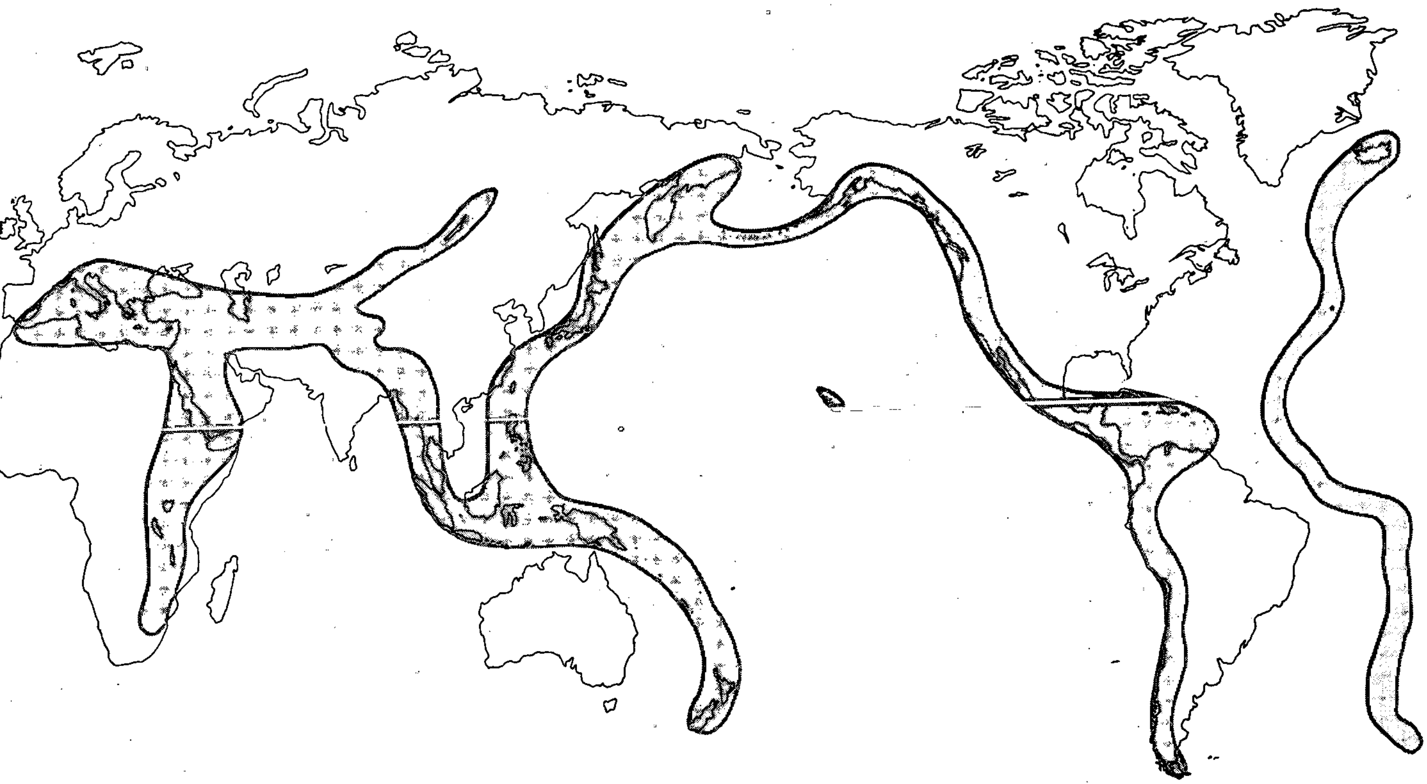

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Review of

# GEOTHERMAL SUBSIDENCE

by

S. L. Phillips, J. A. Fair, F. B. Henderson III, and S. R. Schwartz

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PHYSICAL CHEMISTRY Deals with the basic thermodynamic, thermophysical, and kinetic data at elevated temperatures and pressures of geothermal minerals, rocks, solutions, and gases.

UTILIZATION Encompasses the development and production of a geothermal reservoir for both electrical and non-electrical uses: hot water (brine) transport; space, process, and agricultural heating; power generation; binary cycle power generation; corrosion, erosion, and scaling; resource evaluation.

ENVIRONMENTAL Considers aspects to the air, land, and water environments of geothermal energy utilization: subsidence; hydrogen sulfide; ammonia; metals; boron; silica; seismicity; noise; land-use.

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RESERVOIR CHARACTERIZATION Includes review and evaluation of data relevant to the development and production of wells covering: porosity; artificial stimulation; natural recharge; artificial recharge; modeling; well tests and measurements.

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NATIONAL GEOTHERMAL
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The National Geothermal Information Program encompasses diverse fields. It is recognized that no single office or laboratory has expertise on all aspects of geothermal science and technology. For this reason, GRID has formed a Technical Advisory Committee consisting of persons from installations selected for their expertise in fields relevant to the evaluation of geothermal data. The purpose of the Committee is to provide advice on the scope of geothermal information gathering activities. The current membership is as follows:

NATIONAL GEOTHERMAL
INFORMATION RESOURCE

Prologue
Sept. 1975

How happy is the man who finds wisdom,
The man who gains understanding!
...
She is more precious than corals,
And none of your heart's desires can compare with her
...
Her ways are ways of pleasantness
And all her paths are peace.
She is a tree of life to those who grasp her,
And happy is every one who holds her fast.

Proverbs

Rigidity threatens all realization: what lives and glows today may be crusted over tomorrow and, becoming all-powerful, suppress the strivings of the day after.

Martin Buber

CONTENTS FOR GEOTHERMAL SUBSIDENCE



Front cover map shows major worldwide regions of intense geothermal phenomena: the circum-Pacific margin; island groups of the mid-Atlantic rift; the rift zones of east Africa and adjacent Middle East; and the Mediterranean, Asia Minor, and Asia belt.

The Lawrence Berkeley Laboratory has been funded by the Energy Research and Development Administration to establish a National Geothermal Information Resource (GRID). The objective of GRID is mainly to compile and disseminate evaluated data on the following six major categories of geothermal science and technology: (1) physical chemistry, (2) exploration, (3) utilization, (4) institutional considerations, (5) environmental effects, and (6) reservoir engineering. The content of this report is limited to environmental consideration of land subsidence due to man's withdrawal of geothermal fluids.

## A. INTRODUCTION

An important facet in the development and utilization of geothermal energy is the consideration of any effects to the air, water, and land compartments of the environment (Ref. 1-3). In this report, we have abstracted and compiled a bibliography of one aspect of possible environmental effects: that dealing with subsidence. The interest in subsidence stems from two major concerns: (1) potential damages to the production field pipelines and power plants, for example, the pipe distortion experienced at Wairakei, New Zealand; and, (2) possible effects on communities. An example of (2) is the subsidence of Venice, Italy, due in part to non-geothermal water pumping at Porto Marghera, 7 km distance from Venice (Ref. 4).

The current published literature on land subsidence traceable to man's withdrawal of goethermal fluids is not extensive; this is especially true for reports on geothermal subsidence in the United States. It is expected that additional material will be available as data are obtained from the surveying nets set up to monitor ground movement at several geothermal areas in the United States, including The Geysers and the Imperial Valley. In New Zealand, the Wairakei geothermal field has been the most extensively studied; monitoring networks for land subsidence have been set up at both the Broadlands and Kawerau geothermal areas.

On the other hand, there is a large literature covering subsidence effects due to oil and gas, and groundwater pumping for petroleum, agricultural and drinking purposes. Selected portions of this non-geothermal literature are included here to provide relevant background information on the theory, causes, effects, and means of controlling subsidence due to man's removal of subsurface fluids.

Unless otherwise noted, the material contained in this report was compiled from the original literature; exceptions are so designated in the Abstract indexes. No systematic attempt was made to convert numerical data in the Abstracts to Standard International Units, however, a conversion table is included for the convenience of the reader.

Appended to the end of this report are the Abstracts arranged in alphabetical order according to the last name of the first author, and the following three indexes: (1) Author, (2) Author Affiliation, and (3) Subject Content.

The Author Index lists alphabetically the surname of each author, followed by the last two digits of the year of publication.

The Author Affiliation Index is arranged alphabetically by the organization of the author at the time the abstracted article was published. The present affiliation, if different, is not included in the listing.

The Subject Index is organized into the following four major categories: (1) theory, (2) effects, (3) control, and (4) monitoring methods. An abstract containing information on more than one principal category is listed in each category.

While it is our intent that the compilation be as comprehensive as possible, it is realized that no literature search can be exhaustive. In this context, the reader is urged to communicate important omissions on geothermal subsidence to the National Geothermal Information Resource, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720. This additional information together with new data will be stored in our IRATE/GEODOC computer tape file for subsequent critical evaluation and general dissemination.

Additional information on geothermal subsidence may be obtained from "Measuring Ground Movement in Geothermal Areas of Imperial Valley, California" (Ref. 3), "Ground Movement in New Zealand Geothermal Fields", (Stilwell 75), and the chapter by Bowen on "Environmental Impact of Geothermal Development", (Bowen 73). Of special interest are the two volumes covering papers presented at the First International Symposium on Land Subsidence giving a world-wide overview of the state-of-the-art (Ref. 14). The Second International Conference is scheduled for December 1976 in Los Angeles, CA.

## B. SCOPE

The period covered by this compilation is mainly from 1970 to August 1975. This starting date was selected because literature on geothermal subsidence began to be generally available in 1970, for example, at the U.N Conference held in Pisa, Italy in 1970. Besides citations on geothermal subsidence, this report also includes selected portions of the literature on subsidence due to groundwater overdraft, and oil and gas withdrawal that meet one or more of the following criteria: (1) theory or mechanism of soil compaction and land subsidence, (2) effects (3) methods for abatement and control of subsidence, and (4) monitoring methods.

This bibliography is also intended to provide quick referral to data of interest for the researcher engaged in assessing the effects of subsidence as related to the utilization of geothermal energy.

## C. SUMMARY AND CONCLUSIONS

Land subsidence and frequently associated horizontal ground movement is listed among the environmental effects which may be caused by man's withdrawal of geothermal hot water. It is the surface manifestation of subsurface soil compaction and has been observed for many years in some petroleum fields and areas of groundwater pumping. Although the geologic settings of the various areas may vary considerably, the basic cause of subsidence is the same: reduction of fluid pressure causing a marked increase in effective stress (Ref. 1).

In summary, geothermal subsidence may not occur for vapor dominated systems (e.g., The Geysers, California), see Bowen 73. However, both horizontal and vertical ground movement have been measured at the hot-water field in Wairakei, New Zealand (Hatton 70, Stilwell 75). A series of subsidence monitoring nets have been set up at both The Geysers and in the Imperial Valley, California (Lofgren 74); and in Wairakei, The Broadlands and Kawerau, New Zealand (Stilwell 75). An objective of monitoring in the Imperial Valley is to differentiate natural background subsidence from that caused by man's withdrawal of reservoir hot waters. Brine reinjection or other water injection using recharge wells is a possible means of controlling subsidence (Gringarten 75). However, a number of factors are important for reinjection wells including the following: (1) distance between reinjection wells and producing wells. Mixing of the injected fluid may reduce the reservoir temperature (Ref. 10). The optimum distance may be about 1.5 km for hot water wells. (2) Recharge injection wells may be costly (Ref. 1); and, (3) pipes for recharging can be made inefficient due to scaling formation (Ref. 11). Fluid injection is currently being carried out in the United States at The Geysers and in the Imperial Valley. It is used mainly for the purpose of waste water disposal (Ref. 10, 11, 12).

After reviewing the current geothermal subsidence information in light of the data requirements, some general observations are appropriate. While data currently available are satisfactory in some respects, there are still a number of inadequacies. The optimum future data gathering activities should include:

1. Development of a model for subsidence which takes into account the important parameters for predicting geothermal subsidence. The model should account for the following major parameters: (a) rate of aquifer compaction as a function of fluid removal, (b) rate of land subsidence as a function of aquifer compaction, (c) effect of aquifer depth on land subsidence, (d) effect of recharge rate on aquifer compaction, (e) the relationships between aquitard structure and compaction. Narasimhan and Witherspoon have developed a model for geothermal land subsidence based on the reduced volume of rock skeletons due to a lowering in pore-water pressure (Ref. 13). The models developed by Helm (Ref. 8) and Gambolati, Gatto, and Freeze (Ref. 4) may also assist in developing theories of geothermal land subsidence.

2. Laboratory testing of rocks obtained at depth to measure the rock compaction as a function of important parameters (e.g., porosity, water content, temperature, pressure). The tests will provide site-dependent data on compaction and the likelihood of subsidence, and can also be used to test the applicability of mathematical methods.

3. Development of rock-sampling techniques at depth. The difficulty in obtaining an undisturbed sample of soil for use in predicting settlement rates is discussed by Christian and Hirschfeld (Christian 74).

4. Horizontal and vertical subsidence monitoring instrumentation that provide data quicker than the currently used leveling techniques. Monitors at depth that could detect rock compaction would be of special usefulness. However, these would of necessity be placed in a hostile environment, and therefore must be sufficiently rugged and placed very deep.

Installation of monitors is in progress, as discussed by Lofgren (Ref. 15). Tiltmeters are being installed to monitor land-surface changes at strategic locations. Intermediate depth extensometers have been installed at selected locations in Imperial Valley to differentiate possible geothermal subsidence effects from shallower groundwater and surficial effects. In addition, horizontal monitoring networks are monitored with electronic measuring equipment that is both rapid and inexpensive.

5. Data on natural land subsidence that is not related to man-caused geothermal fluid withdrawal. This information would help to differentiate effects due to extraction of the fluid. Lofgren is currently working in this area (Ref. 3).

6. Analyses of the economic effects of geothermal land subsidence. In some cases, ground movement may have minimal damage to the

affected areas. See McCauley 75 for an example in the case of groundwater overdraft.

7. Means of identifying and locating those parts of known geothermal areas which are most likely to undergo land subsidence. These should be located outside the pumping area, and should not be utilized for power plants or other structures. See Stilwell 75.

8. Fluid injection evaluation to determine the effects on production of seismic noise, reservoir fluids and injected fluid mixing at depth, and control of subsidence. The effect of injection on the temperature of geothermal reservoirs is being studied by Gringarten and Santy (Ref. 10).

D. ACKNOWLEDGMENT

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12. Kubota, K. and Aosaki, K., 1975; "Reinjection of Geothermal Hot Water at the Otake Geothermal Field": Abstracts, Second U.N. Symp. on Dev. and Use of Geothermal Resources, IV-7 (May 20-29, 1975).

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14. Land Subsidence, Proceedings, Tokyo Symposium, Vol. 1 and Vol. 2, International Assoc. of Scientific Hydrology and UNESCO, Tokyo, Japan, 1970. Pubs. 88 and 89. Tison, L.J., ed. Available from: UNIPUB, Box 433, New York, NY 10016. Price $26.50.

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## E. GLOSSARY

The glossary that follows was compiled from the references indicated after each term. It contains both geothermal vocabulary terms as well as terms useful in studies of the mechanics of aquifer systems and land subsidence due to fluid withdrawal. In some cases, changes in the original wording have been made.

Aquiclude: An areally extensive body of saturated but relatively impermeable material that does not yield appreciable quantities of water to wells. Aquicludes are characterized by very low values of "leakance" (the ratio of vertical hydraulic conductivity to thickness), so that they transmit only minor inter-aquifer flow and also have very low rates of yield from compressible storage. Therefore, they constitute boundaries of aquifer flow systems. Ref. 5.

Aquifer System: A heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds separated at least locally by aquitards that impede groundwater movement but do not greatly affect the regional hydraulic continuity of the system. Ref. 5.

Aquitard: A saturated, but poorly permeable, bed that impedes groundwater movement and does not yield water freely to wells, but which may transmit appreciable water to or from adjacent aquifers. Ref. 5.

Artesian Head: The hydrostatic head of an artesian aquifer or of the water in the aquifer. Ref. 6.

Artificial Recharge: Recharge at a rate greater than natural, resulting from the activities of man. Ref. 6.

Benchmark: A relatively permanent metal tablet or other mark firmly embedded in a fixed enduring natural or artificial object, indicating a precisely determined elevation above or below a standard datum and bearing identifying information, and used as a reference. Ref. 6.

Clastic: Pertaining to or being a rock or sediment composed principally of broken fragments that are derived from preexisting rocks or minerals and that have been transported individually for some distance from their places of origin. Ref. 6.

Compaction: Compaction is the decrease in thickness of sediments, as a result of increase in vertical compressive stress ("one-dimensional consolidation").

*Elastic Compaction* is approximately proportional to the change in effective stress over a moderate range of stress, and is fully recoverable if the stress reverts to the initial condition.

*Virgin Compaction* has two components: an inelastic component that is not recoverable upon decrease in stress and a recoverable elastic component. Virgin compaction of aquitards is usually roughly proportional to the logarithm of effective stress increase. Ref. 5.

Confining Bed: A confining bed is areally extensive and forms a nearly impervious or semipervious hydraulic barrier between aquifers above and below. Ref. 5.

Consolidation: Consolidation is the adjustment of a saturated soil in response to increased load, involving the squeezing of water from the pores and a decrease in void ratio. Ref. 5.

Differential Compaction: A kind of compaction produced by uneven settling of homogenous earth material under the influence of gravity, or by differing degrees of compactability of sediments. Ref. 6.

Extensometer: Instrument used to measure small deformations, deflections, or displacements. Ref. 6.

First-Order Leveling: Spirit leveling of high precision and accuracy in which, for a section of 1-2 km in length, the maximum allowable discrepancy in results obtained by running the line first forward to the objective point and then backward to the starting point is 4.0 mm times the square root of the distances in km separating the ends of the line (or 0.017 ft times the square root of the distance in miles). Ref. 6.

Hot-Water Systems: These systems are characterized by liquid water as the continuous, pressure-controlling phase. The water contains varying amounts of both volatile and non-volatile constituents. Ref. 7.

Hydrostatic Head: The height of a vertical column of water, the weight of which, if of unit cross section, is equal to the hydrostatic pressure at a point; static head, as applied to water. See also: Artesian Head. Ref. 6.

Injection Well: See recharge well.

Leveling: The operation of determining the comparative altitude of different points on the Earth's surface, usually by sighting through a leveling instrument at one point to a level rod at another point. Ref. 6.

Recharge Well: A well used to inject water into one or more aquifers in the process of artificial recharge. Also, called reinjection well. Ref. 6.

Reservoir Pressure: The pressure on fluids in a subsurface formation, or the pressure under which fluids are confined in rocks. Ref. 6.

Second-Order Leveling: Spirit leveling that has less stringent requirements than those of first-order leveling, in which lines between benchmarks established by first-order leveling are run in only one direction using first-order instruments and methods (or other lines are divided into sections, over which forward and backward runnings are to be made) and in which the maximum allowable discrepancy is 8.4 mm times the square root of the length of the line (or section) in km (or 0.035 ft times the square root of the distance in miles). Ref. 6.

Spirit Level: A sensitive device for finding a horizontal line or plane, consisting of a closed glass tube or vial of circular cross section, its center line also forming a circular arc, nearly filled with a liquid of low viscosity (such as ether or alcohol) with enough free space being left for the formation of a bubble of air or gas that will always assume a position at the top of the tube. Ref. 6.

Spirit Leveling: A type of leveling using a spirit level to establish a horizontal line of sight. Ref. 6.

Stratification: The formation, accumulation, or deposition of material in layers. Ref. 6.

Stress, Effective: Stress (pressure) that is borne by and transmitted through the grain-to-grain contacts of a deposit, and thus affects its porosity or void ratio and other physical properties. Ref. 5.

Subsidence: Sinking or settlement of the land surface, due to any of several processes. As commonly used, the term relates to the vertical downward movement of natural surfaces although small-scale horizontal components may be present. The term does not include land-slides, which have large-scale horizontal displacements, or settlement of artificial fills. Ref. 5.

Survey Net: A series of surveying (leveling) stations that have been interconnected in such a manner that closed loops or circuits have been formed or that are so arranged as to provide a check on the consistency of the measured values. Ref. 6.

Tiltmeter: Instrument measuring slight changes in the tilt of the earth's surface, usually in relation to a liquid-level surface or to the rest position of a pendulum. Ref. 6.

Vapor-Dominated System: In these systems, liquid water and vapor normally coexist, with vapor as the continuous, pressure-controlling phase. Ref. 7.

## Table of Units and Conversions

| To Convert From | To | Multiply By |
|---|---|---|
| mile | kilometer (km) | 1.609 |
| square mile | square kilometer (sq km) | 2.590 |
| foot | meter (m) | 0.3048 |
| kilogram/square centimeter | bar | 0.9804 |
| bar | pascal (pa) | $10^5$ |
| gallon | liter (1) | 3.785 |
| acre-feet | gallon (gal) | 325,850 |
| atmosphere | pascal (pa) | $1.013 \times 10^5$ |

### Examples

Meters = (0.3048) (1500 ft) = 457 m

Square Kilometers = (2.590) (10,000 sq mi) = 25,900 sq km

Bar = (0.9804) (34 kg/cm) = 33.3 bar

| Literature Sources Scanned | Date |
|---|---|
| A Bibliography<br>Geothermal Resources: Exploration and Exploitation (TID 3354) | March 1975 |
| Abstracts, 2nd U.N. Conference on Development and Use of Geothermal Resources | April 1975 |
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| Department of Interior Final Environmental Statement for the Geothermal Leasing Program | 1973 |
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## F. ABSTRACTS

Following are abstracts of literature dealing with geothermal subsidence, and selected abstracts on subsidence caused by groundwater overdraft and oil and gas exploitation. The literature has been abstracted to highlight the data content in terms of subsidence; other important geothermal data are indicated in the descriptors.

The abstracts were prepared from GRID computer tapes using our IRATE/GEODOC text editing and tape storage system with an extended (12-bit) character set. Copies of the tapes, or microfiche, are available on request, at a nominal cost, from the National Geothermal Information Resource.

Environmental/Subsidence
Axtmann 74

TITLE: **An Environmental Study of the Wairakei Power Plant**

REFERENCE: Physics and Engineering Lab. Report No. 445 (Dec. 1974)

AUTHOR: Axtmann, R.C. (Department of Scientific and Industrial Research, Lower Hutt, New Zealand, Physics and Engineering Laboratory)

ABSTRACT: The report is a comprehensive study on environmental effects at Wairakei. Besides air and water emissions (e.g., $H_2S$, Hg) and environmental studies (e.g., water quality), subsidence effects are included. Vertical ground movement first became apparent in 1956; it now covers an area greater than 65 sq km. The region of maximum subsidence is 460 m north of the steam mains, and is displaced from both the production field and the power station. Movement is 0.4 m/year at the point of maximum deflection; total movement since 1956 exceeds 3.7 m. Horizontal movement was detected in 1965: A telescopic joint inserted at a break point showed a movement of 10.2 cm in 1970.

DESCRIPTORS: New Zealand; Wairakei geothermal field; environmental effects; ground motion; ground subsidence; plants; fishes; air pollution; water pollution.
PROPOSED DESCRIPTORS: Earth movements; chemical compounds;

Environmental/Subsidence
Bailey 73

TITLE: **Post-Subsidence Volcanism and Structure of Long Valley Caldera, California**

REFERENCE: Geol. Soc. Am., Abstracts with Program, v.5, n.1, p.7

AUTHOR: Bailey, R.A. [Geological Survey, Denver, CO (USA), Geologic Div.]

DESCRIPTORS: California; Long Valley; ground subsidence; volcanism

Environmental/Subsidence
Bolton 73

TITLE: **Management of a Geothermal Field**

REFERENCE: In Geothermal Energy. Review of Research and Development, Armstead, H.C.H. (ed.); The Unesco Press, 7 Place de Fontenoy, 75700 Paris, France, p.175-184 (1973).

AUTHOR: Bolton, R.S. (Ministry of Works, Wellington, New Zealand)

ABSTRACT: The methods of estimating the energy potential and effects of exploitation a geothermal field are discussed. A secondary effect of exploitation includes ground movement; an effect observed on expoitation of cold water aquifers and oil fields (e.g.,

Mexico City, Long Beach, CA). At Wairakei, the ground movement has a strong vertical and horizontal component. The maximum rate of subsidence has been 0.4 m (1.3 ft/year); the total maximum subsidence is estimated at over 3 m (10 ft). The center of subsidence is about 450 m (1500 ft) from the nearest wells, and 1.8 km (6000 ft) from the region of greatest draw-off. The movement is attributed to the bending of the mudstone cap rock resulting from the fall in pressure and the withdrawal of the large mass of fluid. The ground movement has affected steam mains and drainage channels. 1 map.

DESCRIPTORS: New Zealand; Wairakei geothermal field; ground motion; ground subsidence; environmental effects.

Environmental/Subsidence
BOR 72

TITLE: **Geothermal Resource Investigations, Imperial Valley, CA, Developmental Concepts**

REFERENCE: Bureau of Reclamation, U.S. Dept. of the Interior (Jan. 1972)

ABSTRACT: The objectives of the report were to present concepts for geothermal development in the Imperial Valley for augmenting the Colorado River with high quality water, and to outline the need for a research and investigation program. It includes the following major topics: geothermal resource investigations, research and development program, geothermal reserves, and environmental considerations. About 100 injection wells would be drilled on the periphery of the geothermal field to inject residual brines and Salton Sea cooling water for maintenance of reservoir pressures.

DESCRIPTORS: California; Imperial Valley; ground subsidence; injection wells; groundwater recharge.
PROPOSED DESCRIPTORS: Developmental concepts.

Environmental/Subsidence
Bowen 73

TITLE: **Environmental Impact of Geothermal Development**

REFERENCE: Chapter 10 in Kruger, P. and Otte, C. (eds.), "Geothermal Energy", Stanford University Press (1973), Stanford, CA 93405. Price $17.50.

AUTHOR: Bowen, R.G. (Department of Geology and Mineral Industries, State of Oregon, Portland, OR)

ABSTRACT: Aspects of environmental effects cover the impact on the land, air, water; and, hazards to ground water aquifers. Subsidence effects have not been observed either at The Geysers in 12 years of operation, or at Larderello during 60 years of operation. This is not unexpected for vapor-dominated fields, where the pressure and temperature

of the vapor are nearly constant (34 kg/sq cm, 240°C). However, hot-water fields (e.g., Wairakei) are expected to show subsidence effects.

DESCRIPTORS: Geysers geothermal field; Lardarello geothermal field; ground motion; environmental effects; groundwater recharge.
PROPOSED DESCRIPTORS: Earth movements; subsidence effects.

Environmental/Subsidence
Browne 74

TITLE: **Subsidence Rate at Broadlands from Radiocarbon Dates**

REFERENCE: N.Z. J. Geo. Geophys., v.17, n.2, p.494-495 (1974)

AUTHOR: Browne, P.R.L. (Geological Survey, Lower Hutt, New Zealand)

ABSTRACT: Drillhole PH 1A in the Broadlands penetrated woody material at depths between 14.6 and 15.2 m. A sample of the material gave a radiocarbon age of 4280 ± 60 years B.P. This age represents an average accumulation rate of 3.5 ± 0.3 mm per yr. It is likely the accumulation rate approximates the subsidence rate.

DESCRIPTORS: New Zealand; Broadlands geothermal field; ground motion; ground subsidence; carbon isotopes;
PROPOSED DESCRIPTORS: Carbon radioisotopes; radioactive dating;

Environmental/Subsidence
Bull 73

TITLE: **Geologic Factors Affecting Compaction of Deposits in a Land-Subsidence Area**

REFERENCE: Geol. Soc. Am. Bull., v.84, n.12, p.3783-3802 (1973)

AUTHOR: Bull, W.B. [Arizona Univ., Tucson, (USA), Dept. of Geosciences]

ABSTRACT: In the west-central San Joaquin Valley, California, pumping of groundwater has changed water levels, thereby increasing the stresses that tend to compact alluvium by as much as 50% and creating a large area of intense land subsidence. The estimated (1943-1960) specific unit compaction of the deposits in a northern subarea is four times that of a southern subarea, which suggests marked differences in the compressibility of the deposits. Two-thirds of the compressibility difference is only apparent and is attributed to different water-expulsion rates in the clayey beds of different depositional environments. In the northern subarea, the deposits are mainly flood-plain sediments that contain extensive sand beds and thin clayey beds that are dewatered relatively quickly under increasing effective stress. In the southern subarea, the sediments are mainly alluvial-fan deposits that contain thick clayey sequences adjacent to lensing sandy beds. These deposits are watered more slowly than those in the northern subarea. (KNAPP-USGS, WRA). 16 Fig., 2 Tab., 14 Ref.

DESCRIPTORS: Ground subsidence; California; San Joaquin Valley.
PROPOSED DESCRIPTORS: Compaction; alluvium; compressibility.

Environmental/Subsidence
Chasteen 74

TITLE: **Geothermal Steam Condensate Reinjection**

REFERENCE: In Proc. Conf. on Research for the Development of Geothermal Energy Resources, p.340, (Dec. 31, 1974)

AUTHOR: Chasteen, A.J. (Union Oil Co., Santa Rosa, CA)

ABSTRACT: Geothermal electric generating plants which use condensing turbines generate an excess of condensed steam which must be disposed of. At the Geysers, California, the largest geothermal development in the world, this steam condensate has been reinjected into the steam reservoir since 1968. A total of 3,150,000,000 gallons of steam condensate has been reinjected since that time with no noticeable effect on the adjacent producing wells. Currently, 3,700,000 gallons/day from 412 MW of installed capacity are being injected into 5 wells. Reinjection has also proven to be a satisfactory method of disposing of geothermal condensate at Imperial Valley, California, and at the Valles Caldera, New Mexico. The Geysers is a vapor-dominated reservoir with a reservoir pressure not exceeding 500 psig. Since the average depth of the injection wells is 5380 feet, no pumping of the injected water is required. The surface facilities consist of a settling basin to remove solids, transfer pumps, deaerating vessels, and fiberglass or plastic-coated steel pipelines. (Auth.).

DESCRIPTORS: California; The Geysers; Imperial Valley, reinjection.

Environmental/Subsidence
Christian 74

TITLE: **Subsidence of Venice: Predictive Difficulties**

REFERENCE: Science, v.185, p.1185 (1974)

AUTHOR: Christian, J.T. (Stone and Webster Engineering Corp., Geotechnical Div., Boston, MA 02107); Hirschfeld, R.C. (Geotechnical Engineers, Inc., Winchester, MA 01890)

ABSTRACT: The accuracy of prediction for the rate of settlement depends very heavily on the precision with which the properties of undisturbed soil or rock at depth are measured. However, it is difficult to obtain an undisturbed sample. Extrapolation to predict future subsidence rates can be precarious: e.g., there is not a good correlation between predicted and measured subsidence for Long Beach, CA. At Long Beach, subsidence was stopped at 8.5 m (28 ft) by injecting water back into the field. Besides sampling, other problems in predicting subsidence include: (1) details of stratification, (2) fluid pressure measurements; and, (3) silt compressibility. In many cases, predictions of future settlement have been much smaller than the actual settlement that subsequently occured. 1 Fig.

DESCRIPTORS: California; Long Beach; ground subsidence; ground motion; Italy; forecasting;
PROPSED DESCRIPTORS: Subsidence effects; Venice;

Enviornmental/Subsidence
DOI 73

TITLE: **Promulgation of Leasing and Operating Regulations for the Geothermal Leasing Program**

REFERENCE: Final Environmental Statement for the Geothermal Leasing Program, v.I, p.III-36 (1973)

AUTHOR: Office of the Secretary, Department of the Interior

ABSTRACT: Ground subsidence can result from withdrawal of large volumes of fluids, but may be minimized by reinjection of geothermal fluids after utilization of the fluid heat. It is possible that there would be no serious land use or environmental consequences if subsidence did occur.

DESCRIPTORS: Ground motion; leasing; legislation; legal aspects; ground subsidence; artificial recharge; KGRAS.
PROPOSED DESCRIPTORS: Earth movements;

Environmental/Subsidence
Duncan 73

TITLE: **Earth Pressures on Structures Due to Fault Movement**

REFERENCE: Proc. Am. Soc. Civ. Eng. 99 (Dec. 1973)

AUTHOR: Duncan, J.M. and Lefebyre, G. [California Univ., Berkeley (USA), Dept. of Geol. Eng.]

Environmental/Subsidence
Dutcher 72

TITLE: **Prelimary Appraisal of Ground Water in Storage with Reference to Geothermal Resources in the Imperial Valley Area**

REFERENCE: U.S. Geol. Surv. Circ. 649 (1972), 57 p.

AUTHOR: Dutcher, L.C., Hardt, W.F., and Moyle, W.R., Jr. [Geological Survey, Menlo Park, CA (USA)]

ABSTRACT: This comprehensive report on the ground water in the Imperial Valley, CA, covers the following major subjects: (1) geology, (2) sources of heat and high-temperature anomalies, (3) geothermal gradients, (4) estimated porosity and specific yield of the rocks and deposits; (5) usable and recoverable water, (6) reliability of the estimates, (7) possible environmental hazards, (8) additional data needs. Land subsidence may occur whenever fluid withdrawals exceed the recharge rate. Subsidence results from the compaction of compressible beds of the aquifer system as effective stresses are increased by fluid-pressure reduction. The magnitude of the subsidence depends on: (a) effective stress increase caused by the pressure drop, (b) compressibility of the deposits, (c) thickness of the compressible beds, (d) the time the increased stress has been applied. Most of the parameters for predicting subsidence in Imperial Valley (e.g., anticipated pressure declines, thickness and compressibilities of the water-bearing deposits, and lateral extent of fault blocks) are not well known. Experience in other areas of extensive pumping indicates that ground water cannot be mined without causing land subsidence. In general, one foot of surficial subsidence occurs for each 10-50 ft of long-term artesian-head decline. 20 Fig., 4 Tables, 109 Ref.

AVAILABILITY: U.S. Geological Survey, Washington, DC 20242

DESCRIPTORS: California; Imperial Valley; ground water; ground motion; thermal waters; rocks; water reservoirs; salinity; analyses; environmental effects.

Environmental/Subsidence
Einarsson 75

TITLE: **Disposal of Geothermal Waste Water by Reinjection**

REFERENCE: Abstracts, Second U.N. Symp. on Dev. and Use of Geothermal Resources, San Franciico, CA, IV-6 (May 20-29, 1975)

AUTHOR: Einarsson, S.S. (OTC, United Nations, P.O. Box 3260, Managua, Nicaragua; Vides, R.A.; and Cuéllar, G. (CEL, San Salvado, El Salvador)

ABSTRACT: Disposal of geothermal waste water by reinjection must take into account the following important factors: (1) the effect on the geothermal field, (2) the effect on adjacent shallow or deep aquifers, (3) selection of reinjection site, (4) mineral deposition and scaling, (5) establishment of monitoring systems, (6) plant design, and (7) costs. Highly mineralized waters represented major probelms for exploitation of the Ahuachapán geothermal field. Large scale reinjection experiments were successfully carried out in 1970-71, during which almost 2 million cubic meters of water of 150°C were reinjected at the rates of 91 and 164 liters/sec. by using both gravity and the vapor pressure as driving force. The water was injected into the high-temperature aquifer at depth and resulting cooling effect observed. No technical difficulties from scaling or other nature were experienced. The local cooling effect around the point of injection, which should be minimum 1.5 km away from the production area, was estimated to be of minor significance in relation to the expected benefits. The cost of reinjection was estimated approximately 1 US mil/kWhr and the reinjection of the waste water is considered a

technically and economically feasible disposal method.

DESCRIPTORS: Nicargua; Ahuachápan geothermal field; reinjection.

Environmental/Subsidence
Gabrysch 74

TITLE: **Land-Surface Subsidence in the Area of Burnett, Scott, and Crystal Bays near Baytown, Texas**

REFERENCE: U.S. Geol. Surv., Water Resources Investigations 21-74, September 1974, 48p.

AUTHOR: `Gabrysch, R.K. and Bonnet, C.W. [Geol. Surv., Austin, TX (USA)]

ABSTRACT: Removal of water, oil, and gas from the subsurface in Harris County, Texas, has caused declines in fluid pressures, which in turn have resulted in subsidence of the land surface. Subsidence is becoming critical because much of the area is now subject to inundation by high tides. Production of oil and gas had caused as much as 3.25 feet of subsidence by 1925. Withdrawals of water from large-capacity industrial wells began about 1918. Significant subsidence of the land surface probably began about 1920 and as much as 8.2 feet of subsidence had occurred in the area by 1973. Probable future subsidence was calculated for two loading situations. Case I provided that the artesian heads would continue to decline at a rate of about 6 feet per year until 1980 and then cease. Case II provided that artesian head in the Alta Loma sand would continue to decline at a rate of about 6 feet per year until about 1995, when the potentiometric surface would reach the top of the Alto Loma sand. The ultimate subsidence expected for Case I and Case II is 11.4 feet and 15.1 feet, respectively. However, only 1.4 feet of subsidence below present land surface would occur if artesian heads were maintained at their present levels. Subsidence can be halted in the near future only if artesian head is increased, either by decreasing pumpage or by repressurization by artificial recharge. (KNAPP-USGS, WRA). 27 Fig., 3 Tab., 18 Ref.

DESCRIPTORS: Texas; Harris County; Baytown; subsidence; withdrawal; oil fields; artesian aquifers; land subsidence; water levels; artificial recharge.

Environmental/Subsidence
Gambolati 74

TITLE: **Predictive Simulation of the Subsidence of Venice**

REFERENCE: Science, v.183, p.849-851 (1974)

AUTHOR: Gambolati, G. (IBM Scientific Center, Venice, Italy); Gatto, P. (Consiglio Nazionale delle Ricerche Laboratorio per lo Studio della Dinamica delle Grandi Masse, Venice, Italy); and Freeze, R.A. (Dept. of Geological Sciences, Univ. of British Columbia, Vancouver, Canada)

ABSTRACT: Land subsidence at Venice is the result of sediment compaction in the unconsolidated, aquifer-aquitard system underlying the Venetian Lagoon. Compaction is

caused by the groundwater withdrawals by the port of Porto Marghera, 7 km distance from Venice. Marghera has about 55 wells that tap 5 highly permeable aquifers in the upper 300 m: pumping started in 1930 and had reached a constant 460 liter/sec by 1969. Venice has one well that extracts about 10 liter/sec. The observed subsidence in the period 1952 through 1969 is 9 to 11 cm in Venice; it reaches a maximum of 14 cm at the center of the Marghera well field. By comparison, subsidences for Long Beach, CA and Mexico are 7 to 8 m. Predictive simulations with a calibrated mathematical model were hampered by the sparseness of available data. As a first estimate, the predictions suggest that if withdrawals are kept as constant in the future as they have been since 1969, about 3 cm of further subsidence can be expected. 2 Fig., 7 Ref.

DESCRIPTORS: Italy; ground subsidence; ground motion; forecasting;
PROPOSED DESCRIPTORS: Subsidence effects; Venice; overdraft;

Environmental/Subsidence
Geertsma 73

TITLE: **Land Subsidence Above Compacting Oil and Gas Reservoirs**

REFERENCE: J. Pet. Tech., v.25, p.734-744 (1973)

AUTHOR: Geertsma, J. (Koninklijke/Shell Exploratie en Produktie Lab., Rijswijk, Netherlands)

ABSTRACT: The paper presents factual information on the mechanism of land subsidence above producing oil and gas reservoirs and on its quantitative prediction. Available experimental uniaxial-compaction-coefficient data are presented schematically. This compaction coefficient can be used with conventional reservoir data to predict total reservoir compaction. A simple procedure gives a good estimate of subsidence as a function of reservoir compaction and the ratio between depth of burial and the lateral extent of the reservoir. Except for some large or shallow reservoirs, subsidence is only a fraction of reservoir compaction. 30 refs. (Eng. Index 1973).

DESCRIPTORS: Ground subsidence; forecasting;
PROPOSED DESCRIPTORS: Reservoir compaction;

Environmental/Subsidence
Glover 74

TITLE: **Letter to the Geothermal Co-ordinator, Department of Scientific and Industrial Research, Jan. 4, 1974**

REFERENCE: In Physics and Engineering Lab. Report No. 445 (Dec. 1974)

AUTHOR: Glover, R.B. (Department of Scientific and Industrial Research, Taupo, New Zealand, Chemistry Div.)

ABSTRACT: Vertical subsidence data were analyzed for the 1967-71 period. The following

were concluded: (1) The average ratio of subsidence volume to fluid draw-off volume was 0.0076; (2) There is a time-log of about 4 months between changes in draw-off rate and in subsidence rate; (3) The average ratio of subsidence volume to fluid draw-off volume at Broadlands geothermal area may be somewhat higher than Wairakei.

DESCRIPTORS: New Zealand; Wairakei geothermal field; environmental effects; ground motion, ground subsidence;

Environmental/Subsidence
Goldsmith 71

TITLE: **Geothermal Resources in California--Potentials and Problems**

REFERENCE: EQL Report No. 5, 45 pages (Dec. 1971)

AUTHOR. Goldsmith, M. (Calif. Inst. Tech., Pasadena, CA, Environmental Quality Lab.)

ABSTRACT: Subsidence is included among the environmental effects that may occur on exploitation of geothermal energy.

DESCRIPTORS: California; Imperial Valley; ground motion; land use; waste water; seismic effects; air pollution; thermal pollution; blowouts; environmental effects; economics.

Environmental/Subsidence
Gringarten 75

TITLE: **The Effect of Reinjection on the Temperature of a Geothermal Reservoir Used for Urban Heating**

REFERENCE: Abstracts, Second U.N. Symp. on Dev. and Use of Geothermal Resources, San Francisco, CA, IV-8 (May 20-29, 1975)

AUTHOR: Gringarten, A.C. and Sauty, J.P. (Bureau de recherches géologiques et minières, B.P. 6009, 45018, Orleans Cedex, France)

ABSTRACT: Aquifers at about 2 km depths are being used for space heating in some normal geothermal gradient regions in France. Disposal of the heat-depleted water to sewage lines is unattractive because of mineral contents, temperature, or the volumes involved. One approach is reinjecting the water back into the aquifer. This may have advantage in maintaining the reservoir pressure, preventing subsidence and insuring an indefinite supply of water. However, it also creates a zone of injected water around each injection well at a different temperature from that of the reservoir water. These zones will grow with time and will eventually reach the production wells. After breakthrough occurs, the water temperature is no longer constant at the production wells, and this may reduce drastically the efficiency of the whole operation. A mathematical model is presented for investigating the unsteady state temperature behavior of production wells during the reinjection of heat-depleted water into aquifers with uniform regional flow. Results are presented in terms of dimensionless parameters and are used to maximize heat recovery. Application to practical cases are included.

DESCRIPTORS: France; space heating; reinjection.

Environmental/Subsidence
Hatton 70

TITLE: **Ground Subsidence of a Geothermal Field During Exploitation**

REFERENCE: Geothermics, Special Issue, v.2, n.2, p.1294-1296 (1970)

AUTHOR: Hatton, J.W. (Ministry of Works, Wairakei, New Zealand)

ABSTRACT: A comparison of benchmarks in 1956 with the original 1950 levels gave the first indication of subsidence. One benchmark, A97, had subsided 7.6 cm (0.25 ft) since 1950. Data obtained from a network of benchmarks indicated about 65 sq km (25 sq mi) was affected by subsidence between 1956 and 1966. Two areas of relatively large subsidence were: one apparently centered around benchmark A97; the other at Karapiti approximately 3.2 km (2 mi) south of Wairakei. The area of maximum subsidence occurs outside the production field. The maximum subsidence rate was about 0.4 m per year (1.3 ft). Horizontal surface strain estimated at up to 0.001 per year caused a change in the distance between the pipe anchors of an expansion loop in the steam mains. This was compensated by removing and adding short lenths of steam pipe. Horizontal ground strain caused compression failure of concrete in a drainage channel. 3 Fig.

DESCRIPTORS: New Zealand; Wairakei geothermal field; environmental effects; ground motion; ground subsidence; Broadlands geothermal field;
PROPOSED DESCRIPTORS: Differential subsidences; horizontal surface strain; aquifer pressure;

Environmental/Subsidence
Helm 75

TITLE: **One-Dimensional Simulation of Aquifer System Compaction Near Pixley, California. I. Constant Parameters**

REFERENCE: Water Resour. Res., v.11, n.3, p.465-478 (1975)

AUTHOR: Helm, D.C. [Geological Survey, Sacramento, CA (USA)]

ABSTRACT: The nonrecoverable component of aquifer system compaction occurs almost entirely in fine-grained deposits, so that the role of aquitards in the mechanics of aquifer systems is of critical importance. A key to the problem of predicting subsidence is the correct evaluation of aquitard parameters, including the following: (1) vertical hydraulic conductivity, (2) specific storage, (3) thickness of fine-grained beds, and (4) applied stress values. The author utilizes a computer program with two sets of constant coefficients to calculate the daily deformation due to observed changes in applied stress near Pixley, California. Although water levels fluctuate annually, no long-term water level decline occurred near Pixley between January 1, 1959, and February 4, 1971. During this period, 3.19 ft (0.972 m) of compaction was observed. The net difference between simulated and observed compaction on February 4, 1971, was 1.3% of the observed value. Maximum deviation occurred in mid-1964 and equaled 7% of the observed compaction. 8 Fig., 4 Tables, 20 Ref.

DESCRIPTORS: California; ground motion; ground subsidence; forecasting; mathematical model.
PROPOSED DESCRIPTORS: Pixley; San Joaquin Valley; soil compaction; aquitard deformation.

Environmental/Subsidence
Hot Line 71

TITLE: **Imperial Valley Subsidence Detection Program**

REFERENCE: Geothermal Hot Line, v.1, n.7 (Oct. 20, 1971)

ABSTRACT: The program will be under way with the start of surveying on first- and second-order nets about Nov. 1, 1971. The following is a list of both participants and nets responsibility: (1) National Geodetic Survey (130 ± miles, first order); (2) County of Imperial (70± miles, second order). (3) Imperial Irrigation District (70± miles, second order); (4) Bureau of Reclamation (70± miles, second order).

DESCRIPTORS: California; Imperial Valley; ground subsidences;
PROPOSED DESCRIPTORS: Surveys;

Environmental/Subsidence
Hot Line 72

TITLE: **Recent Publications, Bureau of Reclamation**

REFERENCE: Geothermal Hot Line, v.2, n.2, (March 1972)

AVAILABILITY: Government Printing Office, Superintendent of Documents, Washington, DC 20402.

ABSTRACT: The Bureau of Reclamation's project in the Imperial Valley is discussed, including the following topics: subsidence, seismology, water potential, power potential, environmental, and waste water disposal.

DESCRIPTORS: California; Imperial Valley; Bureau of Reclamation; ground motion; seismology; environmental effects.

Environmental/Subsidence
Hot Line 72b

TITLE: **The Geysers Geothermal Field**

REFERENCE: Geothermal Hot Line, v.2, n.5, p.4 (September 1972)

ABSTRACT: The U.S. Geological Survey initiated a program to monitor possible ground movement in The Geysers area. Three types of control surveys were scheduled for the 1973 fiscal year: (1) A regional network of a dozen or so benchmarks on mountain peaks and ridge tops, extending 10 to 20 miles out from The Geysers; the horizontal distance between these benchmarks to be precisely surveyed biannually by geodolite (accuracy about 2 x $10^7$); (2) A local network of several dozen benchmarks throughout the geothermal production area, precisely tied twice a year to reference benchmarks of the regional network by electronic distance meter (accuracy about 2 x $10^5$); and, (3) A line of levels to first-order accuracies by the National Geodetic Survey, establishing accurate elevations for reference benchmarks in The Geysers area. The regional network, (1) above, will be established by the Survey's Office of Crustal Studies during October 1972. The local network (2), from which both horizontal and vertical changes will be monitored, will be established by the USGS Subsidence Research Office later in 1972. The level network (3), looped through the production area and tied to existing second and third-order level lines outside the production area, is scheduled for spring 1973. Precise surveys by the Pacific Gas and Electric Co. have been run throughout the area. Where pertinent, these are being incorporated in the Survey's monitoring control network.

DESCRIPTORS: California; The Geysers; ground motion; ground subsidence;
PROPOSED DESCRIPTORS: Surveys;

Environmental/Subsidence
Hot Line 73

TITLE: **Survey Net – The Geysers Area**

REFERENCE: Geothermal Hot Line, v.3, n.4, p.2 (July 1973)

ABSTRACT: The National Geodetic Survey completed a 72 km (45 mi) first-order survey for leveling control from Lower Lake in Lake County westerly, along Hwy 29, to its intersection with Hwy 175; thence southeasterly, along Hwy 175, to its intersection with Socrates Mine Road; thence westerly to the Lake-Sonoma County line; thence northwesterly, along the county line (ridgeline of the Mayacmas Mountains) to a point north of The Geysers Geothermal Field; thence southerly, through the field, to Big Sulphur Creek; thence southeasterly, along Big Sulphur Creek, to a tie-in point near the southwest corner of Sec. 33, T. 11 N., R. 8 W., M.D.B. and M. Benchmarks were set at each power plant cooling tower in The Geysers Field. The portion of this line from Lower Lake to the Socrates Mine is re-survey of an old second-order survey.

AVAILABILITY: Unadjusted Field Data and Descriptions of New Benchmarks: U.S. Geological Survey, 2800 Cottage Way, Sacramento, CA 95825

DESCRIPTORS: California; The Geysers; ground motion; ground subsidence;

PROPOSED DESCRIPTORS: Leveling control; surveys; National Geodetic Survey;

Environmental/Subsidence
Hot Line 73b

TITLE: **Imperial Valley-Survey Net**

REFERENCE: Geothermal Hot Line, v.3, n.5, p.3 (Oct. 1973)

ABSTRACT: The Geothermal Unit of the California Division of Oil and Gas is acting as lead agency in a cooperative effort to resurvey the first- and second-order subsidence detection net originally surveyed in the winter of 1971-1972. Work on the project should begin about October 15, 1973. Land surveys in the Imperial Valley are done during the winter months because heat waves generated by temperatures as high as 50°C during the summer cause surveying errors. The purpose of the resurvey is to compile background data for monitoring tectonic movements and possible subsidence in the various geothermal areas before wells are placed on production. Each geothermal well must be tied into the net before it can be produced.

DESCRIPTORS: California; Imperial Valley; ground motion; ground subsidence;
PROPOSED DESCRIPTORS: Surveys; background data;

Environmental/Subsidence
Hot Line 74

TITLE: **Imperial County, California Subsidence Detection Survey**

REFERENCE: Geothermal Hot Line, v.4, n.2, p.1 (April 1974)

ABSTRACT: The second first- and second-order subsidence detection survey in the Imperial Valley will be completed in April 1974. The first general survey was conducted in the winter of 1971-1972; the second during the winter of 1973-1974. The Imperial Valley is a tectonically active area where natural subsidence and uplift are occurring continuously. Most of the valley is flat-lying, fertile plain with an extensive, elaborate irrigation system; subsidence could cause serious problems and lead to legal difficulties. The background data now being gained by the first- and second-order surveys will alow determinations on the extent of subsidence caused by both the production of geothermal fluids and that due to other causes.

DESCRIPTORS: California; Imperial Valley; ground motion; ground subsidence; tectonics;
PROPOSED DESCRIPTORS: Surveys; natural subsidence;

Environmental/Subsidences
Hunt 70

TITLE: **Gravity Changes at Wairakei Geothermal Field, New Zealand**

REFERENCE: Geol. Soc. Amer. Bull, v.81, p.529-536 (1970)

AUTHOR: Hunt, T.M. (Dept. of Scientific and Industrial Research, Wellington, New Zealand, Geophysics Div.)

DESCRIPTORS: New Zealand; Waraikei geothermal field; aquifers; gravity surveys; mass transfer.

Environmental/Subsidence
Hunt 70b

TITLE: **Net Mass Loss from the Wairakei Geothermal Field, New Zealand**

REFERENCE: Geothermics Special Issue, v.2, n.2, p.487-491 (1970)

AUTHOR: Hunt, T.M. (Dept. of Scientifc and Industrial Research, Wellington, New Zealand, Geophyics Div.)

ABSTRACT: A method of monitoring the net mass loss from a geothermal field under exploitation using a gravimeter is described. Measurements of the value of gravity at 50 benchmarks at Wairakei geothermal field, New Zealand, show that differences of up to 0.5 mgal have occurred between 1961 and 1967, and up to 0.1 mgal between 1967 and 1968. These differences, corrected for known changes in elevation, reflect the net mass of water lost from the aquifer. Extensive ground subsidence in the area was revealed by repeated relevelling of benchmarks and drew attention to the consequence of this substantial mass loss. The net loss between 1961 and 1967 is determined as being about 2.9 x $10^4$ g and hence only about 20% of the water drawn off was replaced, but between 1967 and 1968 there was little or no net loss. The gravity method can also give an indication of the area from which the water has been drawn.

DESCRIPTORS: New Zealand; Wairakei geothermal field; environmental effects; ground subsidence.

Environmental/Subsidence
Johnson 70

TITLE: **Relationship of Consolidation Characteristics and Atterberg Limits for Subsiding Sediments in Central California**

REFERENCE: In: Proceedings of the Tokyo Symposium on Land Subsidence, Vol. 2, International Association of Scientific Hydrology and UNESCO, September 1969, Tokyo, p.579-587, 1970. Available: UNIPUB, Box 33, New York, NY 10016. Price $26.50.

AUTHOR: Johnson, A.I. and Moston, R.P. [Geol. Surv., Denver, CO (USA), Water Resources Div.]

ABSTRACT: As one phase of research on land subsidence, laboratory analyses were made on many undistrubed cores obtained from sediments in subsiding areas of central California. In 1948 Terzahi and Peck had presented equations relating compression index or coefficient of consolidation to liquid limit, but present research indicates that the same relationships do not hold for any of the sediments tested from central California. The compression index could be estimated from liquid-limit data, but the relationship was different for each area of subsidence. Comparison of compression indices obtained from consolidation curves with indices computed from liquid limits showed better correlation for sediments of alluvial and lacustrine origin than for sediments of marine origin. Equations for the relationships were otained by computer solution of data trends. In all three areas of subsidence, the coefficient of consolidation showed a general decrease for increasing values of liquid limit. However, the relationship could not be estimated with reasonable accuracy because the coefficient for any particular load range could vary through more than one order of magnitude for any given liquid limit. (KNAPP-USGS, WRA). 5 Fig., 1 Tab., 13 Ref.

DESCRIPTORS: California; consolidation; liquid limit.

Environmental/Subsidence
Kubota 75

TITLE: **Reinjection of Geothermal Hot Water at the Otake Geothermal Field**

REFERENCE: Abstracts, Second U.N. Symp. on Dev. and Use of Geothermal Resurces, IV-7 (May 20-29, 1975)

AUTHOR: Kubota, K. and Aosaki, K. (Kyushu Electric Power Co., Inc., 491-1, Aizo, Shiobaru, Minami-ku, Fukuoka, 815 Japan)

ABSTRACT: Since March 1972, 8 million tons of hot water have been reinjected by three injection wells. The injections were located at the following distances from the No. 8 production well: (1) 500 m, (2) 150 m, (3) about halfway between the first two wells. No effects on groundwater and hot springs have yet been observed; earthquakes due to reinjection were not observed. There was an increase in steam discharge from production wells.

DESCRIPTORS: Japan; Otake geothermal field; reinjection.

Environmental/Subsidence
Lofgren 73

TITLE: **Monitoring Ground Movement in Geothermal Areas**

REFERENCE: Proc. Hydraulic Div. Specialty Conf., Bozeman, MT, Aug. 15-17, 1973

AUTHOR: Lofgren, B.E. [Geological Survey, Sacramento, CA (USA), Water Resources Division]

ABSTRACT: Horizontal and vertical survey nets in The Geysers and the Imperial Valley are

being monitored for possible ground movement and subsidence. The following are five types of ground movement that might occur in a producing geothermal area (1) subsidence or rebound of the land surface, due to fluid-pressure changes; (2) lateral ground movement, due to induced fluid gradients; (3) vertical ground movement, due to thermal expansion or compaction of the rocks; (4) tectonic faulting or folding; and, (5) landslides and mass wasting. Little or no land-surface change is expected at The Geysers as geothermal steam production continues; however, landslides and tectonism are active. Subsidence, horizontal ground movement, and serious encroachment on the ground-water regime are definite hazards in Imperial Valley, unless adequate precautions are taken. An objective of the program is to differentiate natural processes from changes caused by geothermal developments. 4 Fig., 5 Ref.

DESCRIPTORS: Ground motion; monitoring; ground subsidence; California, The Geysers; Imperial Valley; tectonics;
PROPOSED DESCRIPTORS: Natural subsidence; background data; surveys.

Environmental/Subsidence
Lofgren 74

TITLE: **Subsidence and Related Aspects of Geothermal Systems**

REFERENCE: Smithsonian Science Information Exchange, Inc., SIE No. ZUA-3030-1

AUTHOR: Lofgren, B.E. [Geological Survey, Sacrmaneto, CA (USA), Water Resources Division]

ABSTRACT: The objective of the project is a comprehensive study of geothermal subsidence. Included are the following effects of subsidence: vertical and horizontal displacements, land-surface changes, fluid injections, induced subsurface pressure gradients, and formation temperature changes. The problem is to differentiate displacements and changes caused by geothermal development from those related to tectonic and near-surface effects; to analyze and interpret pertinent hydrologic, geodetic, geophysical, and geologic data as a background for this investigation, and attempt to relate geothermal changes to the regional geology; obtain stress-strain parameters of the geothermal system. The study will be coordinated with other agencies to establish networks of benchmarks in areas where geothermal fluids are being extracted and reinjected.

DESCRIPTORS: Ground motion; monitoring; tectonics; California; The Geysers; Imperial Valley; Salton Sea.
PROPOSED DESCRIPTORS: Studies; stress-strain parameters;

Environmental/Subsidence
Lofgren 74b

TITLE: **Measuring Ground Movement in Geothermal Areas of Imperial Valley, California**

REFERENCE: Proc. Conf. on Research for the Dev. of Geothermal Energy Resources, Pasadena, CA, Sept. 23-25, 1974 (Dec. 31, 1974), p.128-133

AUTHOR: Lofgren, B.E. [Geological Survey, Sacramento, CA (USA), Water Resources Division]

ABSTRACT: Regional and local survey nets are being monitored in the Imperial Valley both to detect and to measure possible ground movement caused by future geothermal developments. Land subsidence caused by withdrawal of water, oil, and gas affects about 25,900 sq km (10,000 sq mi) of intensely developed land in 5 states of the U.S. Maximum subsidence is 9 m (29 ft) in the San Joaquin Valley and Long Beach areas in CA., 4 m (13 ft) in the Santa Clara Valley, CA, and in excess of 2.4 m (8 ft) in the outskirts of Houston, TX. Horizontal ground movement exceeds 3.7 m (12 ft) in the Wilmington oil field, Long Beach, CA. Horizontal ground shifting on the margins of heavily pumped basins, principally in Arizona, caused extensive fissures and cracks. At Wairakei geothermal field, subsidence affects an area of over 65 sq km (25 sq mi); the maximum subsidence rate is 0.4 m (1.3 ft) per year, and the total subsidence exceeds 3 m (10 ft). During the two-year interval 1971-1972 to 1973-1974, the following information on vertical subsidence was recorded, with reference to the bedrock tie west of El Centro: (1) little or no change for benchmarks near Calexico and the bedrock tie east of El Centro; (2) El Centro subsided roughly 1.5 cm (0.6 in); (3) a general northward tilt of about 13 cm (5 in) was measured in the 85 km (53 miles) from south to north in the valley. Late data suggest 5 mm/year (0.02 in) of right lateral horizontal tectonic movement in the Obsidian Buttes area southwest of Niland. A principal challenge of this project is to differentiate ground movement caused by geothermal extractions from changes due to other geological processes.

DESCRIPTORS: California; Imperial Valley; monitoring; ground motion; ground subsidence; tectonics; Niland geothermal field;
PROPOSED DESCRIPTORS: Horizontal components; vertical componnnts; background data;

Environmental/Subsidence
McCauley 75

TITLE: **Land Subsidence: An Economic Analysis**

REFERENCE: Water Resour. Bull, v.11, n.1, p.148-154 (1975)

AUTHOR: McCauley, C. (Tucson Gas and Electric Co., Tucson, AZ) and Gum, R. (Arizona University, Tucson, AZ, Dept. of Hydrology and Water Resources)

ABSTRACT: The paper reports results on the economic significance of land subsidence in the area covering the western half of Pinal County, AZ. This area depends principally on groundwater to meet its agricultural needs. During the period 1940 to 1967, over 16 million acre-feet of water were withdrawn. Land subsidence was detected initially in 1948; it had subsided about 0.1 ft since 1905. From 1947 to 1967, more than 7.5 ft of subsidence was recorded; the rate is about 0.11 ft/year. Environmental effects included the following: (1) surface cracking; (2) reduction in aquifer storage capacity caused by compaction; (3) general sinking. Subsidence is less than 2% of water cost, and is of little or no economic significance.

DESCRIPTORS: Arizona; Pinal County; land subsidence; ground water; agriculture;
PROPOSED DESCRIPTORS: Economics;

Environmental/Subsidence
Narasimhan 75

TITLE: **Development of a Numerical Model for Land Subsidence in Geothermal Systems**

REFERENCE: Abstracts, Second U.N. Conf. on Dev. and Use of Geothermal Resources, San Francisco, CA (May 20-29, 1975), IV-10

AUTHOR: Narasimhan, T.N. and Witherspoon, P.A. (California Univ., Berkeley, Lawrence Berkeley Lab.)

ABSTRACT: Subsidence can be artifically induced by significantly lowering the pore-water pressures over a large area within a subsurface formation. The lowered pressure results in a reduced bulk volume of rock skeletons caused by an increase in the effective stress. A numerical model was developed which solves the fluid-heat flow equations in general three dimensions, but uses the one-dimensional consolidation theory for stress-stain relationships. This numerical approach was applied to subsidence.

DESCRIPTORS: Ground motion; numerical solution; ground subsidence;
PROPOSED DESCRIPTORS: Pore-water pressures; bulk volume; model; stress-strain parameters;

Environmental/Subsidences
Poland 69

TITLE: **Land Subsidence Due to Withdrawal of Fluids**

REFERENCE: In Reviews in Engineering Geology, Varnes, D.J., and Kiersch, G. (eds.), Geol. Soc. Am., Boulder, CO., p.187-269, v.II (1969)

AUTHOR: Poland, J.F. [Geological Survey, Sacramento, CA (USA)] and Davis, G.H. [Geological Survey, Washington, DC (USA)]

ABSTRACT: Land-surface subsidence due to the withdrawal of fluids by man has become relatively common in the United States since 1940 and has been described at several other places throughout the world. This paper reviews the known examples of appreciable land subsidence caused by fluid withdrawal. Those related to exploitation of oil and gas fields include Goose Creek, Texas; Wilmington, California; Lake Maracaibo, Venezuela; Niigata, Japan; and the Po Delta in Italy. The areas of major subsidence related to ground-water withdrawal include areas in Japan; Mexico City, Mexico; and Texas, Arizona, Nevada, and California. The areas of greatest extent and maximum subsidence are in California. The principles involved in the compaction of sediments and of aquifer systems, basically the increase in effective stress, are examined briefly,

together with their application to subsidence problems involving head decline both under water table and confined conditions. The amount of compaction that a confined aquifer system will experience is a function of compressibility. Other factors that influence compaction (and, in part, compressibility) include particle size and shape, clay mineralogy, geochemistry of pore water in the clayey beds and of the water in contiguous aquifers, and secondary compression. Land subsidence has caused great damage in some areas. At several of these places, subsidence problems are being alleviated in one or more of several ways; these include (1) cessation of withdrawal and (2) increase or restoration of reservoir pressure by reduction in production rate, artificial recharge, or repressuring by injection of water. The greatest subsidence control measures are being taken at Wilmington, California, where subsidence that had reached 27 feet at the center now is nearly stopped; in addition, significant rebound has occurred. (Author) 49 Fig., 7 Photos, 2 Tables, cver 100 Ref.

DESCRIPTORS: Ground subsidence; ground motion; groundwater;
PROPOSED DESCRIPTORS: Fluid withdrawal; overdraft; control;

Environmental/Subsidence
Poland 72

TITLE: **Land Subsidence in the Western States Due to Groundwater Overdraft**

REFERENCE: Water Res. Bull, v.8, n.1, p.118-131 (1972)

AUTHOR: Poland, J.F. [Geological Survey, Sacramento, CA (USA)]

ABSTRACT: Pumping draft has exceeded water replenishment in many areas of the western states. Water drawn from 100 to 500 ft levels resulted in increased grain-to-grain stress or effective overburden load on the aquifer systems. This causes compaction of the deposits with a land subsidence as the surface expression. The magnitude of the subsidence generally depends on: (1) thickness and compressibility of the deposits which experienced the stress increase; (2) magnitude of stress increase; and, (3) the length of time of increased stress. Subsidence is discussed for the following major areas: Houston-Galveston, TX; South-Central Arizona; Las Vegas, NV; San Joaquin Valley, CA; Santa Clara Valley, CA. Subsidence may be stopped or alleviated by reduction of withdrawal, increase of recharge, or both of these. 11 Fig., 11 Ref.

DESCRIPTORS: Ground subsidence; ground motion; ground water; California; Texas; Arizona; Nevada.
PROPOSED DESCRIPTORS: Overdraft; abatement; control.

Environmental/Subsidence
Poland 72b

TITLE: **Subsidence and Its Control**

REFERENCE: In Underground Waste Management and Environmental Implications, Memoir, n.18, p.50-71

AUTHOR: Poland, J.F. [Geological Survey, Sacramento, CA (USA)]

ABSTRACT: The effects and controls of subsidence caused by ground water overdraft, and subsidence of oil and gas fields are discussed for the United States, Japan, Italy, Mexico, Taiwan, and Venezuela. The subsidences due to overdraft range from 1 ft (0.3 m) at Baton Rouge, Louisiana, to 28 ft (8 m) in western Fresno County in the San Joaquin Valley, California, and Mexico City, Mexico. The San Joaquin Valley also is the largest known area of subsidence -- 4,200 sq mi (10,875 sq km) has subsided more than 1 ft (0.3 m). The Houston-Galveston area in Texas is the second largest known area of subsidence. Planimetering of the map of subsidence, 1943-64, indicates that about 1,500 sq mi (3,885 sq km) of the Texas Gulf Coast subsided 1 ft (0.3 m) or more and 2,600 sq mi (6,735 sq km) subsided at least 0.5 ft (15 cm) in this 21-year period. The Texas subsidence also was due to artesian-head decline, which, from 1890 to 1961, was as much as 250 ft (75 m) in Houston and 300 ft (90 m) in Galena Park. Local agencies have been working since the 1930's on obtaining water supplies adequate to stop the overdraft of groundwater and raise the artesian head. In California, water imports from the Central Valley through the state's South Bay aqueduct first became available in 1965. Water imports to Santa Clara County increased fourfold from 1964-65 to 1969-70 from 30,000 to 124,000 acre-ft per year. As a result of these imports, above-average local surface-water supply, increased artificial recharge, and decreased pumping, the recovery of water level since 1966 has been dramatic. The average artesian head (based on measurements in more than 100 wells) rose about 57 ft (17 m) from the spring high level of 1967 to 1970; at well 7R1 the rise in the 3 years was 59 ft (18 m). The 1971 spring high-water level at 7R1 was 71 ft (22 m) above that of 1967, and about equal to the level in this well in 1930. Subsidence due to oil and gas is also discussed. 20 Fig., 2 Tables, 51 Ref.

DESCRIPTORS: California; ground motion; environmental effects; Texas; forecasting; montmorillonite; illite; dolomite;
PROPOSED DESCRIPTORS: Subsidence control; overdraft; soil compaction; clastic sediments; compacting clay minerals;

Environmental/Subsidence
Poland 73

TITLE: **Subsidence in United States Due to Ground-Water Overdraft - A Review**

REFERENCE: Proc. Irrigation and Drainage Div. Specialty Conf., Ft. Collins, CO, Am. Soc. Civil Eng., Aug 22-24, 1973

AUTHOR: Poland, J.F. (Geological Survey, Sacramento, CA 95825)

ABSTRACT: The 67% increase in population of the United States since 1930 has greatly accelerated the demand for water. Ground-water pumpage doubled from 1950 to 1970. In many areas, overpumping has drawn down water levels 30 m to as much as 183 m (100-600 ft). Where these declines have occurred in unconsolidated aquifer systems containing many fine grained compressible interbeds, the increase in effective stress has caused extensive land-surface subsidence. Significant subsidence due to water-level decline occurs in five States: Louisiana, Texas, Arizona, Nevada, and California. Subsidence is greatest , 9 m (29 ft), and most extensive 13,470 km² (5,200 mi²), in the San Joaquin Valley, but is at least 4 m (13 ft) in San Jose, 2.4 m (8 ft) near Houston, and 2.3m (7.5 ft) southeast of Phoenix. Principal problems caused by the subsidence are (1) changes of elevation and gradient of natural drainages and water-transport structures, (2) failure of water wells from compressive rupture of casings, due to the compaction, and (3) tidal encroachment in lowland coastal areas. Large imports of surface water to several subsiding areas in California have greatly reduced ground-water pumpage, resulting in dramatic recoveries of artesian head that have slowed or nearly stopped the subsidence. (Author). 15 Fig., 31 Ref.

DESCRIPTORS: Ground subsidence; Arizona; California; Louisiana; Nevada; Texas; ground water; environmental effects;
PROPOSED DESCRIPTORS: Overdraft; environmental problems;

Environmental/Subsidence
Prokopovich 73

TITLE: **Engineering Geology and the Central Valley Project**

REFERENCE: J. Am. Water Works Assoc., v.65, p.186-194 (1973)

AUTHOR: Prokopovich, N.P. (U.S. Dept. of the Interior, Bureau of Reclamation, Sacramento, CA)

ABSTRACT: The California Central Valley Project consists of over 15 dams, several hydropower plants, high-voltage transmission lines, pumping plants, canals, tunnels, and associated features. Land subsidence is one of the problems encountered in the project: it is related to overdraft of confined waters in the San Joaquin Valley. Over the last 50-70 years, irrigation pumpage has caused the piezometric head of the main aquifer in the area to decline locally more than 500 ft. This has caused compaction of subsurface sediments; the surface expression of the compaction is land subsidence which locally has exceeded 25 ft. Because of the subsidence, several bridges, concrete lining, pipe crossings, and other structures became partially or competely submerged. Two references are given to attempts at estimating future subsidence along the San Luis Canal. 9 Fig., 39 Ref.

DESCRIPTORS: California; Central Valley; ground subsidence; environmental effects; irrigation; groundwater.
PROPOSED DESCRIPTORS: Engineering geology; overdraft; land subsidence.

Environmental/Subsidence
Riviere 63

TITLE: **Possible Orogenesis Factor**

REFERENCE: Acad. Sci. Compt. Rend., v.256, n.20, p.4263-4264 (1963)

AUTHOR: Riviere, A.

ABSTRACT: The ejection of solid, liquid, or gaseous matter during volcanic or hydrothermal processes results in a decrease in volume of the earth's interior which, in turn, causes crustal deformation as a result of the action of gravity. (WKS-13004)

DESCRIPTORS: Volcanic regions; hydrothermal systems; ground subsidece; gravitation; volume; deformation;

Environmental/Subsidence
Smith 67

TITLE: **Exploitation of Geothermal Water**

REFERENCE: Proc. Water for Peace Conf. (Superintendent of Documents, U.S. Government Printing Office, Washington DC), v.3, p.1 (1967)

AUTHOR: Smith, J.H.

Environmental/Subsidence
State: CA-OR 74

TITLE: **Proceedings, Workshop on Environmental Aspects of Geothermal Resources Development**

REFERENCE: State of California, Dept. of Conservation, Div. of Oil and Gas; State of Oregon, Dept. of Geol. and Mineral Industries. National Science Foundation, Research Applied to National Needs.

AUTHOR: Anderson, D.N. (State of California, Div. of Oil and Gas) and Bowen, R.G. (State of Oregon, Dept. of Geol. and Mineral Industries). Co-chairmen.

Environmental/Subsidence
Stilwell 75

TITLE: **Ground Movement in New Zealand Geothermal Fields**

REFERENCE: Abstracts, Second U.N. Conf. on Dev. and Use of Geothermal Resources, San Francisco, CA, May 20-29, 1975, IV-15 (April 1975)

AUTHOR: Stilwell, W.B., Hall, W.K., and Tawhai, J. (Ministry of Works and Development, Taupo, New Zealand)

ABSTRACT: Both ground subsidence and horizontal movement have been observed following

almost 20 years of exploitation at Wairakei. Recent work indicated movement of local control points towards the area of greatest subsidence; this movement points out the difficulty of selecting basic control points. A comprehensive and reliable level network and survey control should be established early for new geothermal fields. The Broadlands field shows a subsidence pattern after 5 years of exploitation. Careful monitoring is needed for the Kawerau field, which is currently being assessed, and which is partly used to supply steam to a pulp and paper mill.

DESCRIPTORS: Ground motion; New Zealand; Wairakei geothermal field; monitoring; ground subsidence; Broadlands geothermal field; Kawerau geothermal field.

Environmental/Subsidence
Tison 70

TITLE: **Land Subsidence**

REFERENCE: Proceedings, Tokyo Symposium, Vol. I and Vol. 2, International Assoc. of Scientific Hydrology and UNESCO, Pubs. 88 and 89, Tison, L.J., ed. Available from UNIPUB, Box 433, New York, NY 10016. Price $26.50.

Environmental/Subsidence
Voight 70

TITLE: **State of Predictive Art in Subsidence Engineering**

REFERENCE: Proc. Am. Soc. Civ. Eng., v.96, p.721-750 (Mar. 1970)

AUTHOR: Voight, B. and Pariseau, W.

Environmental/Subsidence
White 74

TITLE: **Water and Power from Geothermal Resources in California. An Overview**

REFERENCE: Bulletin 190, State of California, The Resources Agency, Department of Water Resources (Dec. 1974)

AUTHOR: White, C.R. and Yates, P.J.

ABSTRACT: The report includes the following aspects of geothermal resources: origin, types, history of development, power production in 1973 and 1974, exploration, problems in exploitation covering technical, environmental, legal, institutional, ownership, regulatory and jurisdictional, and marketing aspects. The degree of subsidence depends on various factors including: (1) geological structure of the underground reservoir, (2) nature of the sediments containing the fluids, (3) the change in pressure within the sediments that occur as fluid is withdrawn and is injected. Injection of water to replace withdrawn fluid

can minimize subsidence in oil fields (e.g., Wilmington Oil Field, Los Angeles and Long Beach, CA).

DESCRIPTORS: Ground motion; power generation; environmental effects; injection wells; exploration; laws;
PROPOSED DESCRIPTORS: Fluids reinjection;

Environmental/Subsidence
Whiting 74

TITLE: **Possible Effects of Geothermal Water and Steam Production on the Subsurface Environment**

REFERENCE: AIChE Symp. Ser. 70, n.136, p.762-771 (1974)

AUTHOR: Whiting, R.L. (Dept. Pet. Eng., Texas A and M Univ., College Station, TX)

DESCRIPTORS: Environmental effects.

Aosaki, K. (See Kubota 75).

Axtmann 74; An Environmental Study of the Wairakei Power Plant.

*Bailey 73; Post-Subsidence Volcanism and Structure of Long Valley Caldera, California.

Bolton 73; Management of a Geothermal Field.

Bonnet, L.W. (See Gabrysch 74)

BOR 71; Geothermal Resources Investigations, Imperial Valley, CA, Status Report.

Bowen 73; Environmental Impact of Geothermal Development.

Browne 74; Subsidence Rate of Broadlands from Radiocarbon Dates.

*Bull 73; Geologic Factors Affecting Compaction of Deposits in a Land-Subsidence Area.

Chasteen 74; Geothermal Steam Condensate Reinjection.

Christian 74; Subsidence of Venice: Predictive Difficulties.

Cuellar, G. (See Einarsson 75).

DOI 73; Promulgation of Leasing and Operative Regulations.

Duncan 73; Earth Pressure on Structures Due to Fault Movement.

Dutcher 72; Preliminary Appraisal of Ground Water in Storage with Reference to Geothermal Resources in the Imperial Valley Area.

Einarsson 75; Disposal of Geothermal Waste Water by Reinjection.

Freeze, R.A. (See Gambolati 74).

Gabrysch 74; Land-Surface Subsidence in the Area of Barnett, Scott, and Crystal Bays Near Baytown, Texas.

Gambolati 74; Predictive Simulation of the Subsidence of Venice.

Gatto, P. (See Gambolati 74).

Geertsma 73; Land Subsidence Above Compacting Oil and Gas Reservoirs.

Glover 74; Letter to the Geothermal Co-ordinator, Department of Scientific and Industrial Research, Jan 4, 1974.

Goldsmith 71; Geothermal Resources in California -- Potentials and Problems.

Gringarten 75; The Effect of Reinjection on the Temperature of a Geothermal Reservoir Used for Urban Heating.

Hardt, W.F. (See Dutcher 72)

Hatton 70; Ground Subsidence of a Geothermal Field During Exploitation.

Helm 75; One-Dimensional Simulation of Aquifer Compaction Near Pixley, California. I. Constant Parameters.

Hirschfeld, R.C. (See Christian 74).

Hot Line 71; Imperial Valley Subsidence Detection Program.

Hot Line 72; Recent Publications, Bureau of Reclamation.

Hot Line 72b; The Geysers Geothermal Field.

Hot Line 73; Survey Net - The Geysers Area.

Hot Line 73b; Imperial Valley - Survey Net.

Hot Line 74; Imperial County, California Subsidence Detection Survey.

*Hunt 70; Gravity Changes at Wairakei Geothermal Field, New Zealand.

Hunt 70b; Net Mass Loss from the Wairakei Geothermal Field, New Zealand.

Johnson 70; Relationship of Consolidation Characteristics and Atterberg Limits for Subsiding Sediments in Central California.

Kubota 75; Reinjection of Geothermal Hot Water at the Otake Geothermal Field.

Lefebyre, G. (See Duncan 73)

Lofgren 73; Monitoring Ground Movement in Geothermal Areas: Hydraulic Engineering and the Environment.

Lofgren 74; Subsidence and Related Aspects of Geothermal Systems.

Lofgren 74B; Monitoring Ground Movement in Geothermal Areas at Imperial Valley, California.

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