RECEIVED BY TIC MAR 0 6 1980

Presented at the Fifth Workshop, Geothermal Reservoir Engineering, Stanford University, December 12-14, 1979

LBL-10299

CONF-791235--1

MASTER

A PRELIMINARY SIMULATION OF LAND SUBSIDENCE AT THE WAIRAKEI GEOTHERMAL FIELD IN NEW ZEALAND

T. N. Narasimhan and K. P. Goyal

December 1979

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LBL-10299

A Preliminary Simulation of Land Subsidence At the Wairakei Geothermal Field in New Zealand

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

T. N. Narasimhan and K.P. Goyal

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California,
Berkeley, California 94720

Several types of geothermal systems exist in nature but only hydrothermal convective systems are being exploited at the present time because of their proximity to the earth's surface and their amenability to utilization. Among the geothermal systems discovered to date, hot water systems are perhaps twenty times as common as vapor dominated systems (Muffler and White, 1972). Since the energy contents of liquid water is relatively less than that of pure steam, comparatively large volumes of geothermal liquids have to be produced for economic heat extraction. Such large scale production of geothermal fluids should generally be expected to cause significant reductions in pore fluid pressures leading to appreciable rock deformations and displacement at or near the ground surface. This phenomenon has already been observed over the Wairakei and Broadlands geothermal fields of New Zealand (Stilwell, et al., 1975 and Otway 1976). Since ground displacements may affect engineering structures related or unrelated to the operation of the geothermal field, it is important to be able to predict the pattern and magnitude of the deformations that may result from fluid production so that appropriate ameliorative actions could be taken in advance.

There are two fundamental processes which determine land displacements due to fluid withdrawal from underground systems. The first is the deformation of the reservoir (defined as the region which releases fluid from storage to compensate for the fluid being withdrawn; e.g., aquifers and aquitards) due to internally generated stresses resulting from changes in pore fluid pressures induced by fluid withdrawal. The second is the propagation of the deformation through the overburden to the ground surface. Overburden is defined as the region which does not release fluid from storage to compensate for the fluid withdrawn. It includes all material intervening between the top of the reservoir system and the land surface. The exact boundary between the reservoir and the overburden may be time dependent and difficult to define, yet from a computational standpoint this ambiguity in its location may not be too critical.

A most general approach to modeling land subsidence due to fluid withdrawal is to treat the entire region including the reservoir and the overburden as the total system. Within this system the fluid flow equation and the stress-deformation equation would be simultaneously solved with appropriate coupling between them. The stress-deformation will, in general, be three dimensional, with material properties being elastic or non-elastic in nature. In regard to geothermal subsidence, in as much as very limited field data is currently available, the aforesaid generalized approach appears to be too sophisticated and elaborate to justify the efforts involved in their implementation. Under the circumstances, alternative simplified approaches appear desirable.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

One such simplified approach is to (a) decouple the reservoir and the overburden and (b) to consider only vertical deformation in the reservoir. In this context, the reservoir is taken to include the highly permeable zones as well as the less permeable but relatively more compressible zones which hold significant quantities of fluid in available storage. In contrast to this, the overburden is the zone which deforms without fluid release in response to deformation of the reservoir. The decoupling concept tacitly assumes that the overburden deformation does not induce any appreciable stress changes in the reservoir. The one dimensional consolidation assumption will be especially realistic in those systems in which the highly permeable, producing layers of the reservoir are more rigid than the less permeable fine grained layers which primarily conduct water in the vertical direction to the producing layers.

Results presented in this paper pertain solely to reservoir deformation according to the one-dimensional consolidation theory. It is assumed that the vertical displacements obtained at the interface of the reservoir and overburden are completely transmitted to the ground surface. The reservoir simulator, which combines a three dimensional flow field with one dimensional deformation is discussed elsewhere by Narasimhan and Witherspoon (1976). The purpose of the present study has been to make a preliminary study of the ground subsidence observed over the geothermal field at Wairakei, New Zealand and to find whether the field observations can be reasonably explained in terms of the well known geotechnical principles of consolidation. As the study is preliminary in nature, the geothermal system has been treated as an isothermal, liquid system.

The geology of the Wairakei field has been discussed by Grindley (1965), Healy (1965) and Grange (1937); reservoir engineering data has been compiled by Pritchett et al. (1978). The total subsidence observed at Wairakei is shown in Figure 1. It can be noted that the subsidence bowl is offset from the main production area. This subsidence pattern is possible if the Huka Falls formation (a relatively more compressible layer) is thicker in that region or alternatively the compressibility of the formation in the highly subsided zone is greater than in other areas. In our idealized model, we are using the first approach with a reasonable compressiblity value of the Huka Falls formation. A plot of reservoir pressure drop versus subsidence at benchmark A97 (Figure 1) is shown in Figure 2. It can be noted that the drop in the reservoir pressure is linearly proportional to subsidence during early production times. However, in later periods, reservoir pressure seems to stabilize while subsidence continues. Such a behavior could be explained if one assumes that the deforming material passes from a state of preconsolidation to one of normal consolidation. Our preliminary model, then, studies the effect of heterogeneity and plasticity on the subsidence phenonemon.

For purposes of simulation we can idealize the system as consisting of the Waiora aquifer and the overlying Huka Falls (mudstone) aquitard. A Pumice overburden extends from the top of the Huka Falls to the ground surface. This idealized model is shown in Figure 3. The thickness of the overburden (holocene Pumice and Wairakei Breccia) is assumed to be 200 meters (Table 5.1, p. 30, Pritchett et al. 1978). The depth of the reservoir, including Huka Falls formation, is assumed to be 400 meters.

The maximum thickness of the Huka Falls formation is assumed to be 200 meters near the zone of maximum subsidence (Figure 5.21, p. 52, Pritchett et al. 1978). The reservoir is divided into six layers. The lowest layer which is 200 meters thick carries 100-level nodes. (By 100-level nodes we mean that the nodes in this layer are identified by numbers ranging from 100 - 199.) The other five layers, each 40 meters thick, lie over this layer and carry 200-300-400-500- and 600-level nodes. Figure 4 shows the numbers assigned to the 100-level nodes. In this three digit system, first digit represents the level while the number of node is represented by the other two. Thus the node 618 lies in the 600-level layer and is vertically above the nodes 118, 218, 318, 418 and 518. In horizontal plane its shape is exactly same as that of the node 118 (Figure 4). The sides AB and AC are each extended to 19.2 km and 27.15 km respectively with large size nodes to represent far away zones from the production area.

To model subsidence, we have used an idealized graded thickness of the Huka Falls formation of 40 m, 80m, 120 m, 160 m, and 200 meters (Figure 4). The maximum thickness of 200 meters over the nodes 138, 145 and 146 corresponds to the area of maximum subsidence (Figure 1). Node 107 is modeled as a production zone, indicative of the area of maximum discharge in Figure 1. To offset the subsidence bowl from the main production area, the thickness of the overburden is increased to 360 meters over the nodes 207 to 216. Rest of the volume elements represent the Wairora formation. Impermeable boundary conditions are imposed on the sides AB and AC. An initial potential of 600 meters of water is specified everywhere in the system. Material properties used in the model are follows:

<u>Huka Falls Formation</u>

Pemeability = 10^{-14} m^2 (Mercer et al. 1975)
Coefficient of compressibility for virgin curve
(a_v) = $5x10^{-8}$ m^2/N
Coefficient of compressibility for swelling curve
(a_{vs}) = $5x10^{-9}$ m^2/N

<u>Waiora Formation</u>

Permeability = 8.5×10^{-14} m^2
Coefficient of compressibility for virgin as well as swelling curve ($a_v = a_{vs}$) = 10^{-10} m^2/N
Relative density of the saturated soil = 2.

This model also assumes that the soil is preconsolidated. The preconsolidation pressure over and above hydrostatic pressure is about 225 meters of water. The properties used for the liquid are:

Viscosity = 0.2 centipoise,
Density = 940 kg/m^3,
Compressibility = 4.9×10^{-10}, m^2/N.

Total mass production for the Wairakei/Tauhara system as of December 31, 1976 was 2329×10^9 lbs (Pritchett, et al. 1978). This amounts to an average volumetric production rate of about 1.48 m^3/sec. Since our trianglular model (Figure 4) considers only one-eighth of the total area, the production rate is correspondingly reduced to about .185 m^3/sec. It

can be noted that this rate applies to both Wairakei and Tauhara fields. To consider only the area of maximum discharge (Figure 1), this amount should somewhat be reduced. In this study we have considered an average production rate of .1 m^3/sec. This amount is produced from the node 107 at the depth of 500 meters.

Subsidence produced under aforementioned conditions is shown in Figure 5. A comparison with Figure 1 shows that the results are qualitatively similar. Measured and calculated reservoir pressure drop vs. subsidence at the bench mark A97 and node 142 are shown in Figure 6. A qualitatively similar pattern is seen for the preconsolidated soil. This figure also shows the behavior of the normally consolidated soil which is quite different to that of the preconsolidated soil.

In summary, we developed and tested a preliminary model to explain subsidence in the Wairakei field and obtained results which are qualitatively similar to those measured at the site. The effect of preconsolidation stresses seems to be important to explain the changing slope of the reservoir pressure-subsidence relationship shown in Figure 2.

Acknowledgements

This work was supported by the Division of Geothermal Energy of the U.S. Department of Energy under contract No. W-7405-ENG-48.

References

Grange, L.I, The Geology of the Rotorua-Taupo Subdivision, Rotorua and Kaimanawa Divisions, DSIR Bulletin 37, 1937.

Grindley, G.W., The Geology, Structure, Exploitation of the Wairakei Field, Taupo, New Zealand, N.Z. Geol. Surv. Bull. 75, 131, 1965.

Healy, J., Geology of the Wairakei Geothermal Field, Proceedings, Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand, New Zealand Section, 1965.

Mercer, J.W., G.F. Pinder and I.G. Donaldson, A Galerkin-Finite Element Analysis of the Hydrothermal System at Wairakei, New Zealand. Journal of Geophysical Research, vol. 80, no. 17, pp. 2608-2621, 1975.

Muffler, L.J.P. and D.E. White, Geothermal Energy, The Science Teacher, vol. 39, No. 3, pp. 40-43, 1972.

Narasimhan, T.N. and P.A. Witherspoon, An Integrated Finite Difference Method for Analyzing Fluid Flow in Porous Media, Water Resources Res., vol. 12, p. 57, 1976.

Otway, P.M., Report on Results on Precise and Tilt Leveling. Broadlands Reinjection Project, 1968-1976. International Conference on the Geothermal Reservoir held at Wairakei, New Zealand, Aug. 29 - Sept. 3, 1976.

Pritchett, J.W., L.F. Rice and S.K. Garg, Reservoir Engineering Data: Wairakei Geothermal Field, New Zealand, vol. 1, SSS-R-78-3597-1, Systems, Science and Software, La Jolla, California, 1978.

Pritchett, J.W., S.K. Garg, D.H. Brownell, Numerical Simulation of Production and Subsidence at Wairakei, New Zealand, Report SGP-TR-20, Stanford Geothermal Program, Stanford, California, pp. 310-323, Dec. 1976.

Stilwell, W.B., W.K. Hall and J. Tawhai, Ground Movements in New Zealand Geothermal Fields, Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, vol. 2, pp. 1427-1434, May 1975.

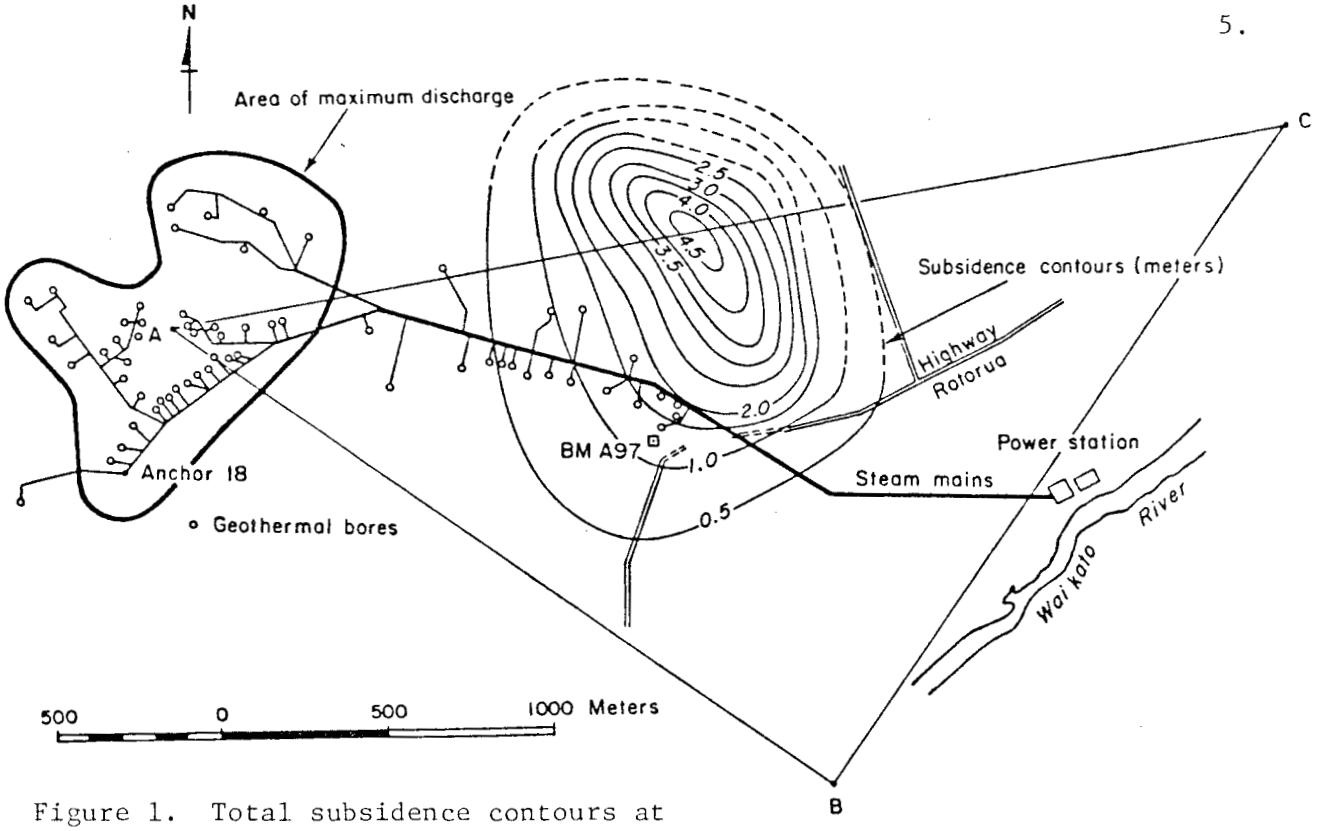
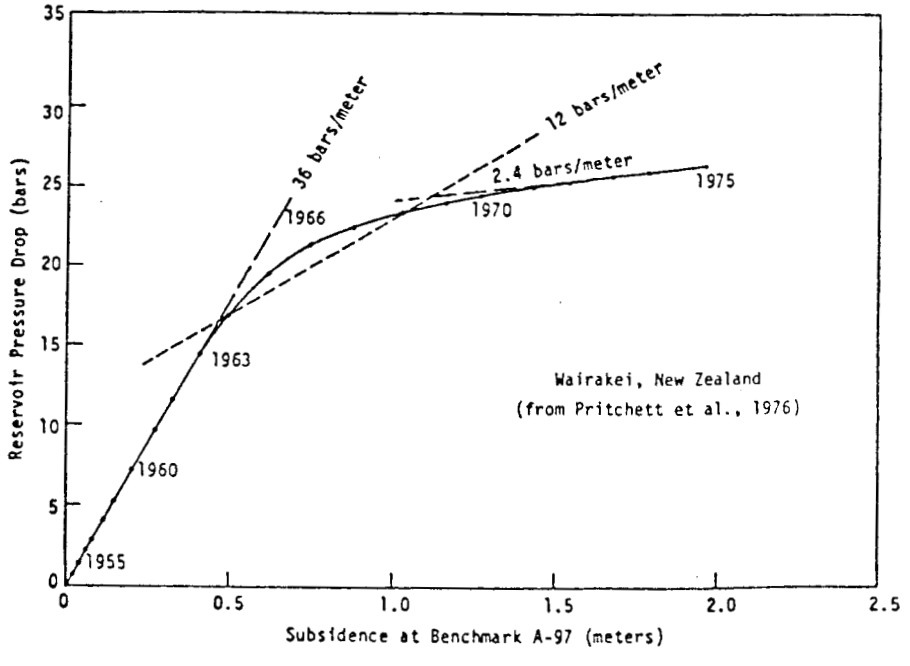


Figure 1. Total subsidence contours at Wairakei and the area of investigation ABC. (From Stilwell et al 1975)

XBL7911-13203



XBL 7738173

Figure 2. Reservoir pressure drop versus subsidence observed at the Wairakei geothermal field, New Zealand.

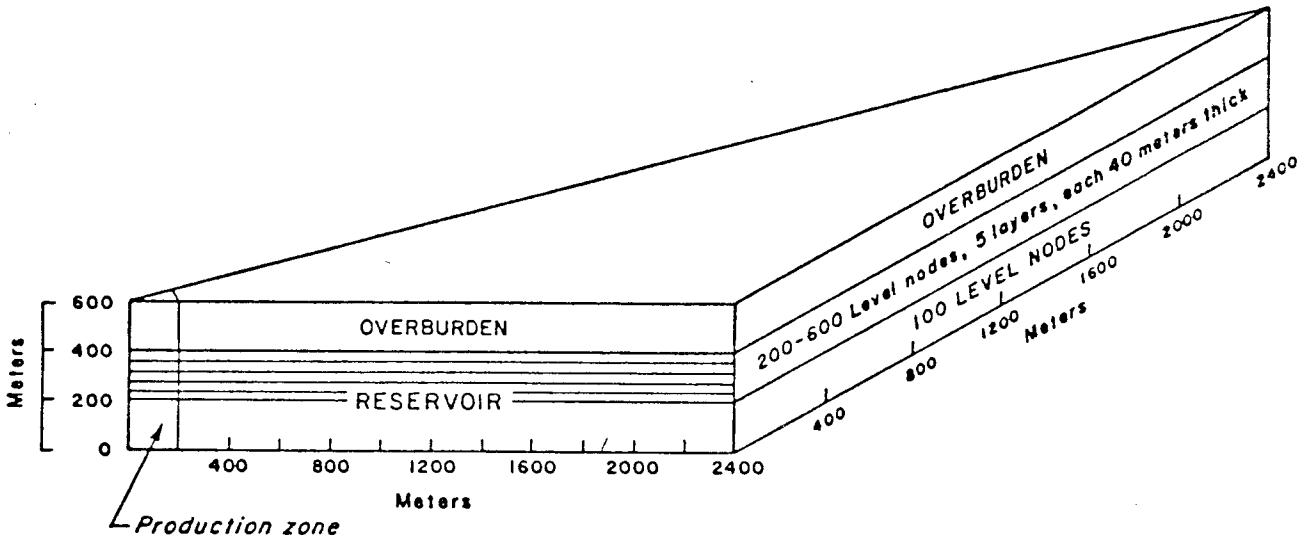
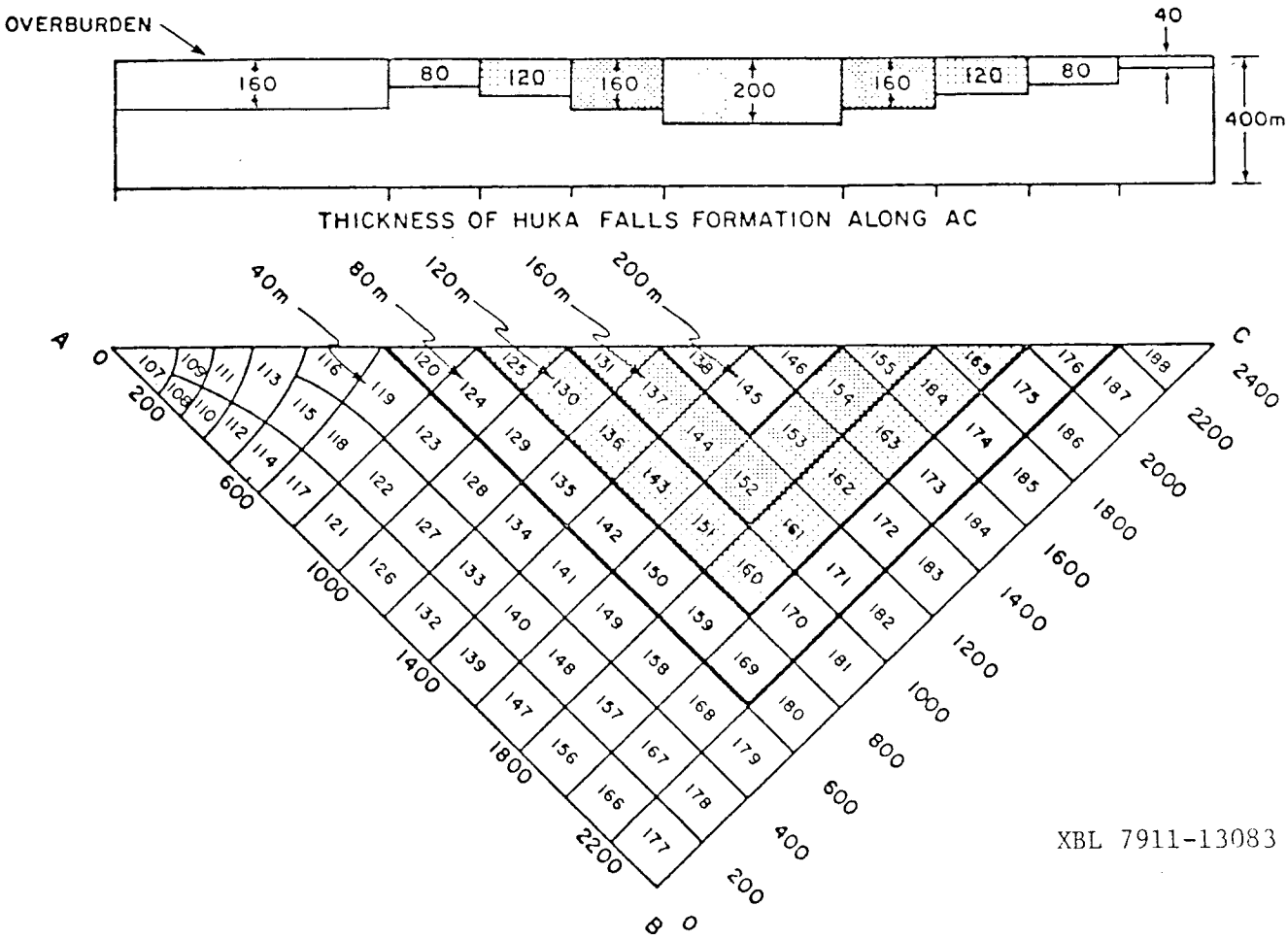


Figure 3. An idealized three-dimensional subsidence model of the Wairakei geothermal system.

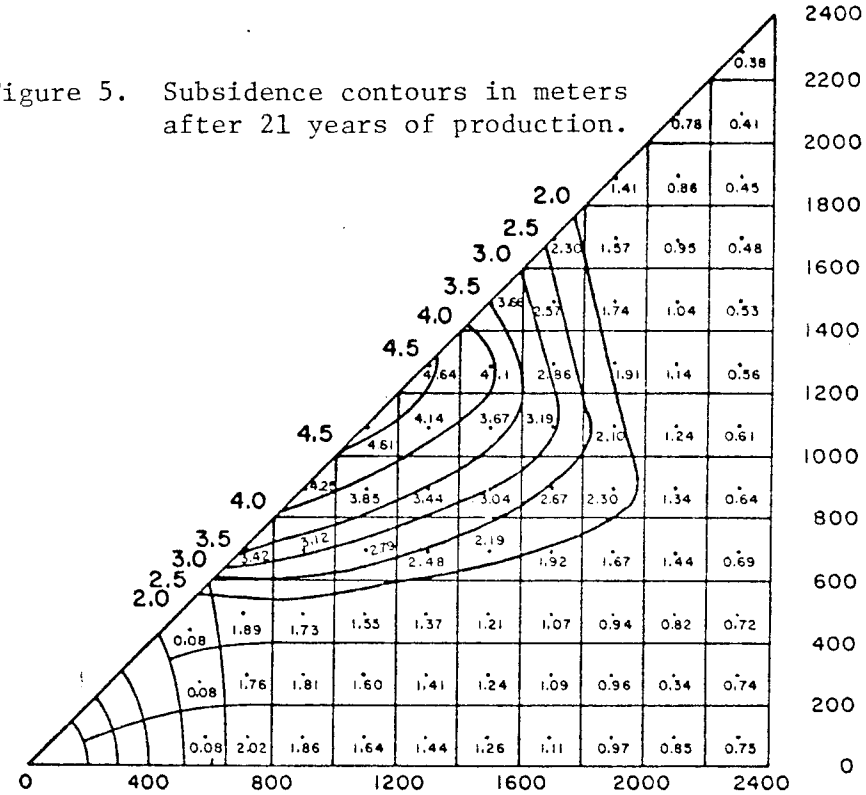
XBL 7911-13085



XBL 7911-13083

Figure 4. The thicknesses of the Huka Falls formation and the node numbers used in the model.

Figure 5. Subsidence contours in meters after 21 years of production.



XBL 7911-13091

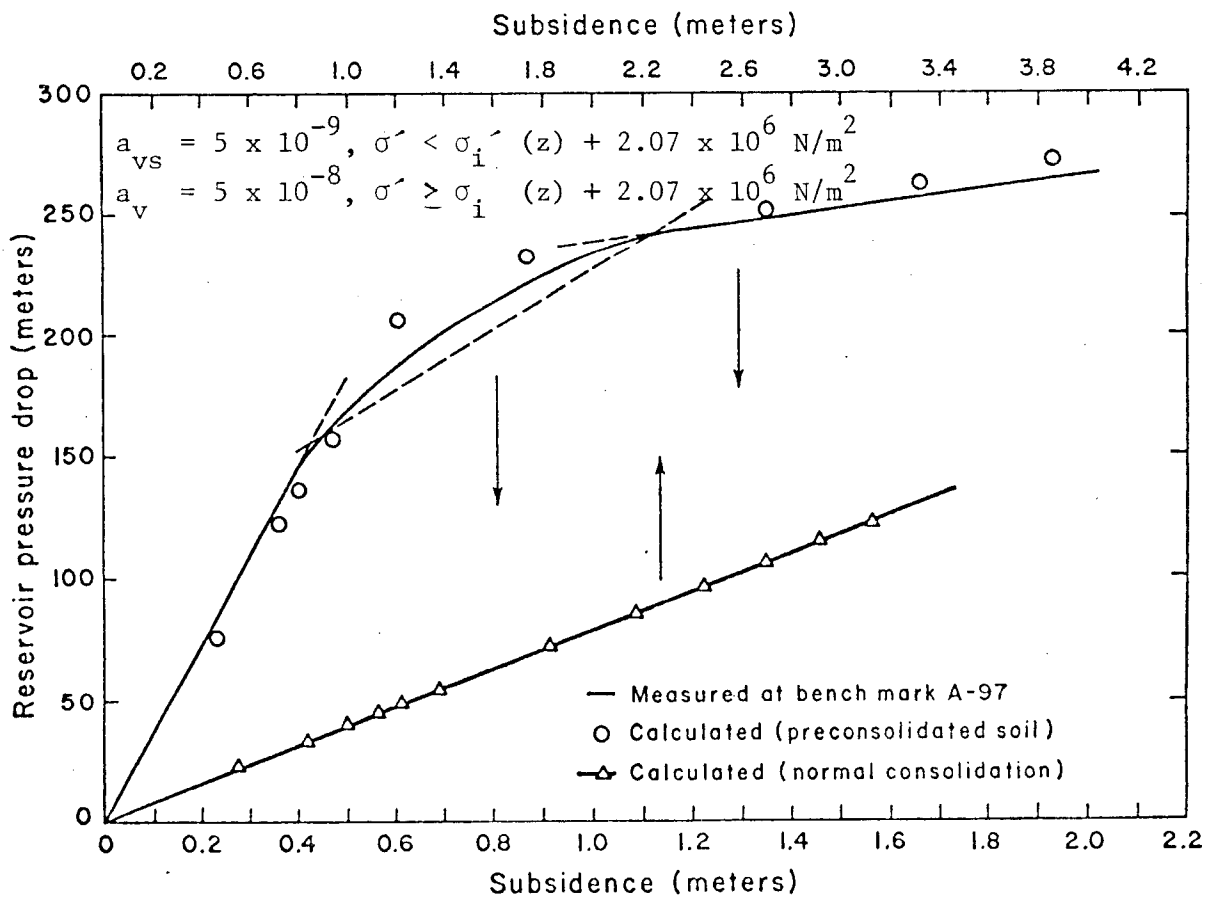


Figure 6. A comparison of the measured subsidence with that calculated at the node 142.

XBL 7911-13408

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720