SGP-TR-20-42

PROCEEDINGS
SECOND WORKSHOP
GEOTHERMAL RESERVOIR ENGINEERING
December 1-3, 1976

Paul Kruger and Henry J. Ramey, Jr., Editors
Stanford Geothermal Program
Workshop Report SGP-TR-20*

*Conducted under Grant No. NSF-AER-72-03490 supported by the RANN program of the National Science Foundation and Contract No. E043-326-PA-50 from the Geothermal Energy Division, Energy Research and Development Administration.

DISCLAIMER

DISCLAIMER

NUMERICAL SIMULATION OF PRODUCTION AND SUBSIDENCE AT WAIRAKEI, NEW ZEALAND

John W. Pritchett, Sabodh K. Garg, D. H. Brownell
Systems, Science and Software
P. O. Box 1620, La Jolla, California 92038

A numerical simulation of the fluid production history at the Wairakei field has been performed in a two-dimensional vertical plane which passes through the principal features of the reservoir. A successful history match, in terms of the pressure decline in the system, was obtained. Details of that simulation have been reported elsewhere (Garg, et al., 1976) but the results are summarized herein for clarity.

As is well known, substantial land surface subsidence has accompanied production at Wairakei. Both the location of the region of maximum subsidence and the character of the deformation are somewhat anomalous, in that the greatest subsidence occurred outside the production area and substantial evidence exists for non-linear rock behavior during production. The reasons for this peculiar behavior are discussed, and speculations are presented concerning the adequacy of existing subsidence-prediction techniques.

Simulation of Wairakei Production History

The Wairakei geothermal system is located north of Lake Taupo and west of the Waikato River (Figure 1); it occupies a surface area of approximately 15 km^2 (Grindley, 1965), and extends westward from the river approximately 5 km. In order to simulate the behavior of the field, we consider a two-dimensional vertical cross-section (line AB in Figure 1) which extends through the main production area and the region of large surface subsidence. The geologic stratification, as determined from wellbore logs (Grindley, 1965; Grange, 1955) is shown in Figure 2. The numerical grid is shown in Figure 3. Most of the fluid production comes from the Waiora formation (see Figure 3). The Waiora formation dips steeply in the east (Figure 2); the exact depth is, however, unknown and, therefore, the indicated depth in Figure 2 may be in substantial error. To the west, the Waiora formation is cut by the much less permeable rhyolites. There are indications that the reservoir extends beyond A in the west (Bolton, 1970); for purposes of the present study this is, however, not very important. The reservoir is assumed to be 3 km thick (in the direction transverse to AB); this yields a surface area of 15 km^2 for the reservoir. The rock properites (permeability, porosity, density, specific heat, thermal conductivity, etc.) are determined from the available field data (c.f., Mercer, et al., 1975) and studies of core samples performed for S^3 by Terra Tek.

The field behavior was simulated from 1953 through 1967 since the subsidence is well documented (for 1967), and the data readily accessible through 1967. Figure 4 shows a comparison of calculated pressure-drop history for the production area with the data. In general the agreement is extremely good. Borehole 36 is of special interest insofar as it lies toward the eastern end of the field; observed pressure drops in borehole 36 are generally lower than those observed elsewhere in the field. This suggests that the Waiora formation in the east has a lower pearmeability than that in the rest of the geothermal field (c.f., Mercer, et al., 1975). The computed pressures for borehole 36 are also in good agreement with the data (see Figure 4).

The behavior of the Wairakei field, under exploitation, is primarily governed by the saturation temperature-pressure relation for water (Bolton, 1970). The upper portions of the reservoir start flashing soon after the production commences (see Figure 5a.); this helps to maintain the reservoir pressures in the early years (Figures 4, 6a). The two-phase boiling region keeps on growing with continued production; in the years 1959-1960, the two-phase flow begins to invade the production horizon (Figure 5b). Field pressures now (1959-1960) begin to drop rapidly (see Figures 4 and 6b) due to the relative permeability effect in two-phase flow. Eventually (around 1964) the entire production region starts to boil (see Figure 5c); this marks the onset of the relative flattening of the pressure drop curve (Figure 4). The above discussion illustrates the dominating influence exercised by boiling on the reservoir pressure response; as a matter of fact, all the important stages (initial flat portion, middle large pressure drop region, and final relatively flat part, Figure 4) in the reservoir pressure history can be traced to boiling in one or another part of the reservoir.

Subsidence at Wairakei

Ground subsidence at Wairakei was first measured in 1956 when benchmark levels were compared with those established in 1950; periodic measurements have indicated that the area affected by subsidence probably exceeds 25 square miles (Hatton, 1970). The area of maximum subsidence (subsidence $\geq$ 0.5 m), however, lies outside the main production region. Cross-section AB (Figures 1-3) passes through the large subsidence region; the intersection of the subsidence region with AB is indicated in Figure 3. The maximum subsidence region, in the shape of an elliptical bowl, overlies the thicker part of Waiora formation (Figure 3). Maximum subsidence at Wairakei (1964-1974) is of the order of 4.5 m; this has been accompanied by horizontal movements of the order of 0.5 m (Stillwell, et al., 1975; see Figure 7).

Pressure profiles (Figures 6a-c) show that the region of largest pressure drop lies directly below the maximum subsidence area; furthermore, the region of large pressure drop to the west of the subsidence region (i.e., in the thinner part of Waiora) is relatively small. This strongly suggests that the subsidence pattern observed at Wairakei is the combined result of the local geology and the fluid production history.

Laboratory measurements have been performed upon core samples from Wairakei by Terra Tek (see Pritchett, et al., 1976). These measurements yielded, among other quantities, the bulk (K) and shear (μ) elastic moduli of the various strata. If the laboratory measurements are taken as correct for the thin surface layers overlying the reservoir (pumice/breccia and Huka Falls formation), we may determine the effective elastic moduli of the Waiora formation through knowledge of (1) the pressure drop history, (2) the measured subsidence history, and (3) the thickness of the Waiora layer. During the interval 1964-1967, reservoir pressures in the Waiora dropped at a rate of 1.77 bars/year, and the mean subsidence rate in that layer was 0.36 m/year. Using a Waiora thickness of 950 meters, we obtain:

$$(K + \frac{4}{3}\mu)_{Waiora} = 4.67 \text{ kilobars.}$$

This value is smaller by a factor of nine than that based upon the small-sample laboratory tests discussed above. This large discrepancy implies that either the Waiora formation in the region of maximum subsidence is much thicker than that assumed in the present simulation or that the Waiora formation is intensely fractured. In view of our analysis of the Wairakei production data and also of available geologic data, we lean towards the second of these explanations.

So far it has been assumed that the rock matrix responds to changes in pore pressure as if it were a linear-elastic material (constant elastic moduli K, μ). There exists substantial evidence which suggests that this assumption is rather poor. Figure 7 (from Stillwell, et al., 1975) is a map of the Wairakei field showing both the areas of principal production and of principal subsidence. Within the subsidence area and somewhat to the south of the center of the region is "Benchmark A-97". Stillwell, et al., (1975) presented both detailed subsidence histories for Benchmark A-97 and measured pressure drop histories at the -150 m (M.S.L.) level in the reservoir. Stillwell's data may be cross-plotted as shown in Figure 8, which illustrates the reservoir pressure drop as a function of the downward movement of Benchmark A-97. The "dots" denote time - 1 January of the year indicated in each case. This plot strongly suggests that nonlinear ground movement processes are operating at Wairakei. At early times, the slope of this (psuedo) stress-strain curve is 36 bars/meter of subsidence - at present, the slope is 2.4 bars/meter, lower by a factor of 15.

On the basis of the subsidence data taken over the interval 1 January 1964 - 1 January 1968, and treating the various formations to be homogeneous and linear elastic, we obtained a mean value of $(K + 4\mu/3)_{Waiora} \approx 4.67$ kb, above. If we make the assumption that the general trend throughout the area of surface subsidence is qualitatively similar to the behavior shown in Figure 8, we can make more definite statements about the behavior of the reservoir rocks. Over the time interval 1964-1967, Figure 8 shows that the average slope of the pressure drop-subsidence curve at Benchmark A-97 was 12 bars/meter: a factor of three lower than the initial slope but a factor of five greater than the current slope. This suggests that, at early times (1953),

$$(K + 4\mu/3)_{\text{Waiora}} \approx 14 \text{ kilobars}$$

and that, at late times (1975),

$$(K + 4\mu/3)_{\text{Waiora}} \approx 0.9 \text{ kilobars.}$$

It is comforting to note that the value of 14 kilobars at early times is substantially closer to the laboratory value than the value of 4.67 kb for the period 1964-1967 - it is low by only a factor of three. The difficulty is, of course, to account for the spectacular decrease in apparent elastic moduli with time.

The apparent increase in rock compressibility at Wairakei with time is typical of many reservoirs (for a case study of an oil/gas reservoir see Merle, et al., 1976). A nonlinearity in the mechanical response of the rock may be ascribed to (1) structural failure at late times and/or (2) decrease in bulk modulus with an increase in $\Delta(P_c-P_f)$. Here, P_c is the total (or "confining") pressure and P_f is the pore pressure. Initially, the reservoir rock behaves in a linear-elastic manner with $K + 4\mu/3 \approx 14$ kbars. From the Benchmark A-97 data, we know that this model is probably adequate up to about 1963. At about that time, however, failure must have begun. Hence, it should be possible to estimate, based upon elastically-calculated 1963 shear stresses, the yield strength of the rock. Rock which has yielded should thereafter be assigned an effective incremental shear modulus of zero. The elastically-calculated 1963 response would also enable us to estimate the threshold value of $\Delta(P_c-P_f)$ at which the bulk modulus K starts to decrease with increasing $\Delta(P_c-P_f)$. The functional dependence of K on $\Delta(P_c-P_f)$ would be, of course, determined by history-matching (see also Merle, et al., 1976 in this connection).

The foregoing discussion illustrates the difficulties associated with matching (and predicting for the future) the subsidence history at Wairakei. It is also worthwhile to point out the implications of our analysis of the Wairakei subsidence data for predicting subsidence in a virgin geothermal field. If for example we attempt to predict subsidence in the Salton Sea field due to some specified production/injection strategy, we would necessarily have to use elastic moduli based on measurements of the early-state moduli (derived from seismic measurements, for instance). If, however, in reality the effective moduli were to decline by a factor on the order of 15 during production as they did at Wairakei, we would thereby drastically underestimate the subsidence hazard. Clearly, it would be desirable to determine the appropriate long-term nonlinear stress-strain relations prior to making such theoretical predictions.

At this time it is not clear how these material parameters can be measured. Neither laboratory tests on small core samples nor pre-production seismic measurements are likely to be of much help. It may be possible to obtain some guidance from the analysis of geological, subsidence, and production data for geothermal and oil/gas reservoirs with well documented production and subsidence histories. Such an analysis may help in identifying the mechanisms which cause the nonlinear behavior. Some examples of such mechanisms are:

1. Geological history of the field.
2. Dewatering of interspersed shales.
3. Thermal effects on the mechanical properties of the rock.
4. Chemical dissolution of intergranular cementing minerals by fresh water recharge.
5. Mechanical scouring and weakening of the matrix by fluid motion.

An understanding of these mechanisms, to the extent necessary to assess their relative magnitudes, appears to be required before devising experimental procedures for characterizing rock response and making subsidence predictions at a virgin geothermal field.

REFERENCES

Bolton, R. S., 1970, The behavior of the Wairakei geothermal field during exploitation, Geothermics, Special Issue 2, pp. 1426-1439.

Garg, S. K., J. W. Pritchett, L. F. Rice and D. H. Brownell, Jr., Study of the geothermal production and subsidence history of the Wairakei Field, Proc. 17th U.S. Symposium on Rock Mechanics, Snowbird, Utah, pp. 3B3-1-3B3-5.

Grange, L. I., 1955, Geothermal steam for power in New Zealand, New Zealand DSIR, Bulletin No. 117.

Grindley, G. W., 1965, The geology, structure, and exploitation of the Wairakei geothermal field, Taupo, New Zealand, New Zealand Geological Survey, Bulletin No. 75.

Hatton, J. W., 1970, Ground subsidence of a geothermal field during production, Geothermics, Special Issue 2, pp. 1294-1296.

Mercer, J. W., G. F. Pinder, and I. G. Donaldson, 1975, A Galerkin-finite element analysis of the hydrothermal system at Wairakei, New Zealand, Journal of Geophysical Research, 80, pp. 2608-2621.

Merle, H. A., J. P. Kentie, C. H. C. Van Opstal and G. M. E. Schneider, 1976, The Backaquero study - a composite analysis of the behavior of a compaction drive/solution drive gas reservoir, J. Petroleum Technology, pp. 1107-1115.

Pritchett, J. W., S. K. Garg, D. H. Brownell, Jr., L. F. Rice, M. H. Rice, T. D. Riney and R. R. Hendrickson, 1976, Geohydrological environmental effects of geothermal power production - Phase IIA, Systems, Science and Software Report SSS-R-77-2998, La Jolla, California.

Stillwell, W. B., W. K. Hall and J. Tawhai, 1975, Ground movement in New Zealand geothermal fields, Proc. 2nd U. N. Symp. on the Development and Use of Geothermal Resources, San Francisco, California, pp. 1427-1434.

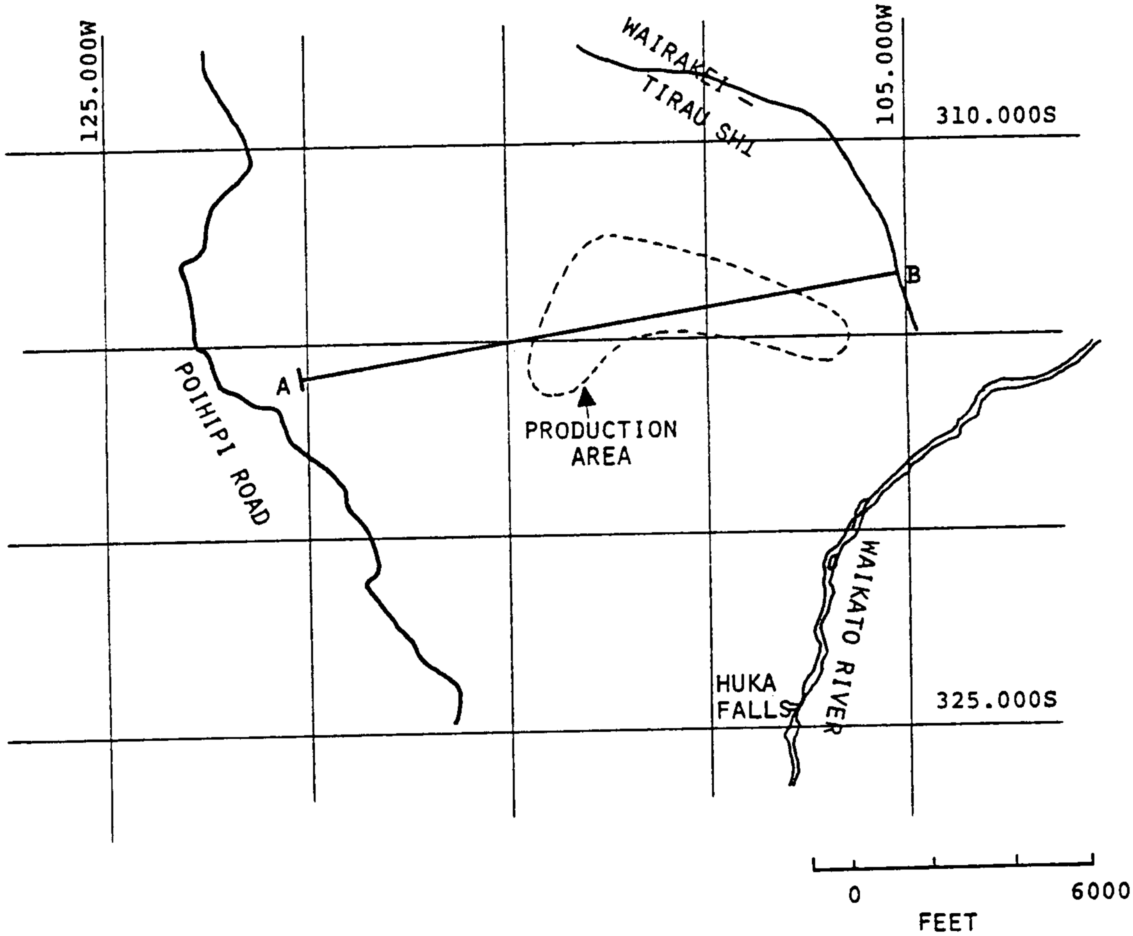


Figure 1. Map showing location of cross-section A-B, of length 5 km, of Wairakei field.

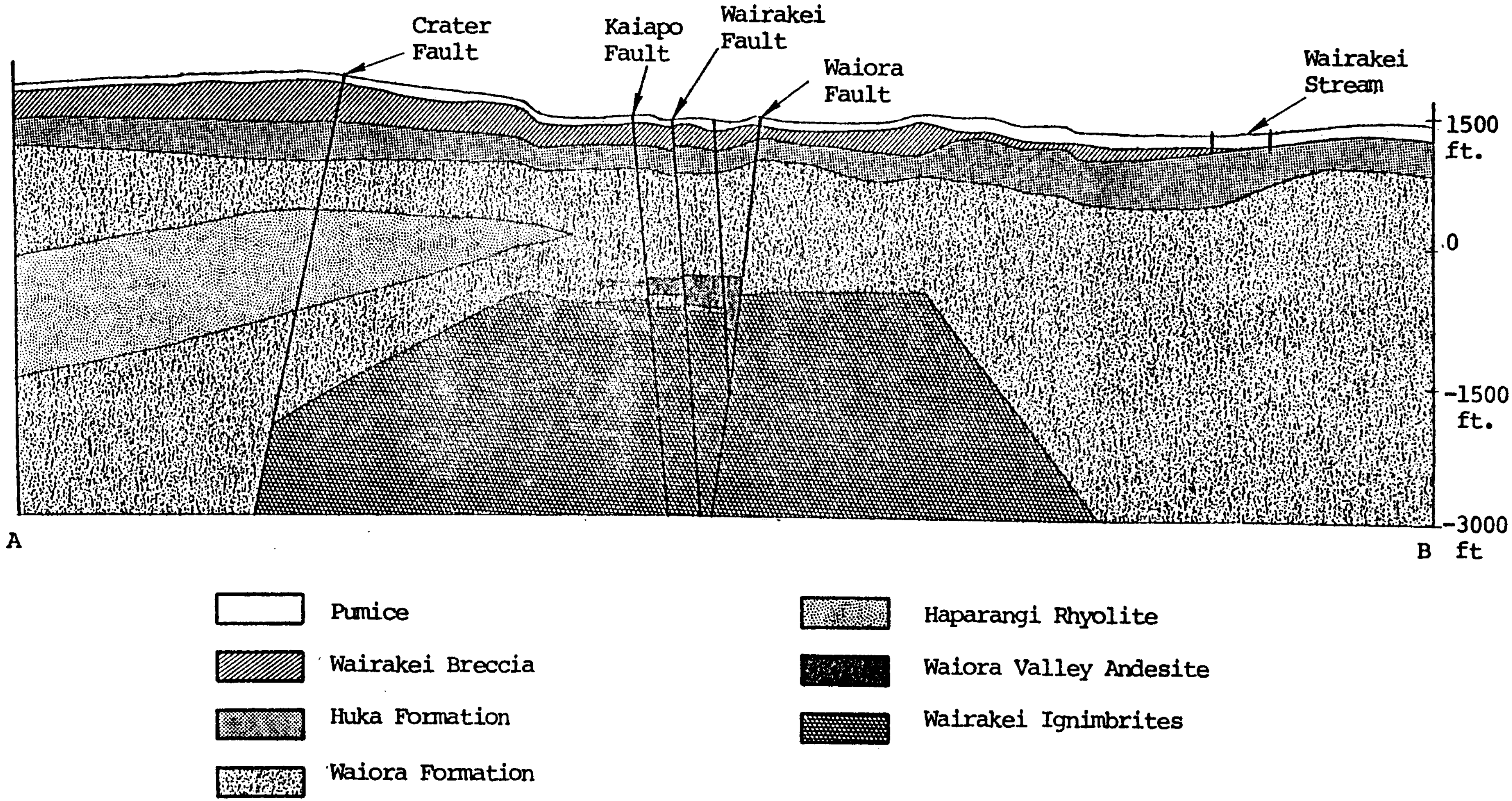
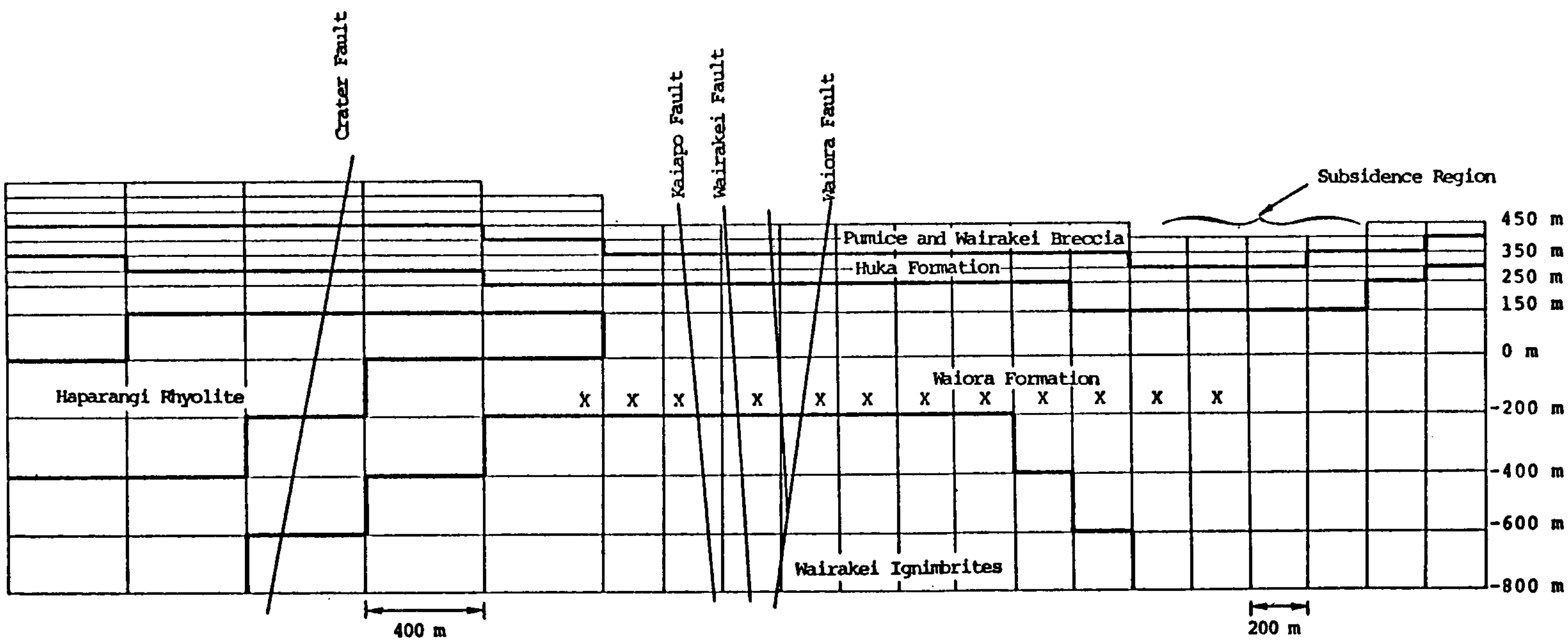


Figure 2. Cross-section of Wairakei field.

Figure 3. Computational grid for two-dimensional vertical cross-section of Wairakei.
X - production region (1967).



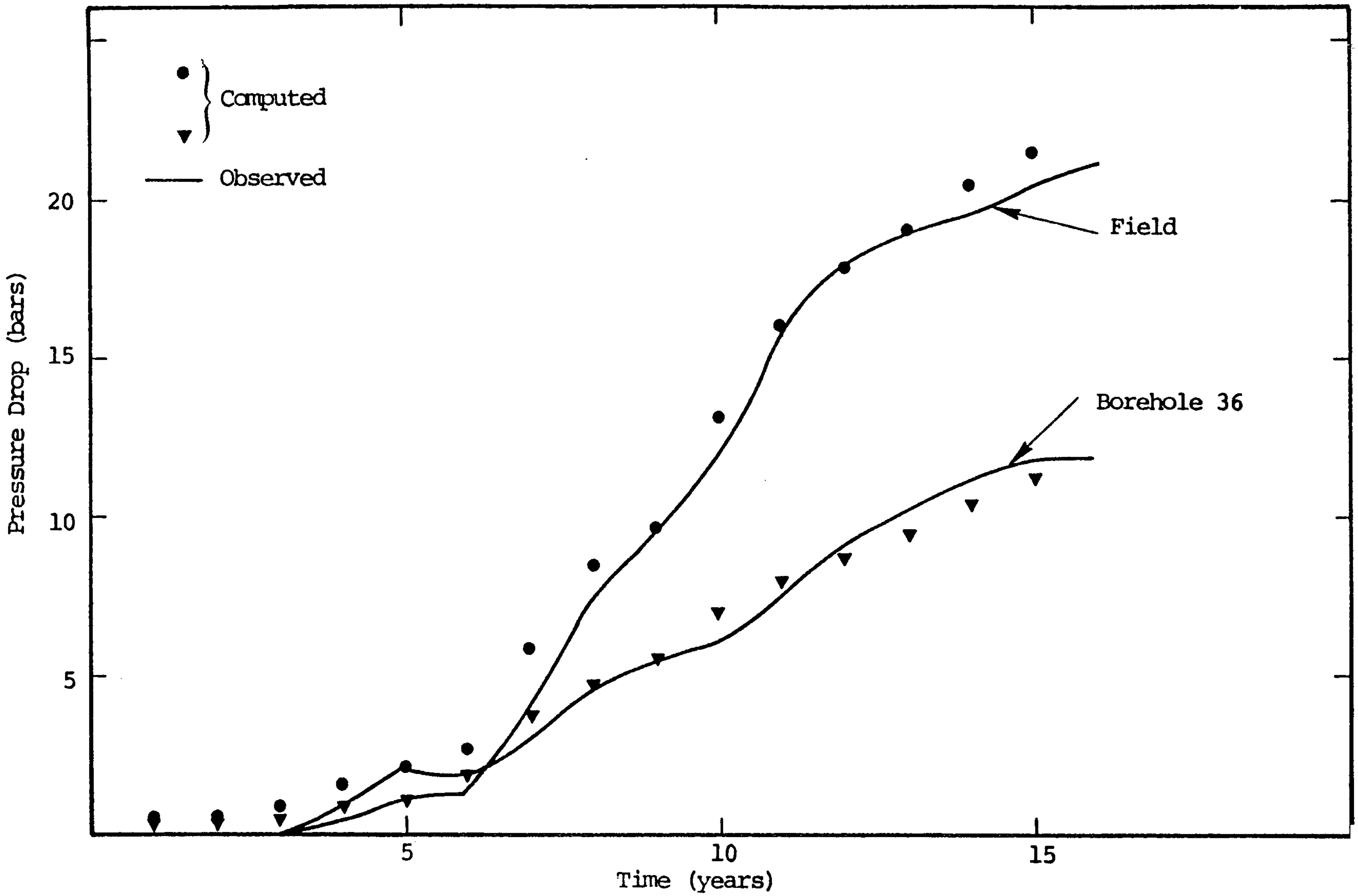


Figure 4. Comparison of calculated pressure drop (field and borehole 36) histories with data.

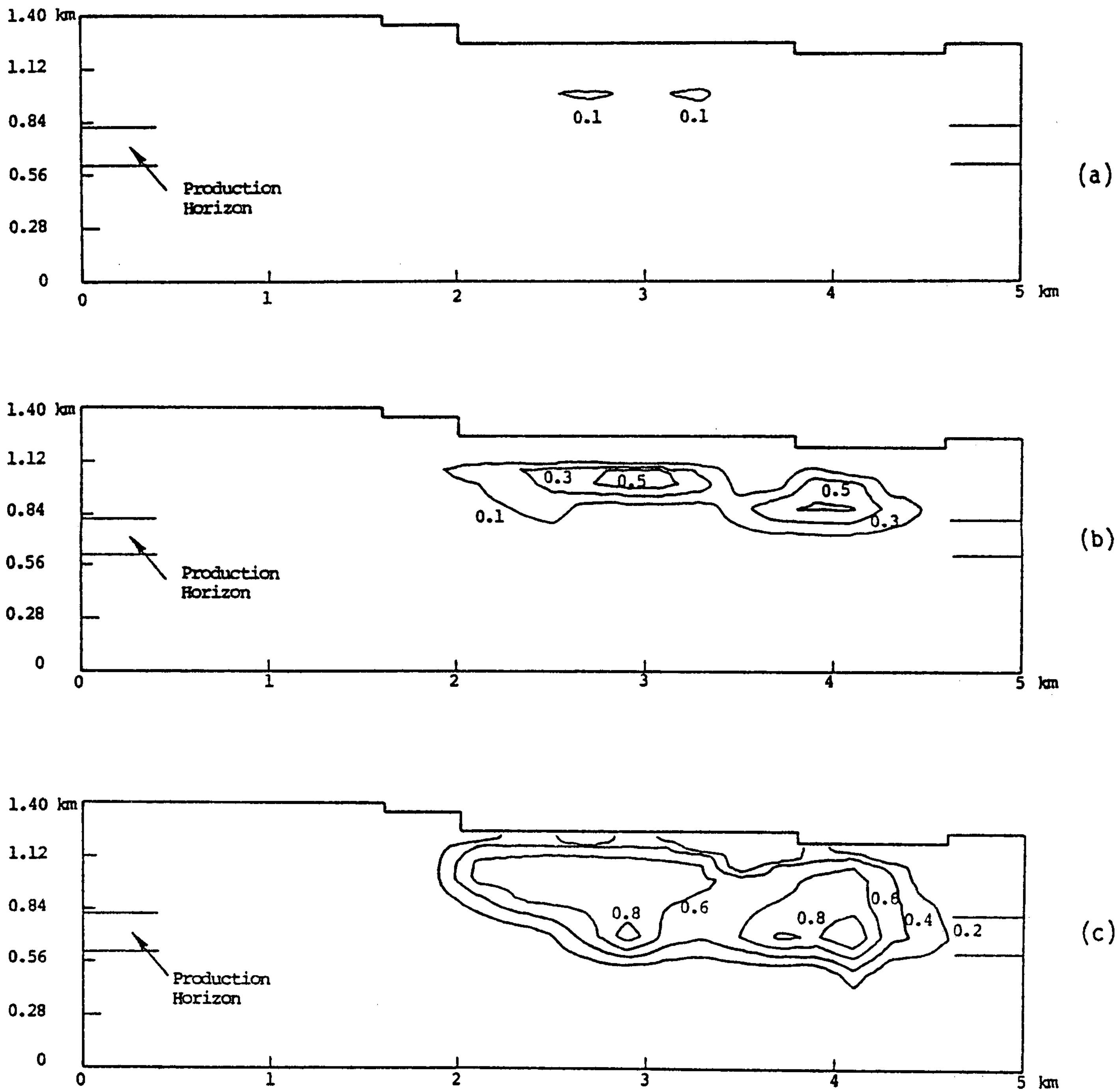


Figure 5. Vapor saturation profiles at the beginning of 1955 (a), 1960 (b), and 1968 (c).

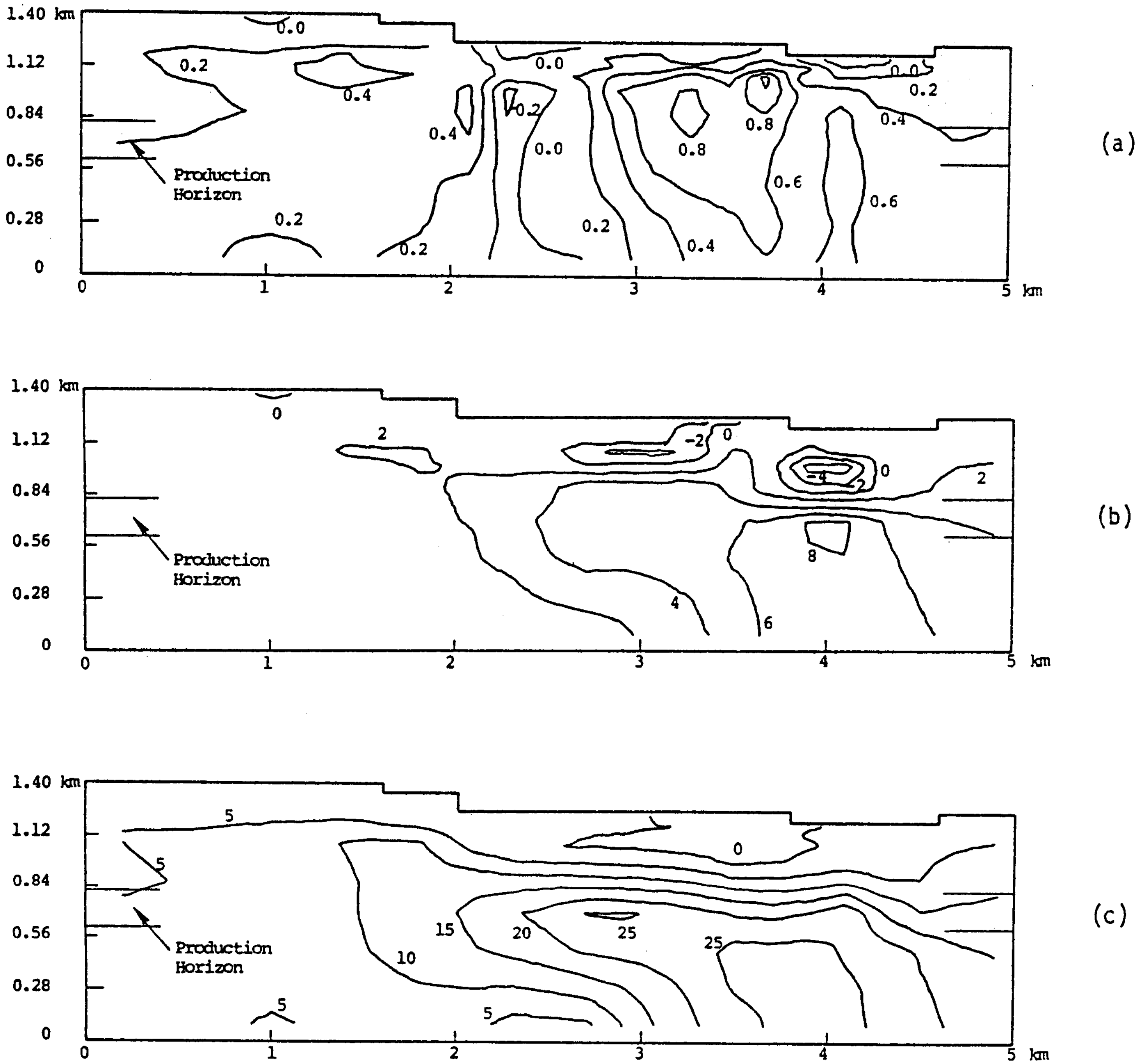
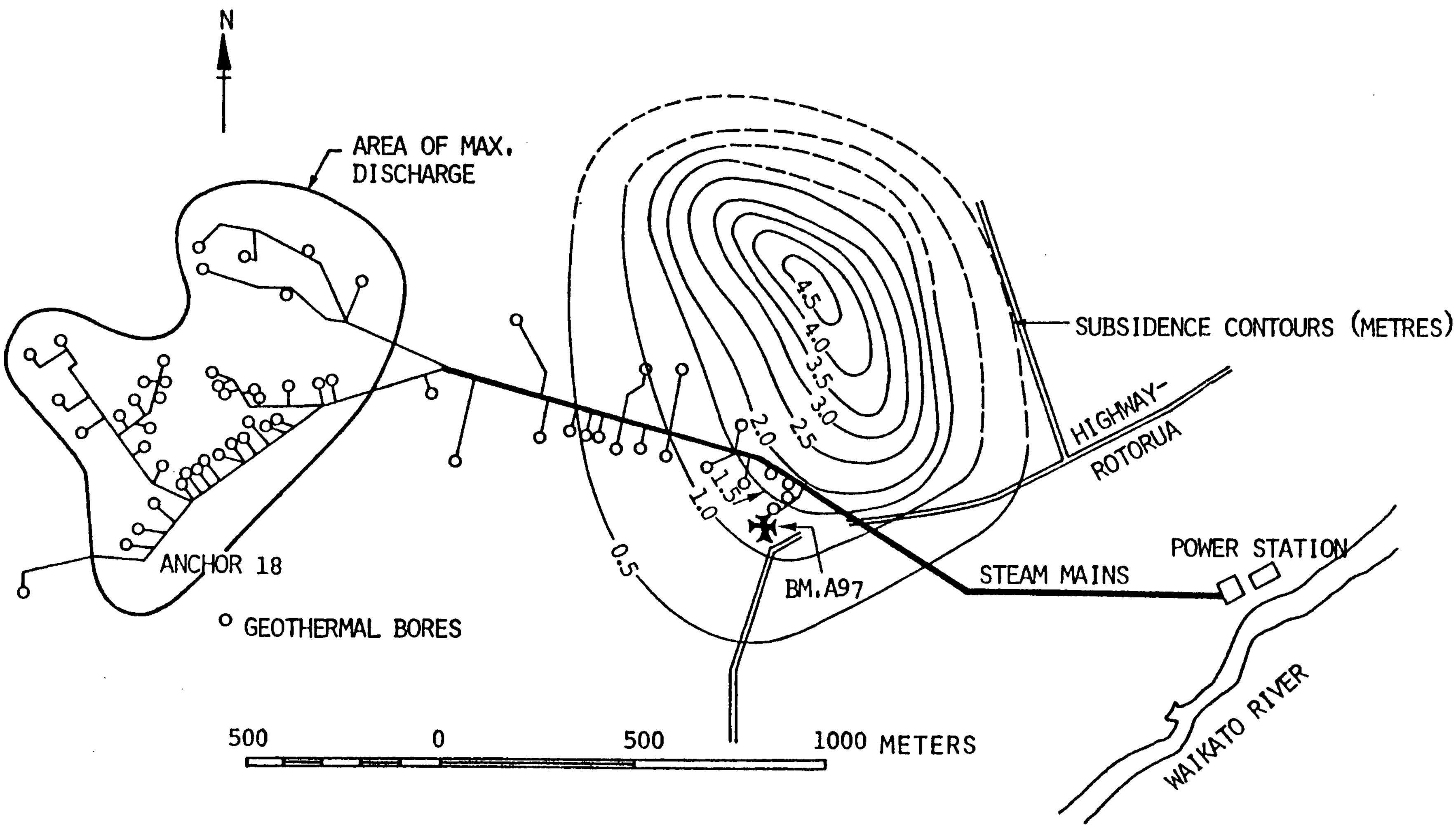


Figure 6. Pressure drop (in bars) profiles at the beginning of 1955 (a), 1960 (b), and 1968 (c).

Figure 7. Total subsidence in meters at Wairakei during period 1964-1974 (Stillwell, et al., 1975).



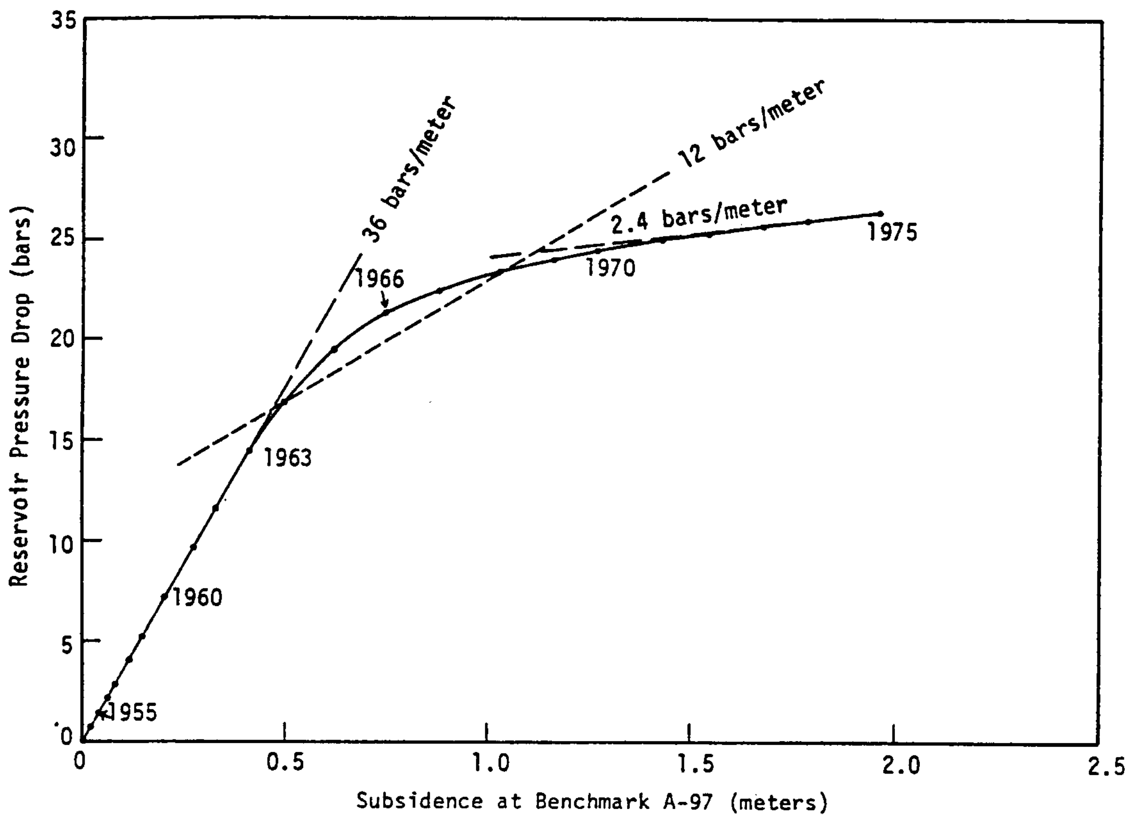


Figure 8. Wairakei subsidence data - reservoir pressure drop versus subsidence at Benchmark A-97.