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Formation permeability at the feedzone of geothermal wells employing inflow type-curves

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RESUMEN

En este trabajo se hace un análisis preliminar de la aplicabilidad de las curvas GIPR (Geothermal Inflow Performance Relationships), para la estimación de permeabilidades de formaciones geotérmicas en las zonas de alimentación de los pozos. Las curvas GIPR (denominadas también curvas-tipo) son curvas características teóricas que relacionan velocidad de flujo másico producido y presión fluyente en la zona de alimentación del pozo. La metodología consiste en traslapar la curva de influjo del pozo (curva característica del pozo) con diferentes curvas tipo y el valor de permeabilidad implícito en la curva tipo del mejor traslape es el valor de permeabilidad buscado. Es importante destacar que esta metodología no requiere medir en campo la curva de influjo del pozo. El empleo de dos curvas de referencia adimensionales del comportamiento de influjo geotérmico previamente obtenidas, una para productividad másica y otra para productividad térmica, permiten el cálculo de la curva de influjo completa del pozo, desde una sola medición flujo másico-presión-entalpía específica (W-P-h) a boca o fondo de pozo, y conociendo la presión del yacimiento en la zona de alimentación del mismo (P_s). Para evaluar la aplicabilidad de la metodología propuesta se consideraron datos (W,P,h) a boca de pozo correspondientes a pruebas de descarga previas de seis pozos del campo geotérmico de Los Azufres. Las permeabilidades inferidas aplicando la metodología están en el rango establecido para este campo. Las curvas de influjo calculadas para los pozos fueron validadas comparando sus respectivas curvas de salida estimadas con los datos completos de las pruebas de descarga correspondientes. Las desviaciones encontradas son del orden del 6% para presión de cabezal y del 2% para entalpía específica, cuando la incertidumbre de los datos de campo es baja. La metodología que se propone en este trabajo puede considerarse como una herramienta complementaria a las mediciones de laboratorio en núcleos de perforación y a las pruebas de presión transitorias efectuadas en campo. Las curvas tipo de influjo incluyen los efectos de las condiciones iniciales del yacimiento, de las propiedades de la formación y el fluido y de la producción másica acumulada del pozo, para pozos con alimentación de flujo bifásico. El factor de daño en los pozos no fue considerado.

PALABRAS CLAVE: Permeabilidad, curvas características de producción, curvas-tipo, metodología, yacimientos geotérmicos, pruebas de descarga.

ABSTRACT

Geothermal Inflow Performance Relationships (GIPR) may be used to estimate formation permeability, by overlapping the well inflow curve with different theoretical GIPR curves. This method does not require field measurement of the well inflow curve. The complete well inflow curve is obtained from a single wellhead or bottomhole measurement of mass flowrate (W), pressure (P) and specific enthalpy (h), and from the static pressure at the well feedzone (P_s). Wellhead data of previous discharge tests from six wells of the Los Azufres geothermal field are used. The permeabilities obtained by the proposed method are in the right range as referred to a reservoir thickness of 100 m. The difference between calculated and field data is on the order of 6% for wellhead pressure and 2% for specific enthalpy when uncertainty of the field data is low. Inflow type-curves include the effects of undisturbed reservoir initial conditions, fluid and formation properties and cumulative mass production, for two-phase inflow. Skin effects were disregarded.

KEY WORDS: Formation permeability, output curves, inflow type-curves, methodology, Geothermal Inflow Performance Relationship (GIPR), geothermal reservoir, discharge tests.

INTRODUCTION

Formation permeability is usually determined from transient pressure tests. However, the use of Geothermal Inflow Performance Relationships (GIPR) may be a viable alternative to estimate permeability. Inflow type-curves provide information concerning the thermophysical properties of rock-fluid media at the well feedzone. Each type-curve reflects behavior which depends on the formation properties. The earliest geothermal inflow type-curves were obtained by Moya (1994) and Moya *et al*. (1995) for a wide range of formation properties, initial conditions and percentages of cumulative mass production (percent of initial fluid mass in-place). The geothermal reservoir simulator used by Moya

(1994) and Moya and Iglesias (1995) was a modified version of the TOUGH simulator (Pruess, 1987). It involved a solubility model of carbon dioxide in water valid up to 350°C and 500 bar (Moya and Iglesias, 1992; Moya, 1994). Our model (Iglesias and Moya, 1990; Moya *et al*., 1995) is a cylindrical, homogeneous reservoir with a fully penetrating well at its center. Radial flow with a reservoir thickness of 100 m was assumed. No skin effects were accounted for. Tables 1 and 2 summarize the cases studied. These cases include Corey-type and linear relative permeabilities which are widely used in the geothermal literature. For both types, the residual saturations were assumed equal to 0.3 for liquid and to 0.05 for steam. Absolute permeabilities of 10 and 100 mD were assumed. The unperturbed initial conditions were liquid with 0.5% by mass of CO_2 at the saturation pressure corresponding to the initial temperature of the unperturbed reservoir. Therefore, two-phase inflow sets in as soon as production begins, and average reservoir pressure and temperature decrease with continued mass production. Initial temperatures varied from 200° to 350°C. All cases described in Tables 1 and 2 were simulated using a 28-zone radial grid. The node positions are given by $r_n=0.1(2)^{(n-1)/2}$ which locates the last node at 1158 m from the origin. Simulations for the different cases were carried out at different constant flowrates until 35% of the initial fluid mass in place had been produced. For each constant flowrate the pressure and flowing enthalpy of the inflow at the feed-point was recorded for 5, 10, 15, 20, 25 and 35% of cumulative mass production.

In this paper, we use superposition of the inflow curve of a geothermal well and the inflow type-curves to infer a value of the formation absolute permeability at the feedzone of the well. The procedure does not require field measurement of the inflow curve of the well. Instead two inflow performance dimensionless reference curves (Moya, 1994; Moya *et al*., 1995; Iglesias and Moya, 1998; Figure 1), one for mass productivity (the W*-P* dimensionless relationship) and another for thermal productivity (the W*-Pow* dimensionless relationship Pow = Wh), allow calculation of the complete inflow curve of the well from a single wellhead measurement $(W,P,h)_{wh}$ or a single bottomhole measurement $(W,P,h)_{wf}$. When the bottomhole measured data are scarce, a geothermal well simulator can be used to generate such values from $(W,P,h)_{wh}$.

These reference curves result from normalizing all the inflow type-curves with the corresponding maximum values of pressure (P_s), mass flowrate (W_{MAX}) and bottomhole thermal power ($Pow_{MAX} = W_{MAX}\ h_{MAX}$), as discussed in Moya (1994). The normalized data collapse in relatively narrow zones (Fig. 1) in spite of the wide range of formation proper-

Table 1

Parameters employed in the obtention of inflow type-curves for each initial temperature (T_0), in the range from 200 to 350°C with increments of 25°C

Absolute Permeability K (mD)	Relative Permeability K_r	Percentages of Cumulative Mass Production
10	Corey	5,10,15,20,25 and 35.
10	Linear	Same
100	Corey	Same
100	Linear	Same

Table 2

Constant rock formation properties.

Property	Base Case	Other cases
Porosity	0.10	0.01 and 0.20
Density	2,700 kg/cm^3	2,700 kg/cm^3
Thermal Conductivity	2.00 W/[m °C]	2.00 W/[m °C]
Specific Heat	1,000 J/[kg °C]	800, 1200 J/[kg °C]

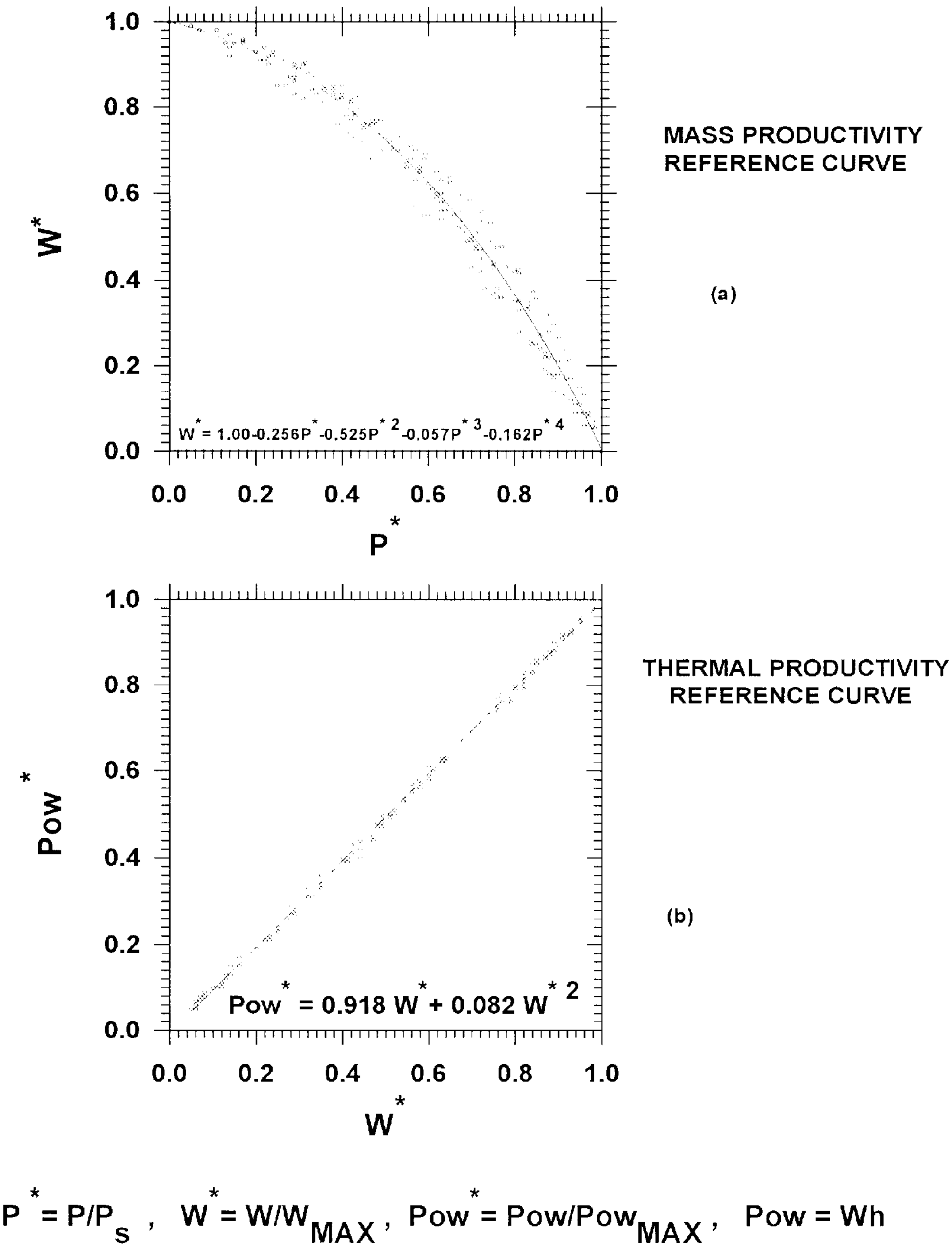

Fig. 1. Dimensionless reference curves of the inflow performance for estimation of geothermal wells inflow curves: a) Mass productivity reference curve, b) Thermal productivity reference curve.

ties, initial conditions and the percentages of cumulative mass production (5,...,35%). The reference curves then allow construction of a complete inflow curve of the well from only P_s and $(W,P,h)_{wf}$.

METHOD

Numerical computation of the inflow curve of a geothermal well is useful for the estimation of the well output curve (Moya *et al.*, 1998) and for the estimation of the formation permeability at the feedzone. The methodology (Figure 2) involves a single measurement $(W,P,h)_{wh}$ from which the corresponding bottomhole $(W,P,h)_{wf}$ values are computed employing a geothermal well simulator. With the computed bottomhole flowing pressure (P_{wf}) and knowledge of P_s at the well feedzone, the dimensionless bottomhole pressure ($P^* = P_{wf}/P_s$) is obtained. Then, use of the mass productivity reference curve (Figure 1a) allows calculation of the respective dimensionless mass flowrate ($W^*=W/W_{MAX}$). Subsequently, the value of the respective dimensionless thermal power ($Pow^* = Pow/Pow_{MAX} = Wh_{wf}/(Wh_{wf})_{MAX}$) is obtained by means of the thermal productivity reference curve (Figure 1b). Once W_{MAX} and Pow_{MAX} are obtained, and using the

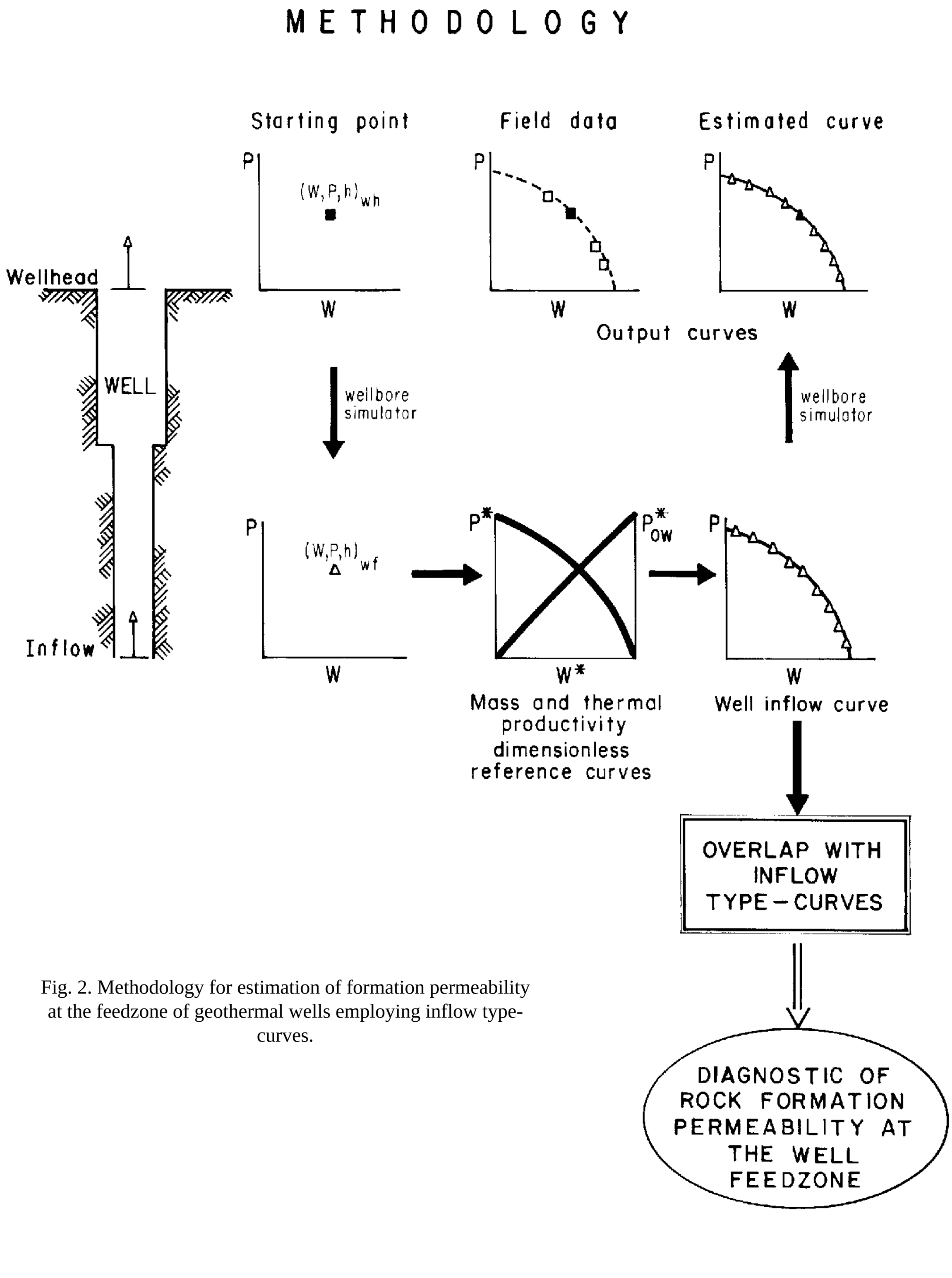

Fig. 2. Methodology for estimation of formation permeability at the feedzone of geothermal wells employing inflow type-curves.

correlations for the reference curves (Figure 1), it is then possible to construct the complete well inflow curve by considering a pre-established range of mass flowrates from 0 to W_{MAX}. The last stage of the process is to overlap the calculated well inflow curve with different type-curves which describe the inflow behavior. The permeability value implicit in the type-curve for the best match is then the permeability value sought. Simultaneously, the calculated well inflow curve allows estimation of the corresponding output curve by considering each calculated point of the inflow curve as the input of a geothermal well simulator (Moya *et al*., 1998).

The well simulator used is VSTEAM (Intercomp, 1981), derived from the work of Gould (1974), which accounts for the geometry of the well, two-phase pressure drop, changes of flow regime, phase changes and heat transfer from the fluid in the wellbore to the surrounding formation. The pressure drop calculation can be carried out including or neglecting the kinetic energy term, and fluid density may be calculated with or without phase slippage. VSTEAM includes conventional flow regime maps such as Ros/Griffith and Aziz, and pressure-drop correlations such as those of Hagedorn and Brown (1965). These maps and correlations are also used in other wellbore simulators, such as WELLSIM (Gunn and Freeston, 1991), WELLBORE (Goyal *et al*., 1980) and WELLFLO (Miller, 1979).

Inflow type-curves so far obtained cover the temperature range from 200 to 350°C (Moya, 1994; Moya *et al*., 1995) in 25°C increments. Figure 3 shows the inflow type-curves corresponding to 250 and 350°C, spanning the values of the parameters indicated in Tables 1 and 2. Comparing these type-curves, it was observed (Moya, 1994) that the shape of the type-curves is highly dependent on the reservoir initial pressure; the linear-type relative permeability gives rise to greater mass flowrates (between 2 and 3 times) than those obtained with the Corey-type relative permeability due to a lesser phase interference. The effect of a greater initial pressure also results in increased mass flowrates (between 3 and 4 times) but with less dependence from the cumulative mass production. The cases of 10 and 100 mD (keeping constant the other parameters) show self similarity on a scale of 10 in agreement with Darcy's law, that is, changes in formation permeability imply proportional changes in mass flowrate. The effect of formation porosity and specific heat are small (Figure 4) in comparison with the effect of the other parameters discussed above.

To facilitate the permeability diagnostic using the above methodology, a computational system was developed (Moya and Uribe, 2000; 2001). This system allows automatic estimation of well output curves and rock formation permeabilities from only one wellhead measurement $(W,P,h)_{wh}$ and P_s, as already discussed. The computerized system shows the estimated mass productivity output curve for the well under analysis and the corresponding output curves of produced thermal power and specific enthalpy. On each curve, the respective maximum values (W_{MAX}, Pow_{MAX}, h_{MAX}) are indicated as well as the initial $(W,P,h)_{wh}$ data and P_s. When it is required to validate the proposed methodology for a particular well, the $(W,P,h)_{wh}$ data may be from a previous discharge test (Figure 2) and then the computerized system will display the estimated output curves comparing them with all the field data of the corresponding discharge test.

To each estimated well output curve corresponds an inflow curve. To infer the formation permeability at the well feedzone (inflow zone), the system permits one to overlap the well inflow curve on different inflow type-curves to select the best possible match. The type-curves which are integrated to the computer system cover the combination of parameters indicated in Tables 1 and 2 in the temperature range from 200 to 350°C in 25°C increments. These type-curves (base cases) correspond to absolute permeabilities of 10 and 100 mD. The system also estimates type-curves for other permeability values through a scale factor which the user may choose. The permeability value implicit in the type-curve of the best match will be the inferred value of formation permeability.

RESULTS AND DISCUSSION

Initial $(W,P,h)_{wh}$ data from previous output tests for 6 wells (Az-6, Az-18, Az-26, Az-33, Az-36 and Az-37) from the Los Azufres geothermal field, Mexico, are considered in the present study. These wells are located in the Tejamaniles sector of the field (Figure 5) and cover the range from low to high steam qualities. Los Azufres is a field with permeabilities between 48 and 248 mD corresponding to the producing strata of the Tejamaniles sector (Suárez, 1994). The average values of the petrophysical parameters for the same strata are (Suárez *et al*., 1989; Contreras *et al*., 1988; Suárez, 1994): porosity on the order of 10%; density = 2700 kg/m^3; thermal conductivity = 2 W/m°C; and a specific heat measured in water saturated rock samples of 1165 J/kg°C. Average fluid pressure is less than 60 bar. Corey-type relative permeabilities are used since they are the most accepted type for the Los Azufres geothermal field due to the fact that most wells are not directly fed by flow from fractures (Suárez *et al*., 1989; 1990).

The calculated inflow curves for the wells considered herein are shown overlapping the inflow type-curve that best represents the performance of the wells (Figures 6-11). Also shown on the figures are the estimated mass and thermal productivity output curves associated with the well inflow curves and compared with the field data from the respective discharge test. The initial $(W,P,h)_{wh}$ data considered for application of the present methodology is indicated with an arrow

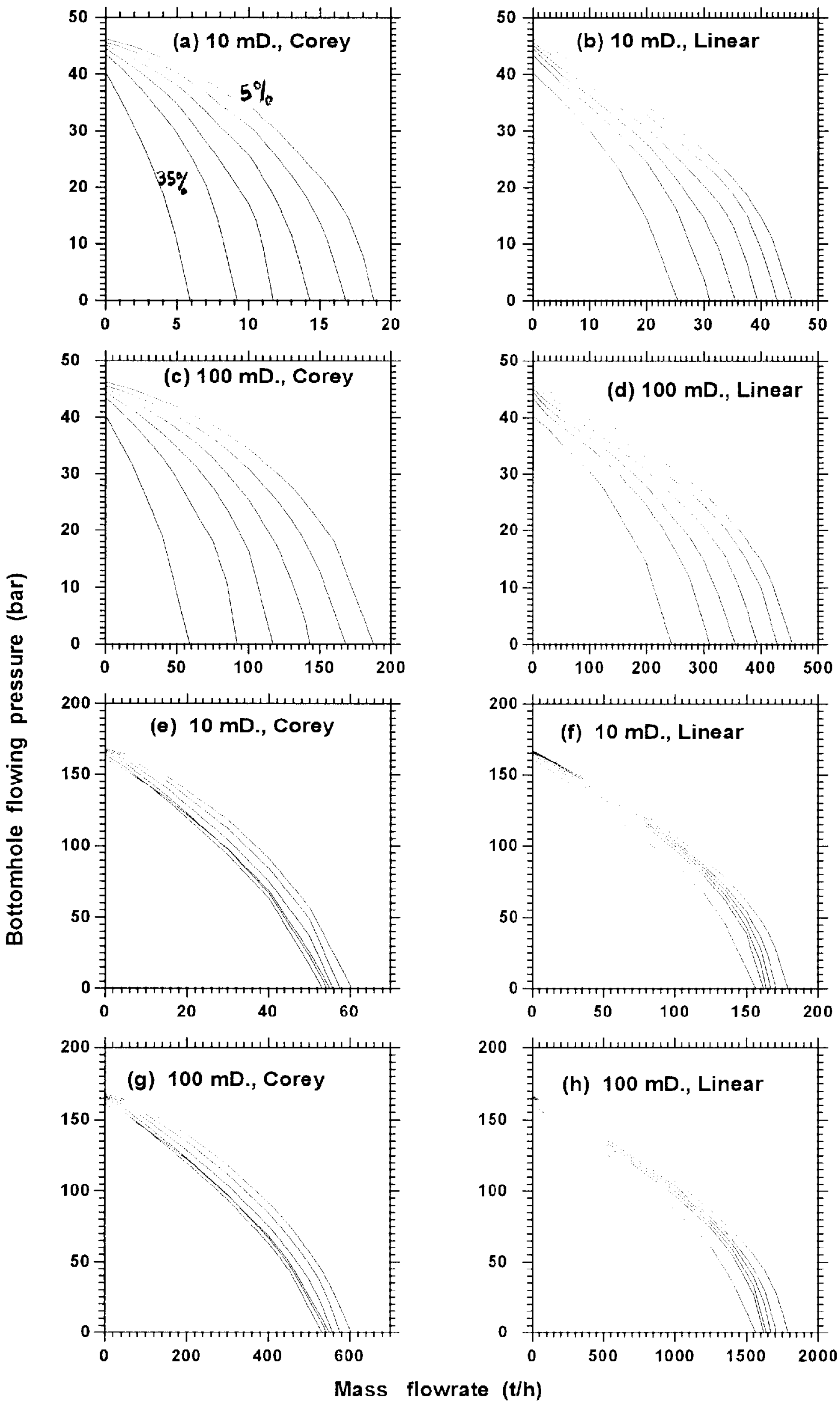

Fig. 3. Inflow type-curves for geothermal reservoirs with 0.5% CO_2 initial mass: (a-d) T_0= 250°C, P_0= 50 bar; (e-h) T_0= 350°C, P_0=170 bar. The values of the other parameters are shown in Table 2 (base case). The percentage of cumulative mass production (5, 10, 15, 20, 25, 30 y 35%) increases towards lower curves.

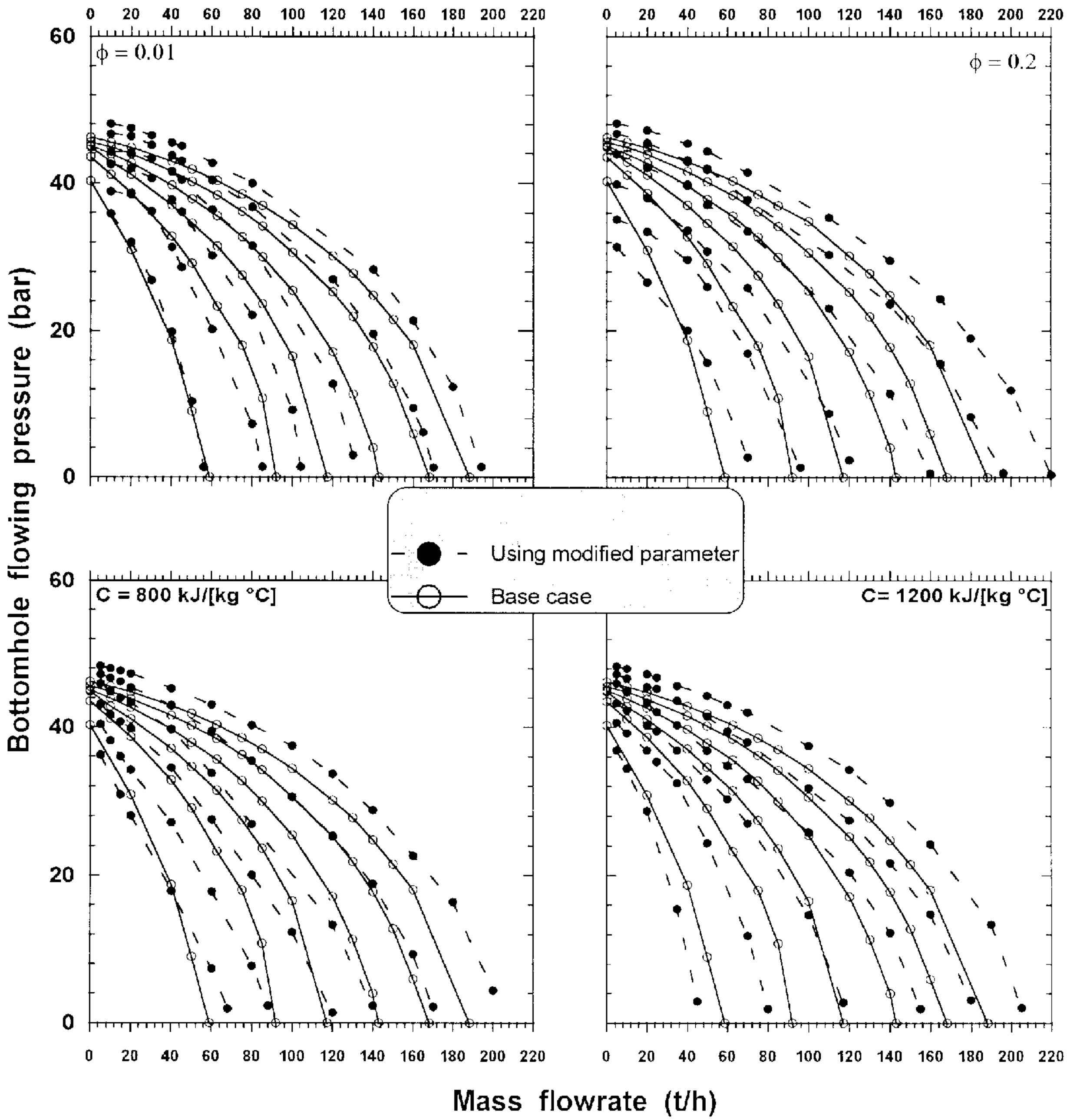

Fig. 4. Effect of porosity and specific heat on the type-curves base case (Table 2).

on Figures 6b-11b. The reservoir static pressures considered are field values. The sensitivity of the estimated curves to the values of $(W,P,h)_{wh}$ and P_s is discussed by Iglesias and Moya (1998) and Moya *et al.* (1998). All the permeability values inferred in the present work are referred to a value of the reservoir thickness of 100 m.

Wells Az-33 and Az-36

The calculated inflow curves for wells Az-33 (initial point from the delivery test of October 1983) and Az-36 (initial point from the delivery test of December 1989 through January 1990) are shown on Figures 6a and 7a, respectively. These calculated curves overlap (match) well the type-curves corresponding to a reservoir initial temperature of 275°C (69 bar total pressure) and a Corey-type relative permeability. The permeability values of these type-curves that best match the wells inflow curves were determined with the aid of the computerized system described before. These values are 63 and 105 mD for the formations surrounding wells Az-33 and Az-36, respectively.

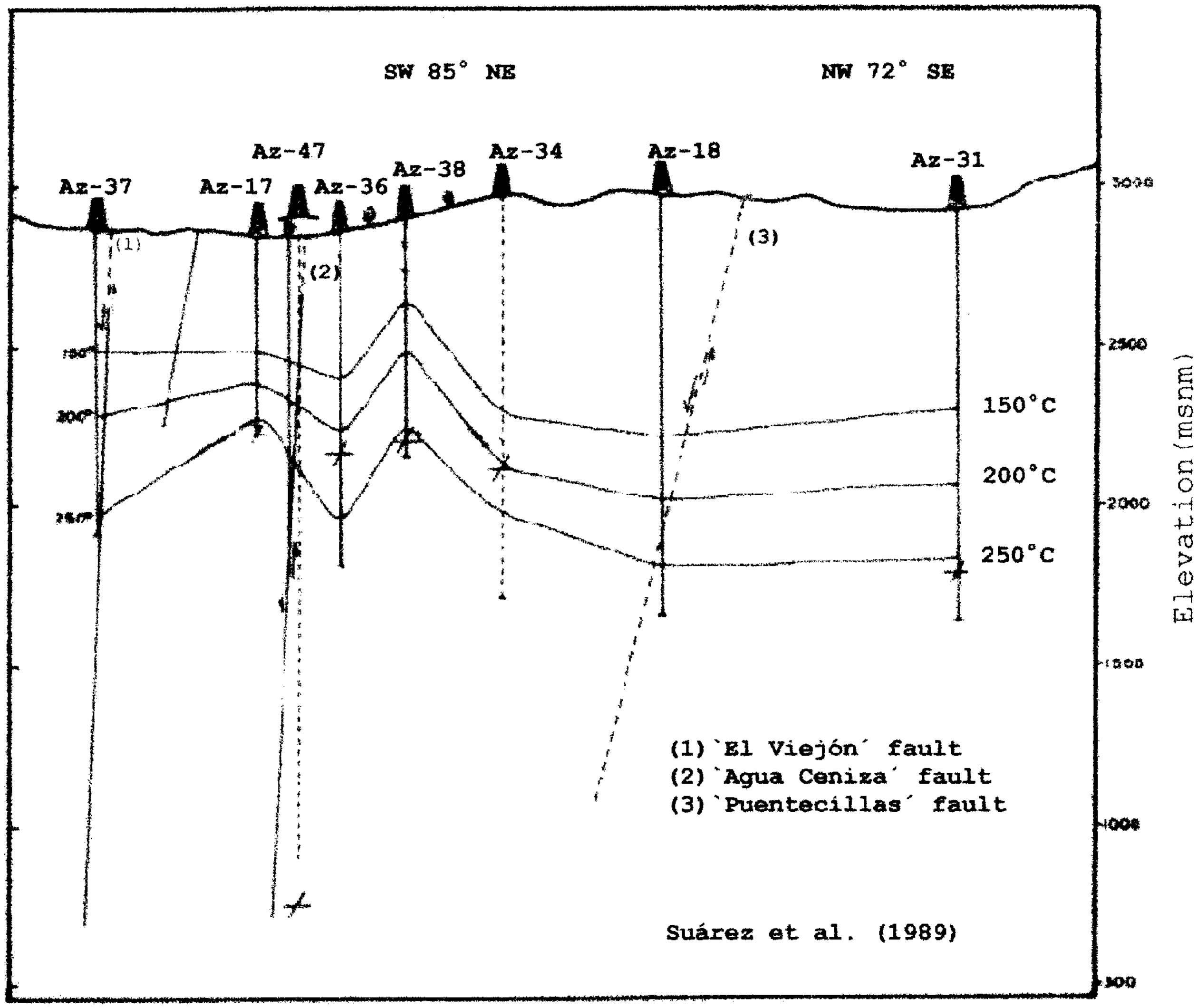

Fig. 5. Well location map and isotherms of Tejamaniles sector of the Los Azufres geothermal field.

Wells Az-33 and Az-36 are located very close to each other and practically at the boundary of the steam dominant and liquid dominant two-phase zones of the Tejamaniles sector of the Los Azufres geothermal field. In this region (elevation of 1900-2200 masl), Suárez (1994) establishes a rock formation permeability between 48 mD (for the 1600-2000 masl range) and 248 mD (for the 2000-2300 masl range). Therefore, the permeabilities inferred with the methodology proposed in this paper are within this permeability range. Wells Az-33 (2267 masl) and Az-36 (1900 masl) are indirectly fed by different faults (Tejamaniles and Puentecillas, respectively) which explains the relatively high effective permeability values.

The presence of these faults is the reason that the fluid injected since 1982 in well Az-7 is able to maintain a pressure which is adequate for fluid production in wells Az-33 and Az-36 (Suárez *et al.*, 1990) but with a detrimental effect on the enthalpy. In fact, it may be observed from Figure 7c that the bottomhole specific enthalpy of well Az-36 was less than 1618 kJ/kg during the discharge tests of December 1989. On the other hand, the specific enthalpy of well Az-33 was less than 2586 kJ/kg (Figure 6c) during the discharge tests of October 1983, when the effect of fluid injection was not important. Both wells started feeling drastic effects of reinjection from December 1989 onwards (Suárez *et al.*, 1990).

To check the validity of the calculated inflow curves, the corresponding mass and thermal productivity output curves are compared with the field data of the respective complete discharge tests (Figures 6b-c and 7b-c). As observed, the estimated curves compare well with the field data,

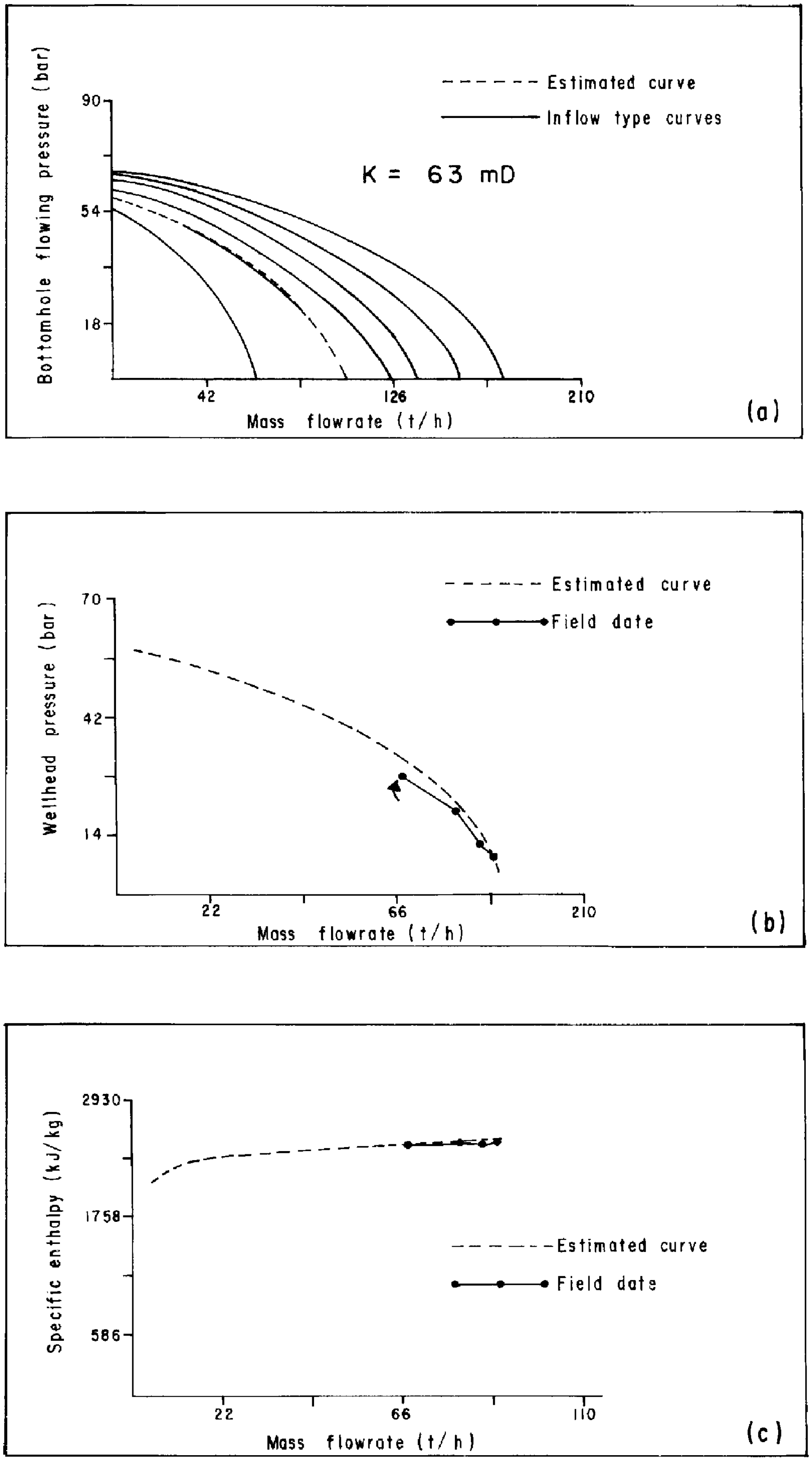

Fig. 6. Permeability diagnostic for Well Az-33 [Table 3]. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 275°C, P_0=68.56 bar and Corey-type relative permeability. Inferred absolute permeability: 63 mD; (b) Estimated output curve of mass productivity, associated to the well inflow curve; (c) Estimated output curve of thermal productivity, associated to the well inflow curve.

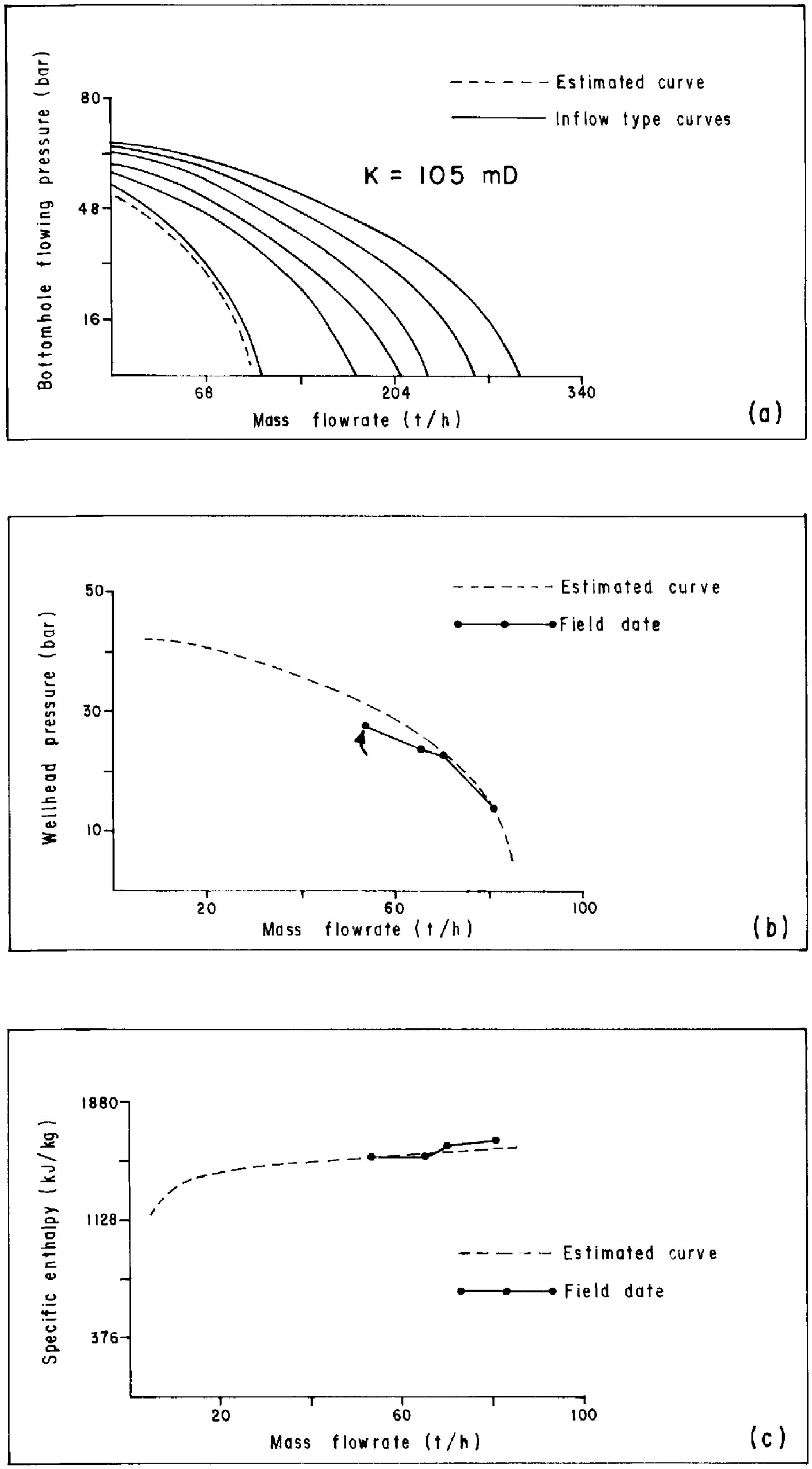

Fig. 7. Permeability diagnostic for well Az-36 [Table 3]. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 275°C, P_0=68.56 bar and Corey-type relative permeability. Inferred absolute permeability: 105 mD; (b) Estimated output curve of mass productivity; (c) Estimated output curve of thermal productivity.

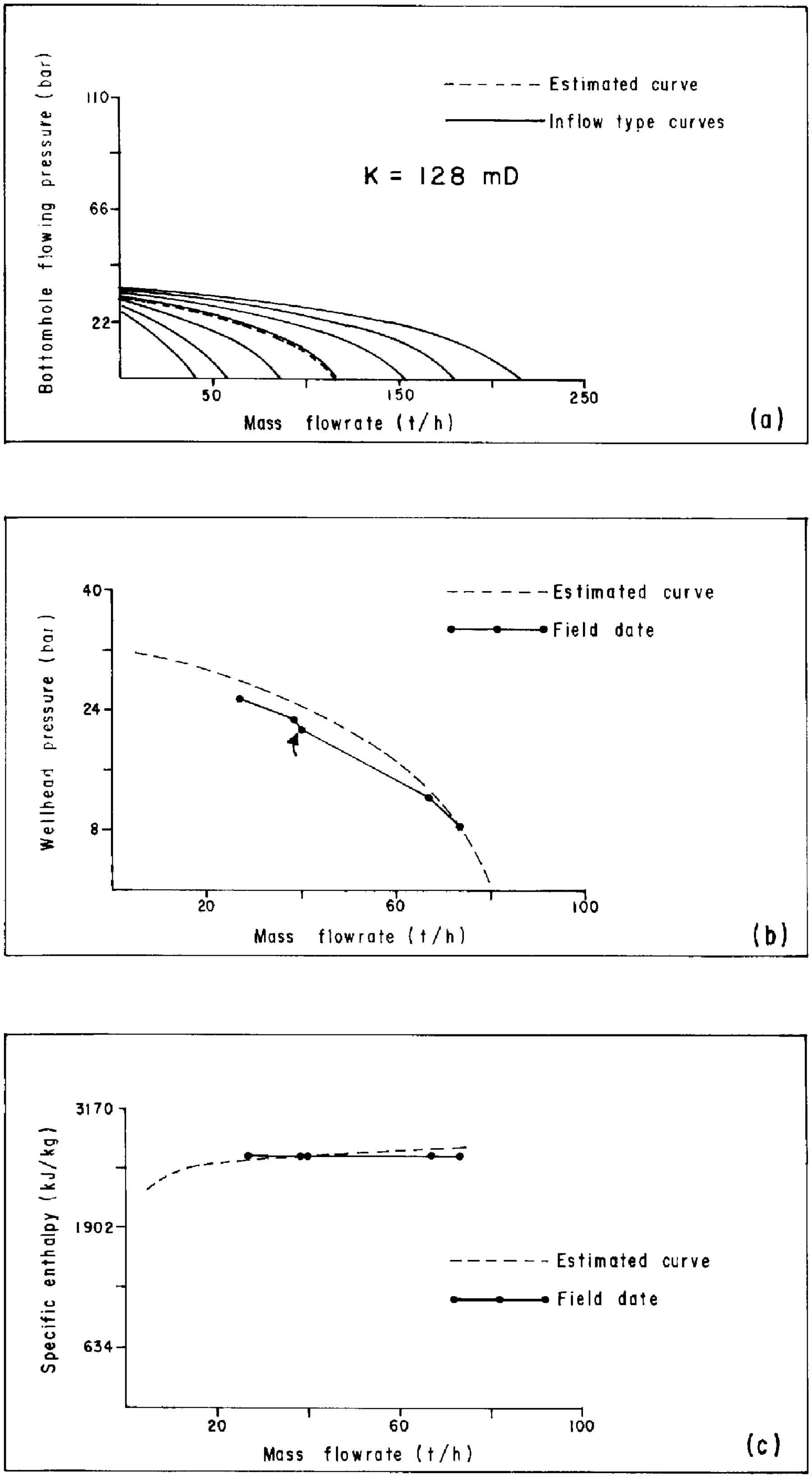

Fig. 8. Permeability diagnostic for well Az-37 [Table 3]. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 225°C, P_0=36.80 bar and Corey-type relative permeability. Inferred absolute permeability: 128 mD; (b) Estimated output curve of mass productivity; (c) Estimated output curve of thermal productivity.

especially the produced specific enthalpy curves. These thermal productivity curves show deviations smaller than 2% on the average while the deviations for mass productivity are greater, on the order of 16 and 6% for wells Az-33 and Az-36, respectively. It is important to note that the field data do not exhibit a clearly defined trend. This may be due to experimental measurement errors which produce greater deviations of the estimated curves with respect to the field data. The discharge test of well Az-33 shows uncertainty in the high mass flowrate range where the deviations are greater due to the strong pressure gradients. The effect of measurement errors on the accuracy of the estimated curves has been discussed by Iglesias and Moya (1998) and Moya *et al*., (1998). On the other hand, these authors also discuss the sensitivity of the estimated curves to the initial $(W,P,h)_{wh}$ data considered from the respective discharge test, and to the value of the P_s considered.

Well Az-37

Well Az-37 is located in the two-phase zone near the liquid dominant condition and close to the dominant steam zone at 1987 masl. The pressure of this well is low and the inflow curve associated with the discharge test of May-June 1986 matches well the type-curves corresponding to an initial temperature of 225°C (P=37 bar) and an absolute permeability of 128 mD (Figure 8a). This permeability value is close to the value inferred for well Az-36 (K=105 mD) which is located practically at the same depth as well Az-37. The percentage deviations of the estimated output curves for this well are less than 8 and 2% for mass and thermal productivity, respectively.

Well Az-18

The feedzone of well Az-18 is located in a deeper zone (approximately 1622 masl) and is therefore of lower permeability, about 48 mD (Suárez, 1994). The bottomhole temperature of this well is greater than for the wells considered previously. The inflow curve matches well the type-curves corresponding to a reservoir initial temperature of 275°C, a relative permeability of the Corey type and an absolute permeability of 84 mD (Figure 9a). The mass and thermal productivity estimated curves associated with the inflow curve exhibit an average deviation of 14 and 11%, respectively. The deviation of 11% for specific enthalpy is extraordinarily high since it is generally less than 2%. As observed from Figure 9c, the first specific enthalpy field datum is a value with a high uncertainty which explains the deviation obtained. Likewise, the deviation of 14% for the mass productivity output curve is justifiable in that the wellhead pressure field data in the range of high flowrates also exhibits experimental uncertainty (Figure 9b).

According to the depth of this well, the inferred permeability value (84 mD) would lie in the lower limit of the 48-248 mD permeability range established by Suárez (1994) for the producing strata of the Tejamaniles sector. The overlap of the well inflow curve on the linear relative permeability type-curves allows estimation of a possible minimum permeability value. This overlap is shown on Figure 9d where it is observed that the inferred permeability is 29.5 mD. Thus, the methodology herein presented establishes a permeability range of 29-84 mD for the rock formation surrounding well Az-18 at its feedzone. The Corey relative permeability curves are generally established for the Tejamaniles sector of the Los Azufres geothermal field (Suárez *et al*., 1989). Then, an effective permeability value close to 84 mD, is the best possible estimation using the proposed methodology. This permeability value in turn indicates that well Az-18 is being fed indirectly by a fault.

Well Az-26

The feedzone of well Az-26 is located at about 1709

Table 3

Complementary information to Figures 6-11.

Fig.	Well	Discharge Test Date	$(W,P,h)_{wh}$ [t/h,bar,kJ/kg]	P_s [bar]	Type Curves $(T_0$-P_0-$K_r)$ [°C-bar-]	Permeability Diagnostic (K) [mD]
6	Az-33	October 1983	(67,28,2487)	59	(275-69-C)	63
7	Az-36	December 89	(53,27,1520)	53	(275-69-C)	105
8	Az-37	May 1985	(40,21,2662)	32	(225-37-C)	128
9	Az-18	November 84	(69,36,1507)	68	(275-69-C)	84
					(275-69-L)	29
10	Az-26	March 1985	(97,22,1180)	47	(250-50-C)	460
11	Az-6	December 79	(19,37,2665)	49	(250-50-C)	30

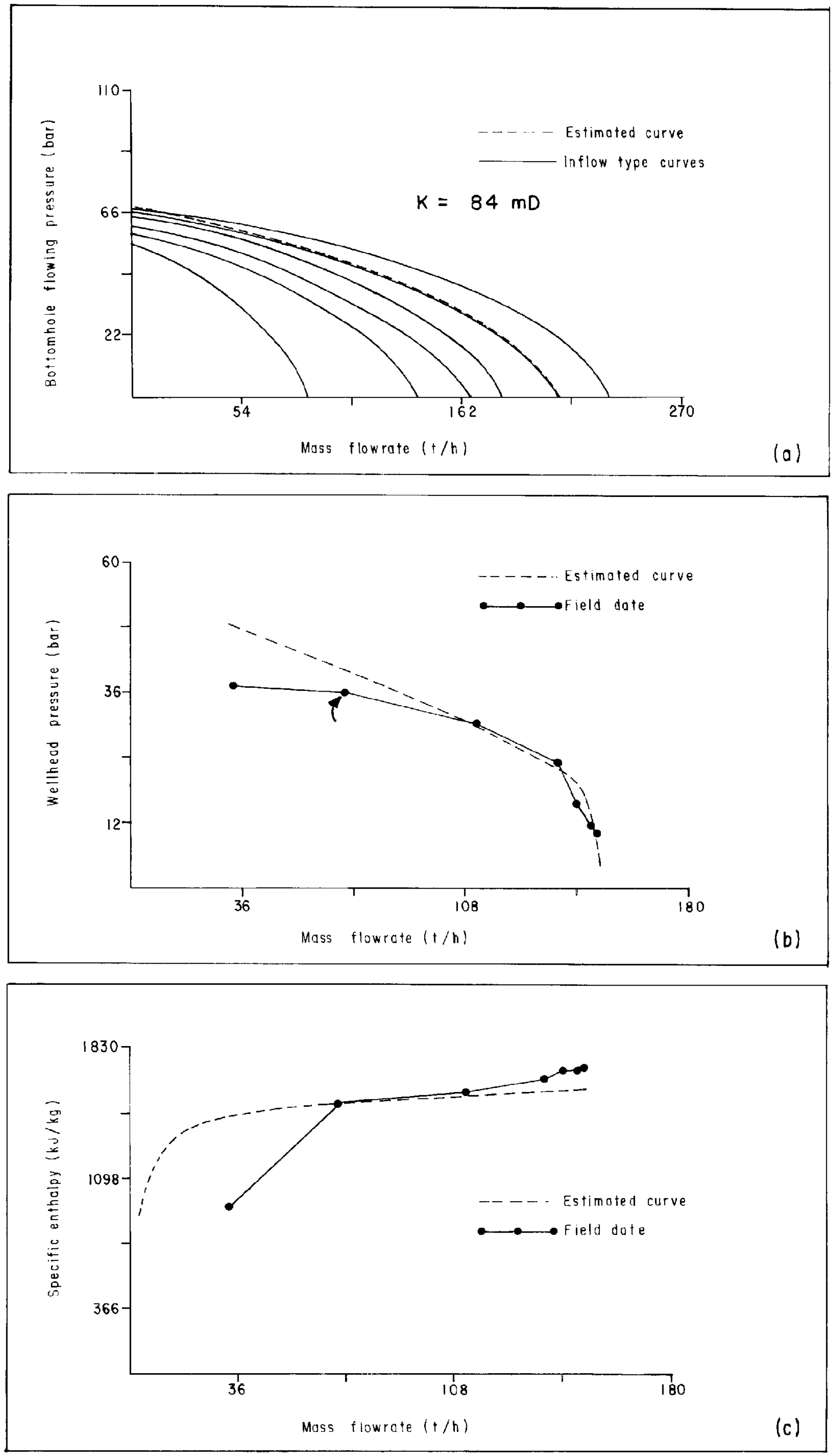

Fig. 9. Permeability diagnostic for well Az-18 [Table 3]. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 275°C, P_0= 68.56 bar and Corey-type relative permeability. Inferred absolute permeability: 84 mD; (b) Estimated output curve of mass productivity; (c) Estimated output curve of thermal productivity. (d) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 275°C, P_0 = 68.56 bar and lineal-type relative permeability. Inferred absolute permeability: 29.5 mD.

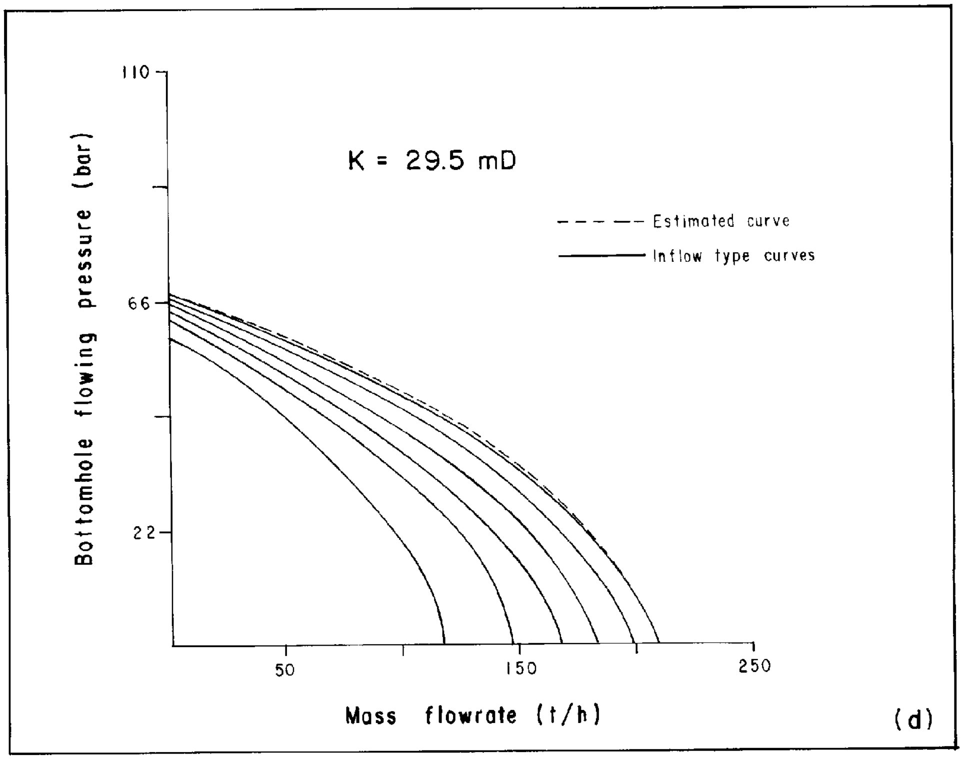

Fig. 9. Continued.

masl in the liquid dominant two-phase zone close to the re-injection well Az-31. The calculated inflow curve for well Az-26 overlaps the inflow type-curves corresponding to the following parameter combination: 250°C-460mD-Corey type (Figure 10a). The estimated output curves exhibit deviations on the order of 6 and 1% for the mass and thermal productivities, respectively (Figures 10b and 10c). These small deviations validate the calculated well inflow curve, and therefore, the 760 t/h value of the parameter W_{MAX}. This in turn justifies the inferred value of absolute permeability of 460 mD. The behaviour of this well may be explained as follows.

The depth of the feedzone for well Az-26 corresponds to a stratum where the fluid temperature is on the order of 280°C. However, the temperature of the fluid feeding well Az-26 is much lower, about 250°C. At first, it was thought that well Az-26 is being affected by reinjection taking place in nearby well Az-31. However, the rock formation surrounding well Az-31 has low permeability. Also, well Az-26 is located near a cold-water lateral recharge zone, which probably explains the low temperature of the fluid feeding this well and the low quality of the steam produced. On the other hand, the high mass flowrates indicate that the well is being fed from some fractured zones that exist in this geothermal field and in consequence, the effective permeability of the rock formation is much greater, in concordance with the estimated value of 460 mD. As a reference point, the possible minimum value of permeability is 168 mD when the linear relative permeability function is considered.

Well Az-6

The feedzone for well Az-6 is located at 1920 masl, in the dominant steam zone. The inflow curve calculated from a single field datum from discharge tests carried out in December 1979 is shown on Figure 11a. This curve matches the type-curves corresponding to the following parameter combination: 250°C-30.5mD-Corey type permeability. The deviations obtained for the mass and thermal productivity output curves are 6 and 3%, respectively.

In one convective heat transfer numerical study (Suárez *et al.*, 1989) carried out in the Tejamaniles sector of the Los Azufres field where the Az-6 well is located, an absolute permeability of 50 mD and a Corey-type relative permeability were established. Suárez *et al* (1989) used this permeability based on petrophysical measurements performed by Contreras *et al.* (1988) at ambient pressure and temperature conditions. Furthermore, the isotherms in Tejamaniles (Suárez *et al.*, 1989; Figure 7) show that the temperature of the fluid in the feedzone of well Az-6 is 250°C. Hence, a good agreement between these parameters and the inferred parameters from the application of the present type-curve methodology is obtained.

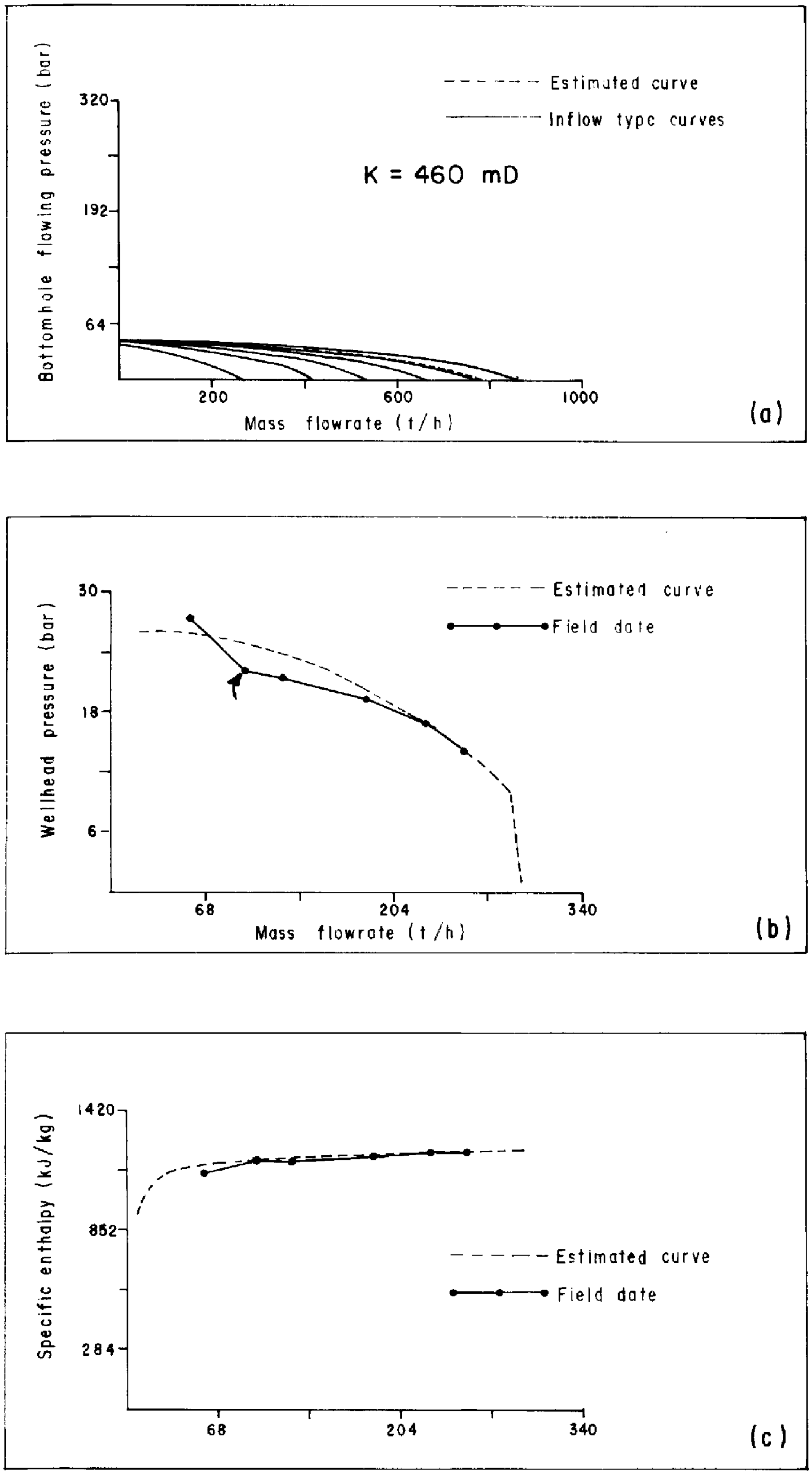

Fig. 10. Permeability diagnostic for well Az-26 [Table 3]. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 250°C, P_0=49.84 bar and Corey-type relative permeability. Inferred absolute permeability: 460 mD; (b) Estimated output curve of mass productivity; (c) Estimated output curve of thermal productivity.

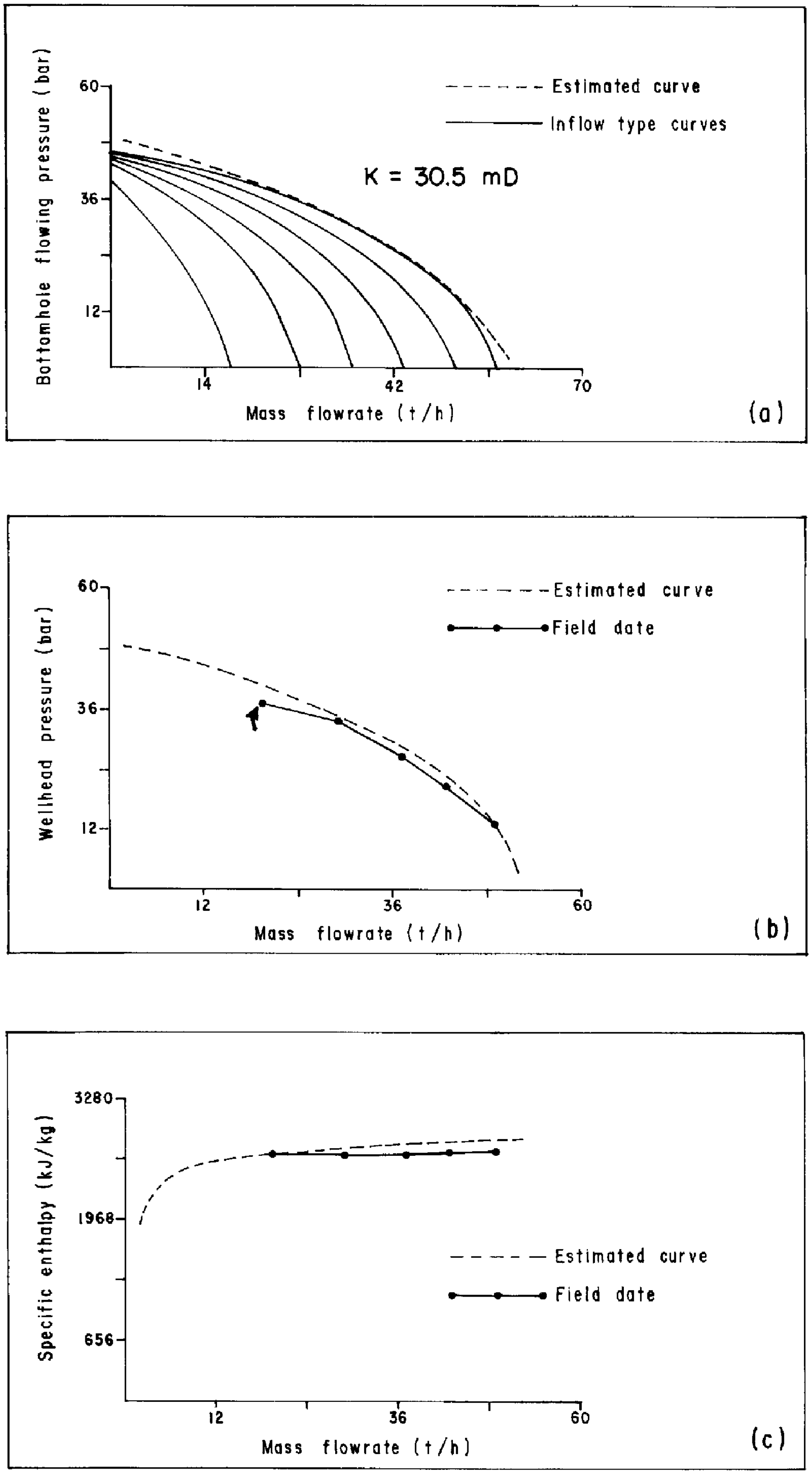

Figure 11. Permeability diagnostic for well Az-6. (a) Overlap of well inflow curve with the inflow type-curves corresponding to T_0 = 250°C, P_0=49.84 bar and Corey-type relative permeability. Inferred absolute permeability: 30.5 mD; (b) Estimated output curve of mass productivity, associated to the well inflow curve; (c) Estimated output curve of thermal productivity, associated to the well inflow curve.

CONCLUSIONS

The applicability of the inflow type-curves for the characterization of geothermal reservoir permeabilities at the well feedzone has been demonstrated for 6 wells from the Los Azufres geothermal field. The calculated well inflow curves overlap (match) well the inflow type-curves, and the inferred permeabilities are in the range established by Suárez (1994) for the producing strata of the Tejamaniles sector of the Los Azufres geothermal field. The deviations of the estimated output curves with respect to the field data are on the order of 6% for wellhead pressure and 2% for specific enthalpy. These deviations are greater when there exists uncertainty in the measurement of field data, as is the case of wells Az-33 and Az-18. The methodology herein described could be considered as an additional tool for the characterization of geothermal reservoirs, complementary to the transient pressure tests in wells and to the laboratory measurements on drill cores. It is also economically viable since it only requires a single measurement of mass flowrate, pressure and enthalpy at the wellhead, $(W,P,h)_{wh}$, or at bottomhole, $(W,P,h)_{wf}$, or a single $(W,P,h)_{wh}$ value from previous delivery tests for each well considered. The $(W,P,h)_{wh}$ or $(W,P,h)_{wf}$ value allows calculation of the complete well inflow curve by use of the inflow performance dimensionless reference curves and with knowledge of the reservoir static pressure (P_s). The present methodology does not require field measurement to develop well inflow curve.

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