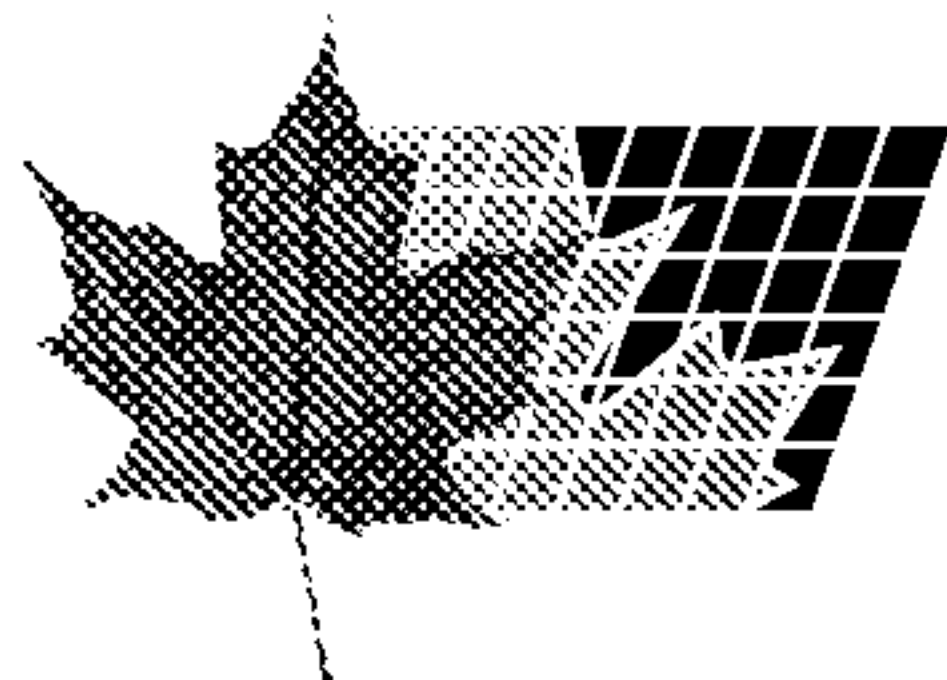




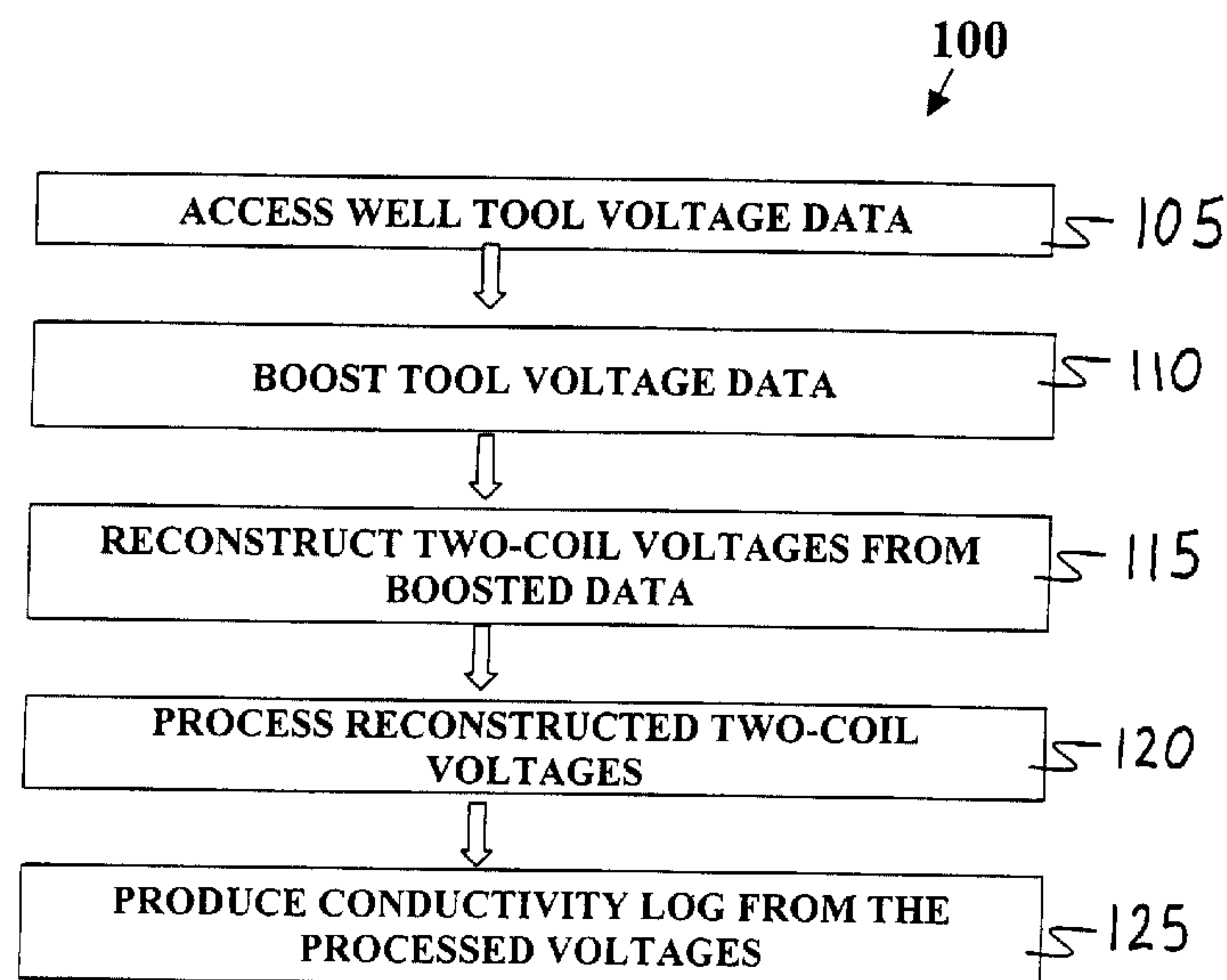
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(51) Int.Cl.⁷ G01V 3/18, G01V 3/30, G01V 3/28

(30) 1999/09/07 (09/391,149) US

(54) **SYSTEME ET METHODE POUR PRODUIRE UN
ENREGISTREMENT DE CONDUCTIVITE A L'EPREUVE DES
EFFETS D'EPAULE ET DU PENDANGE, A PARTIR DES
DONNEES DE TENSION OBTENUES D'UNE SONDE DE PUIITS**
(54) **SYSTEM AND METHOD FOR PRODUCING A CONDUCTIVITY
LOG UNAFFECTED BY SHOULDER EFFECT AND DIP FROM
DATA DEVELOPED BY A WELL TOOL**



(57) A system and method for producing a conductivity log, unaffected by shoulder effect and dip, from voltage data developed by a well tool (205) disposed in a borehole. The method involves accessing the voltage data developed by the tool, processing the data, reconstructing two-coil voltage data, and computing differences of the two-coil data, to derive a conductivity profile representative of the formation. A system including a well tool adapted to move through a borehole with an apparatus (210) coupled to the tool. The apparatus adapted with means to access voltage data developed by the receivers disposed on the well tool. The apparatus further adapted with means for boosting the voltage data, means for reconstructing two-coil voltages from the boosted voltage data, means for processing the reconstructed two-coil voltage data, and means for producing a conductivity log from the processed two-coil voltages.

ABSTRACT

A system and method for producing a conductivity log, unaffected by shoulder effect and dip, from voltage data developed by a well tool (205) disposed in a borehole. The method involves accessing the voltage data developed by the tool, processing the data, reconstructing two-coil voltage data, and computing differences of the two-coil data, to derive a conductivity profile representative of the formation. A system including a well tool adapted to move through a borehole with an apparatus (210) coupled to the tool. The apparatus adapted with means to access voltage data developed by the receivers disposed on the well tool. The apparatus further adapted with means for boosting the voltage data, means for reconstructing two-coil voltages from the boosted voltage data, means for processing the reconstructed two-coil voltage data, and means for producing a conductivity log from the processed two-coil voltages.

SYSTEM AND METHOD FOR PRODUCING A LOG UNAFFECTED BY SHOULDER EFFECT AND DIP FROM DATA DEVELOPED BY A WELL TOOL

1. BACKGROUND OF THE INVENTION

5 1.1 Field of the Invention

This invention relates to the field of well logging and, more particularly, to well logging methods and apparatus for determining formation properties, such as conductivity, in high-contrast thin-layer formations or at high dip angles, with greater accuracy than prior methods. Still more particularly, this invention relates to an improved method for processing multiple voltage data obtained during logging with an induction array well tool and creating a depth tagged representation of resistivity or conductivity from a formulated difference of the voltage data. The invention has general application in the well logging art, but is particularly useful at a well site while logging.

15 1.2. Description of Related Art

Induction logging is a well-known form of electromagnetic logging used to make a determination of the conductivity (or its inverse, resistivity) profile of the earth formations surrounding a borehole. U.S. Pat. Nos. 3,340,464; 3,147,429; 3,179,879; 3,056,917; and 4,472,684 are illustrative of typical well logging tools that utilize the basic principles of induction logging.

Conventional induction logging tools or "sondes" include a transmitter and a receiver array consisting of a set of coils mounted on a support and axially spaced from each other in the direction of the borehole. The transmitting coil is energized by an alternating current, which in turn generates an electric field that induces eddy currents in the formation surrounding the borehole. The intensity of the eddy currents is proportional to the conductivity of the formation. The field generated in turn by these eddy currents induces an electromotive force in the receiving coil. Phase-locked detection, amplification, and digitization of this signal determines the amplitude and phase of the receiver voltage, usually expressed as a complex number (phasor voltage). By processing the receiver coil voltages, an evaluation of the formation conductivity profile is obtained. U.S. Pat. No. 5,157,605 (assigned to the present assignee) discloses

an induction array well tool that may be used to develop voltage data for processing by the present invention.

Conventional techniques for evaluating the conductivity of formations have practical limitations. Neighboring layers in high-contrast (in terms of resistivity) thin-layer formations can corrupt the measurement results – known as shoulder effect. At high dip angles, horns and other artifacts are seen in the resistivity logs. Modeling and actual measurements have confirmed these effects. See B. Anderson et al., *Response of 2-MHz LWD Resistivity and Wireline Induction Tools in Dipping Beds and Laminated Formations*, SPWLA THIRTY-FIRST ANNUAL LOGGING SYMPOSIUM, pp. 1-25, 1990. The cause of the horns is transverse magnetic (“TM”) coupling, which becomes important at high dip angles. The TM horns observed are useful to detect layer boundaries, but are detrimental for quantitative formation evaluation.

U.S. Pat. No. 5,041,975 describes a method for correcting data developed by the well tool of the ‘605 patent, to eliminate the effects of the borehole on the measured data. U.S. Pat. No. 5,184,079 describes a method for correcting logs, developed from a logging tool, disposed in a wellbore at a dip angle relative to the formation layers, to eliminate the effects of the dip angle on the resistivity logs. The applicability of this correction method is limited to dip angles less than about 45 degrees. Another method for correcting induction logs with high apparent dip angle effects was described by Barber et al., *Interpretation of Multiarray Induction Logs in Invaded Formations at High Relative Dip Angles*, SPWLA THIRTY-NINTH ANNUAL LOGGING SYMPOSIUM, June, 1998. This method requires time-consuming model calculations, making it less desirable for operations at the well site while logging. An underlying criterion of the methods described by the ‘079 patent and Barber et al. is the requirement that the dip angle be known before the methods can be applied.

It is desirable to obtain a simplified method of processing data, acquired from a well tool, to correct for dip effect and neighboring layers in high-contrast thin-layer formations. Still further, it is desired to implement a data processing technique that is not restricted to piecewise constant formations and does not require prior knowledge of dip angles. Thus, there remains a need for a simplified process and apparatus that produces

accurate conductivity profiles of unrestricted formations from data developed by a well tool.

2. SUMMARY OF THE INVENTION

5 A method for producing a log unaffected by shoulder effect and dip from data developed by a well tool is provided. The tool includes a transmitter and a plurality of receiver pairs, when the tool is disposed in a borehole traversing a formation, the method characterized by: accessing the developed tool data; boosting the developed tool data; reconstructing two-coil voltages from the boosted tool data; processing the reconstructed
10 two-coil voltages; and producing the log from the processed two-coil voltages.

A system for producing a log unaffected by shoulder effect and dip from data developed by a well tool is provided. The tool being adapted to move through a borehole and an apparatus adapted to be coupled to the tool, the tool including at least one transmitter and a plurality of receiver pairs where each receiver pair develops tool data
15 from energy transmitted by each at least one transmitter, the apparatus being adapted to respond to the tool data to produce the log and to record the log on an output record medium, the apparatus characterized by: means for accessing the tool data; means for boosting the tool data; means for reconstructing two-coil voltages from the boosted tool data; means for processing the reconstructed two-coil voltages; and means for producing
20 the log from the processed two-coil voltages.

3. BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

25 Figure 1 is a schematic of two well tool designs for implementation of the present invention.

Figure 2 shows measurements obtained with a well tool disposed in a vertical well with uniform bedding planes.

Figure 3 shows measurements obtained with a well tool disposed in a deviated
30 borehole, or when the formation beds dip with respect to the borehole.

Figure 4 is a schematic diagram of a basic dip-corrected measurement in accordance with the present invention.

Figure 5 illustrates graphically a sequence of points where two-coil voltage data can be reconstructed in accordance with the present invention.

5 Figure 6 illustrates graphically a sequence of points where two-coil voltage data can be reconstructed in accordance with the present invention.

Figure 7 is another schematic diagram of a mutual-balanced dip-corrected measurement in accordance with the present invention.

10 Figure 8 illustrates a flow diagram of a method for implementation of the present invention.

Figure 9 shows a logging system including a well tool and a computer apparatus in accordance with the present invention.

Figure 10 illustrates graphically the Born radial response function for a well tool design of Figure 1.

15 Figure 11 illustrates graphically the Born radial response function for dip-corrected conductivity data synthesized in accordance with the present invention.

Figure 12 illustrates graphically the Born radial response function for mutual-balanced dip-corrected conductivity data synthesized in accordance with the present invention.

20 Figure 13 shows a conductivity log of a computed response of well tool design A of Figure 1.

Figure 14 shows a conductivity log of the same data set of Figure 13 after application of the dip-correction process of the present invention.

25 Figure 15 shows a conductivity log of the same data set of Figure 13 after application of the mutual-balanced dip-correction process of the present invention.

Figure 16 shows a conductivity log of a computed response of well tool design B of Figure 1.

Figure 17 shows a conductivity log of the same data set of Figure 16 after application of the dip-correction process of the present invention.

30 Figure 18 shows a conductivity log of the same data set of Figure 16 after application of the mutual-balanced dip-correction process of the present invention.

Figure 19 shows a conductivity log of data from a field log produced by well tool design B of Figure 1.

Figure 20 shows a conductivity log of the same data set of Figure 19 after application of the dip-correction process of the present invention.

5 Figure 21 shows a conductivity log of the same data set of Figure 19 after application of the mutual-balanced dip-correction process of the present invention.

4. DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

10 In the interest of clarity, not all features of actual implementation are described in this specification. It will be appreciated that although the development of any such actual implementation might be complex and time-consuming, it would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

15 4.1 Overview of the Problem

Figure 1 shows the coil layouts of two induction array well tool designs A, B (disclosed in the '605 patent) which may be used to implement the present invention. Each design includes a transmitter T1 and a plurality of receiver pairs R_n ($n > 0$). As discussed above, energy transmitted into a formation propagates in the formation and is
20 detected by a receiver pair R_n as a complex-valued phasor voltage (not shown). Several processing steps are applied to the receiver voltage data to obtain estimates of the formation conductivity as described by J. F. Hunka et al., *A New Resistivity Measurement System for Deep Formation Imaging and High-Resolution Formation Evaluation*, Paper SPE 20559, 1990 SPE TECHNICAL CONFERENCE AND EXHIBITION, September, 1990.
25 After applying borehole corrections and skin effect corrections, a multi-channel deconvolution technique is used to produce conductivity logs with matched vertical resolution and different depths of investigation.

As discussed above, these processing techniques often produce incorrect estimations in the presence of dip or high-contrast thin layers. Figure 2 shows
30 qualitatively the focused range of investigation obtained with a well logging tool 10 disposed in a vertical well with uniform bedding planes. As seen in Figure 2, the focused

tool response is concentrated within a plane layer (A). Figure 3 shows the response when the tool 10 is disposed in a deviated borehole, or when the formation beds dip with respect to the borehole. As seen in Figure 3, the response range crosses the bedding planes to include adjacent layers (B), resulting in a corrupted measurement. In resistive
 5 beds, the logs are strongly influenced by the presence of conductive neighboring beds.

4.2 Difference Processing Method

The approach of the present invention is based on a simple property of two-coil EM measurements. Figure 4 shows a conceptual measurement with two identical
 10 transmitter coils T1, T2 and two identical receiver coils R1, R2. L_1 is the separation between transmitter T2 and receiver R1; L_2 is the separation between transmitter T1 and receiver R2. L_1 and L_2 differ by a small amount. The transmitters are activated one at a time. Let V_{21} be the voltage measured on receiver R2 when transmitter T1 is active, and V_{12} be the voltage measured on receiver R1 when transmitter T2 is active (not shown). If
 15 all the coils are in a sufficiently thick uniform layer, the voltage difference $D = V_{21} - V_{12}$ will be independent of the tool position. If the layer is sufficiently thick, the voltage difference D will have the same value as in an infinite uniform medium. The voltage difference D will be unaffected by neighboring layers, and unaffected by dip. This property of two-coil measurements is derived mathematically in the following section.
 20 The formation conductivity may be estimated by comparing the measured data for D against values (obtained from theoretical modeling) that would be obtained in an infinite uniform medium.

As seen in Figure 1, the well tool A, B has eight arrays with two receiver coils Rn each. The arrays share a common transmitter coil T1. The receiver coils Rn are
 25 connected in series in pairs. The number of turns on the receiver coils is chosen to produce a mutual balance condition (zero signal in air). Because the receiver coils Rn have unequal turns, the difference processing method (based on the difference D) cannot be applied directly. However, in tool designs A and B, the main receiver coil Rn for each array is approximately at the same distance to the transmitter T1 as the bucking coil of
 30 the next array, as seen in Figure 1 and described in the '605 patent. This overlap in coil separations makes it possible to reconstruct two-coil voltages. By interpolating and

differentiating the reconstructed two-coil voltage data, a good approximation to difference processing can be obtained.

4.3 Two-Coil Response

5 Analysis of the present invention begins with the solution for the response of a two-coil (one transmitter, one receiver) tool or sonde. [In the present disclosure, any references to coils are intended to generally mean solenoid coils, of the type used as transmitters and receivers in conventional induction and propagation well tools.] The effects of the tool and borehole are neglected; the coils are approximated as point
10 magnetic dipoles. The transmitter carries unit current (one ampere).

For a two-coil sonde, the transfer impedance Z_{RT} is defined as the receiver voltage divided by the transmitter current. Z_{RT} is expressed as

$$\begin{aligned}
 Z_{RT} = & -\frac{ik_0 Z_0}{2\pi} s_R s_T \int_0^\infty \left\{ \cos^2 \alpha q^3 J_0(q\rho) \gamma^h(z_R, z_T) \right. \\
 & + \sin \alpha \cos \alpha q^2 J_1(q\rho) \left(\frac{\partial}{\partial z_T} \gamma^h(z_R, z_T) - \frac{\partial}{\partial z_R} \gamma^h(z_R, z_T) \right) \\
 & + \sin^2 \alpha q J_1'(q\rho) \left(\frac{\partial}{\partial z_R} \frac{\partial}{\partial z_T} \gamma^h(z_R, z_T) \right) \\
 & \left. + k_0^2 \sin^2 \alpha \frac{1}{\rho} J_1(q\rho) \mu_r(z_R) \mu_r(z_T) \gamma^e(z_R, z_T) \right\} dq. \quad (1)
 \end{aligned}$$

Here s_T is the transmitter dipole strength (number of turns $\times$ area); s_R is the receiver dipole strength. z_T and z_R denote the respective vertical position (formation depth) of the
20 transmitter and receiver coils, ρ is the horizontal separation. The dip angle α is assumed to be constant. J_0 , and J_1 are Bessel functions of order zero and unity; J_1' is the derivative of J_1 .

The electrical parameters of the medium are represented by

$$k_0 = \omega \sqrt{\mu_0 \epsilon_0}, \quad \epsilon_r = \frac{\epsilon}{\epsilon_0} + \frac{i\sigma}{\omega \epsilon_0}, \quad \mu_r = \frac{\mu}{\mu_0}, \quad (2)$$

where ε , μ and σ respectively represent permittivity, permeability, and conductivity. ω is the angular frequency. The zero subscripts on ε and μ denote free-space values. $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 376.7$ ohms is the impedance of free space.

To construct the Green's functions γ , consider first solutions of the homogeneous
5 one-dimensional equations

$$\begin{aligned}\frac{d}{dz} \frac{1}{\varepsilon_r} \frac{d}{dz} \psi^e + \left(k_0^2 \mu_r - \frac{q^2}{\varepsilon_r} \right) \psi^e &= 0, \\ \frac{d}{dz} \frac{1}{\mu_r} \frac{d}{dz} \psi^h + \left(k_0^2 \varepsilon_r - \frac{q^2}{\mu_r} \right) \psi^h &= 0.\end{aligned}\quad (3)$$

Let ψ^{e-} , ψ^{h-} be solutions that are regular at $z = -\infty$ and ψ^{e+} , ψ^{h+} solutions that are regular
10 at $z = +\infty$. From these solutions one can construct Green's functions by Lagrange's method. The Green's functions γ are solutions of the equations

$$\begin{aligned}\frac{d}{dz} \frac{1}{\varepsilon_r} \frac{d}{dz} \gamma^e(z, z') + \left(k_0^2 \mu_r - \frac{q^2}{\varepsilon_r} \right) \gamma^e(z, z') &= \delta(z - z'), \\ \frac{d}{dz} \frac{1}{\mu_r} \frac{d}{dz} \gamma^h(z, z') + \left(k_0^2 \varepsilon_r - \frac{q^2}{\mu_r} \right) \gamma^h(z, z') &= \delta(z - z').\end{aligned}\quad (4)$$

15 They can be computed from the expressions

$$\begin{aligned}\gamma^e(z, z') &= \frac{\psi^{e-}(z_<) \psi^{e+}(z_>)}{W^e}, \\ \gamma^h(z, z') &= \frac{\psi^{h-}(z_<) \psi^{h+}(z_>)}{W^h},\end{aligned}\quad (5)$$

where $z_< = \min(z, z')$, and $z_> = \max(z, z')$. The Wronskians W^e , W^h , defined by

$$\begin{aligned}W^e &= \frac{1}{\varepsilon_r} \left[\psi^{e-}(z) \frac{d}{dz} \psi^{e+}(z) - \psi^{e+}(z) \frac{d}{dz} \psi^{e-}(z) \right], \\ W^h &= \frac{1}{\mu_r} \left[\psi^{h-}(z) \frac{d}{dz} \psi^{h+}(z) - \psi^{h+}(z) \frac{d}{dz} \psi^{h-}(z) \right],\end{aligned}\quad (6)$$

are independent of z .

When the dip angle α is larger than about 45 degrees, the convergence of the integral is slow, and it is then advantageous to use contour integration in the complex plane of q . By using the identities

$$J_0(x) = \frac{1}{2} [H_0^{(1)}(x) - H_0^{(1)}(xe^{i\pi})], \quad J_1(x) = \frac{1}{2} [H_1^{(1)}(x) - H_1^{(1)}(xe^{i\pi})], \quad (7)$$

equation (1) can be written as a contour integral, where the path of integration C must lie above the origin and below the singularities of γ^e and γ^h :

$$\begin{aligned} Z_{RT} = & -\frac{ik_0 Z_0}{4\pi} s_R s_T \int_C \{ \cos^2 \alpha q^3 H_0^{(1)}(q\rho) \gamma^h(z_R, z_T) \\ & + \sin \alpha \cos \alpha q^2 H_1^{(1)}(q\rho) \left(\frac{\partial}{\partial z_T} \gamma^h(z_R, z_T) - \frac{\partial}{\partial z_R} \gamma^h(z_R, z_T) \right) \\ & + \sin^2 \alpha q H_1^{(1)'}(q\rho) \left(\frac{\partial}{\partial z_R} \frac{\partial}{\partial z_T} \gamma^h(z_R, z_T) \right) \\ & + k_0^2 \sin^2 \alpha \frac{1}{\rho} H_1^{(1)}(q\rho) \mu_r(z_R) \mu_r(z_T) \gamma^e(z_R, z_T) \} dq. \end{aligned} \quad (8)$$

Equation (5) shows that the Green's functions γ are symmetric:

$$\gamma^e(z_R, z_T) = \gamma^e(z_T, z_R), \quad \gamma^h(z_R, z_T) = \gamma^h(z_T, z_R). \quad (9)$$

From equation (4), it is seen that γ^e and γ^h satisfy the following partial differential equations:

$$\begin{aligned} & \left(\epsilon_r(z_R) \frac{\partial}{\partial z_R} \frac{1}{\epsilon_r(z_R)} \frac{\partial}{\partial z_R} - \epsilon_r(z_T) \frac{\partial}{\partial z_T} \frac{1}{\epsilon_r(z_T)} \frac{\partial}{\partial z_T} \right) \gamma^e(z_R, z_T) \\ & = -k_0^2 (\mu_r(z_R) \epsilon_r(z_R) - \mu_r(z_T) \epsilon_r(z_T)) \gamma^e(z_R, z_T), \\ & \left(\mu_r(z_R) \frac{\partial}{\partial z_R} \frac{1}{\mu_r(z_R)} \frac{\partial}{\partial z_R} - \mu_r(z_T) \frac{\partial}{\partial z_T} \frac{1}{\mu_r(z_T)} \frac{\partial}{\partial z_T} \right) \gamma^h(z_R, z_T) \\ & = -k_0^2 (\epsilon_r(z_R) \mu_r(z_R) - \epsilon_r(z_T) \mu_r(z_T)) \gamma^h(z_R, z_T). \end{aligned} \quad (10)$$

If the transmitter and receiver coils are both in a uniform layer with no z variation, one simply gets

$$\begin{aligned}\left(\frac{\partial^2}{\partial z_R^2} - \frac{\partial^2}{\partial z_T^2}\right)\gamma^e(z_R, z_T) &= 0, \\ \left(\frac{\partial^2}{\partial z_R^2} - \frac{\partial^2}{\partial z_T^2}\right)\gamma^h(z_R, z_T) &= 0.\end{aligned}\tag{11}$$

5

The partial derivatives can be factored as

$$\begin{aligned}\left(\frac{\partial}{\partial z_R} + \frac{\partial}{\partial z_T}\right)\left(\frac{\partial}{\partial z_R} - \frac{\partial}{\partial z_T}\right)\gamma^e(z_R, z_T) &= 0, \\ \left(\frac{\partial}{\partial z_R} + \frac{\partial}{\partial z_T}\right)\left(\frac{\partial}{\partial z_R} - \frac{\partial}{\partial z_T}\right)\gamma^h(z_R, z_T) &= 0.\end{aligned}\tag{12}$$

10 The desired result is that

$$\begin{aligned}\left(\frac{\partial}{\partial z_R} - \frac{\partial}{\partial z_T}\right)\gamma^e(z_R, z_T) &= C^e, \\ \left(\frac{\partial}{\partial z_R} - \frac{\partial}{\partial z_T}\right)\gamma^h(z_R, z_T) &= C^h,\end{aligned}\tag{13}$$

where C^e and C^h are independent of $(z_R + z_T)/2$, i.e., independent of the tool position. In a sufficiently thick layer, C^e and C^h will have the same values as in an infinite uniform medium.

15

In a uniform layer, these quantities can be evaluated analytically. Suppose that the electrical parameters ϵ_r, μ_r are independent of z in an interval $z_L < z_T < z_R < z_H$. The solutions Ψ^-, Ψ^+ , from equation (3), have the form

20

$$\begin{aligned}\psi^- &= A^-(e^{\beta z} + R^- e^{-\beta(z-2z_L)}), \\ \psi^+ &= A^+(e^{-\beta z} + R^+ e^{\beta(z-2z_H)}),\end{aligned}\tag{14}$$

where

$$\beta = \sqrt{q^2 - k_0^2 \epsilon_r \mu_r} . \quad (15)$$

The branch of the square root that makes real $(\beta) \geq 0$ should be chosen. Equation (5) gives

$$\left(\frac{\partial}{\partial z_R} - \frac{\partial}{\partial z_T} \right) \gamma^e(z_R, z_T) = \epsilon_r e^{-\beta(z_R - z_T)} \frac{1 - R^- R^+ e^{-2\beta(z_H - z_L - z_R + z_T)}}{1 - R^- R^+ e^{-2\beta(z_H - z_L)}} , \quad (16)$$

and a similar expression for γ^h . If $R^- = 0$ or $R^+ = 0$, we get the same result as in an infinite uniform medium. In particular, a semi-infinite uniform layer gives the same result as the infinite uniform medium. The first order terms in the reflection coefficients R^- , R^+ cancel; only the product $R^- R^+$ survives. Generally, the magnitude of reflection coefficients is smaller than unity. The exponential factor provides further attenuation since real $(\beta) \geq 0$. Thus one can expect that, in a thick layer,

$$\left| R^- R^+ e^{-2\beta(z_H - z_L)} \right| < \left| R^- R^+ e^{-2\beta(z_H - z_L - z_R + z_T)} \right| \ll 1 , \quad (17)$$

giving approximately the same result as an infinite uniform medium. It is seen that the partial derivatives in equation (13) suppress reflected waves to first order, which leads to reduced shoulder effect in the estimated conductivity.

These relations are now expressed in terms of the log depth h (measured along the borehole):

$$\begin{aligned} z_R &= h_R \cos \alpha , \\ z_T &= h_T \cos \alpha , \end{aligned} \quad (18)$$

$$\begin{aligned} \left(\frac{\partial}{\partial h_R} - \frac{\partial}{\partial h_T} \right) \gamma^e(z_R, z_T) &= C^e \cos \alpha , \\ \left(\frac{\partial}{\partial h_R} - \frac{\partial}{\partial h_T} \right) \gamma^h(z_R, z_T) &= C^h \cos \alpha . \end{aligned} \quad (19)$$

The horizontal separation ρ can be expressed as $\rho = |h_R - h_T| \sin \alpha$. For any function of ρ ,

$$\left(\frac{\partial}{\partial h_R} - \frac{\partial}{\partial h_T} \right) J(q\rho) = 2 \text{sign}(h_R - h_T) \sin \alpha \frac{\partial}{\partial \rho} J(q\rho) \quad (20)$$

is independent of the tool log depth $(h_R + h_T)/2$. This information allows one to conclude that, if the transmitter and receiver coils are in a uniform layer,

$$\left(\frac{\partial}{\partial h_R} - \frac{\partial}{\partial h_T} \right) Z_{RT} = \text{constant} \quad (21)$$

will be independent of the tool position. Differentiation under the integral signs in equation (1) or (8) is permissible because the integrand has the necessary smoothness and convergence properties. The constant in equation (21) will be the same as in an infinite uniform medium provided the layer is sufficiently thick.

4.4 Inferences from the Analysis

Certain inferences can be drawn from the analysis. The partial derivative in equation (21) can be approximated by a finite difference, varying the separation between the transmitter and receiver in a two-coil sonde. Let $v(h_R, h_T)$ denote the phasor voltage measured at the receiver coil of the two-coil sonde, where h_R, h_T are the positions of the two coils measured downward along the tool axis. If the transmitter current is I amperes, we have, from equation (1),

$$v(h_R, h_T) = I Z_{RT}(h_R, h_T). \quad (22)$$

If the transmitter and receiver coils are in a uniform layer, then, according to equation (21),

$$\left(\frac{\partial}{\partial h_R} - \frac{\partial}{\partial h_T} \right) v(h_R, h_T) = \text{constant} \quad (23)$$

where the constant is independent of $h_R + h_T$. In a thick layer, the constant has the same value as for an infinite homogeneous medium.

Reference is made again to Figure 4, which shows a conceptual measurement to exploit this relationship. The separation L between the transmitter T1 and receiver coils

R1, R2 (dashed lines represent the tool axis) is varied by a small amount, while the midpoint between the transmitter coil T1 and receiver coils R1, R2 is held fixed. Equation (23) shows that the difference in the measured voltage is independent of position if all the coils are in a uniform layer. In a thick bed, the voltage difference is not
 5 affected by the shoulder beds, even in the presence of dip.

The same analysis can be extended to an anisotropic layered formation that is transversely isotropic. It is also applicable to measurements with transmitter or receiver coils that are tilted relative to the tool's longitudinal axis. Also noteworthy is the fact that the dip angle is not required to apply this method. Borehole effects will have more
 10 impact on the disclosed techniques as compared to conventional processing, but are still correctable.

4.5 Tool Sensitivity Factor

In order to reconstruct the two-coil response from the voltage data obtained from
 15 the well tool, the fact that the receiver pairs Rn of the tool have unequal coil turns must be taken into account. Considering the response of a well tool in an infinite homogeneous isotropic medium, the receiver voltage V can be expressed as

$$V = \frac{i\omega\mu}{2\pi} \sum_r \sum_t I N_r A_r N_t A_t e^{ik|h_r - h_t|} (1 - ik|h_r - h_t|) |h_r - h_t|^{-3}. \quad (24)$$

20 Here N_r is the number of turns in a receiver coil, A_r is the effective area of the coil, and I is the transmitter current. Denote the respective positions of the tool transmitter and receiver coils along the tool axis by h_r , h_t . The propagation coefficient k can be computed from

$$k = \sqrt{\varepsilon\mu\omega^2 + i\omega\mu\sigma}, \quad \text{real}(k) \geq 0. \quad (25)$$

25

Here ω is the angular frequency; ε , μ and σ respectively represent permittivity, permeability, and conductivity of the medium.

As described in the '605 patent, the signal developed for each channel j (originating from receiver pair Rn) of the tool is a complex-valued apparent conductivity

σ_{AIT}^j proportional to the receiver voltage V^j , i.e., $\sigma_{AIT}^j = V^j/K_j$. The sensitivity factor K is obtained from the behavior of V at low conductivity, $\sigma \approx 0$:

$$V \approx \frac{i\omega\mu}{2\pi} \sum_i \sum_r IN_r A_r N_i A_i |h_r - h_i|^{-3} - \sigma \sum_i \sum_r \frac{i\omega\mu}{4\pi} IN_r A_r N_i A_i |h_r - h_i|^{-1}. \quad (26)$$

5

To achieve mutual balance, the coil turns are chosen so that

$$\sum_i \sum_r N_r A_r N_i A_i |h_r - h_i|^{-3} = 0, \quad (27)$$

leaving

10

$$V \approx K\sigma,$$

where

$$K = -\sum_i \sum_r \frac{\omega^2 \mu^2}{4\pi} IN_r A_r N_i A_i |h_r - h_i|^{-1}. \quad (28)$$

15

For the well tool designs A, B of Figure 1, this expression simplifies because there is only one transmitter coil T1. The effective area A_r is also the same for all the receiver coils R_n . To reconstruct two-coil responses from the tool voltage data, N_r and $|h_r - h_i|$ need to be taken into account.

4.6 Implementation

20

Processing of the well tool voltage data begins with accessing the data from the tool in the manner described in the '605 patent. In tool design A, some of the arrays operate at two frequencies. The channel number j (not shown) identifies the receiver pair R_n and frequency of the voltage datum. The voltage data for each channel are then transmitted to the surface to be stored and processed as described below.

25

4.6.1 Boosting

A preliminary estimation of the formation conductivity may be derived at this point by boosting the voltage data. Boosting refers to homogeneous medium inversion. Theoretically, homogeneous medium inversion should be the last processing step. However, since the non-linearity of the data is mild, it is more convenient to apply this correction first.

The homogeneous medium conductivity σ_b may be determined in different ways. One way is by using a weighted least squares criterion, for example, one can minimize

$$\varepsilon^j = w \left[\text{real} \left(V_{\text{homog}}^j(\sigma_b) - V_{\text{meas}}^j \right) \right]^2 + (1 - w) \left[\text{imag} \left(V_{\text{homog}}^j(\sigma_b) - V_{\text{meas}}^j \right) \right]^2, \quad (29)$$

10

where the infinite homogeneous voltage V_{homog}^j is computed using equation (24). V_{meas}^j denotes the measured tool voltage data value for channel j . The constant weight w , $0 \leq w \leq 1$, can be adjusted to give more or less emphasis to the real part of V_{meas}^j . For low-conductivity formations, the stored voltage data may be boosted by deriving the following formula:

15

$$\sigma_b \approx \frac{1}{K_j} \left(\text{real } V_{\text{meas}}^j + \text{imag } V_{\text{meas}}^j \right). \quad (30)$$

Another boosting technique may be implemented by establishing a table of voltage data values associated with formation conductivity (based on theoretical modeling) and looking up the tool voltage data values within the table to reference a conductivity value.

20

4.6.2 Reconstructing Two-Coil Voltages

To reconstruct two-coil voltages v^j from well tool voltages V_j , one first computes tool voltages from the boosted apparent conductivity σ_{AIT}^j recorded for each channel j :

25

$$V^j = K_j \sigma_{AIT}^j, \quad (31)$$

here K_j is the channel j sensitivity factor.

The relation between the tool voltage V_j and the two-coil voltage v^j is

$$N_2^j v^j + N_1^j v^{j-1} = V^j, \quad (32)$$

where N_1^j , N_2^j represent the number of turns of the first and second receiver coils of the receiver pair R_n at channel j .

5 This relation allows one to solve for the two-coil voltage v^j recursively:

$$v^j = (V^j - N_1^j v^{j-1}) / N_2^j. \quad (33)$$

An estimate of the first two-coil voltage v^1 is needed to start the recursion in equation (33). One useful estimation formula assumes that

$$10 \quad v^1 / \kappa_1 = v^2 / \kappa_2 \quad (34)$$

where κ is the two-coil sensitivity factor.

4.6.3 Processing Reconstructed Voltages

15 The two-coil voltage v can then be computed for arbitrary two-coil spacings $q = h_R - h_T$ by interpolating v from the tabulated values obtained with equation (33). Linear or spline interpolation may be used for the interpolation. From the interpolated values of v , one can then evaluate an estimator σ_{Grim}^j of the formation conductivity,

$$\sigma_{Grim}^j = \frac{1}{k_j} \frac{\Delta v^j}{\Delta q_j}, \quad (35)$$

20 where Δq_j is the increment in the receiver-to-transmitter spacing for channel j , and k_j is the sensitivity factor for $\Delta v^j / \Delta q_j$.

An alternative approach to selecting the first two-coil voltage v^1 for the recursion in equation (33) can be formulated in terms of σ_{Grim}^j :

$$\sigma_{Grim}^1 = \sigma_{Grim}^2. \quad (36)$$

25

The end product of these processing steps is a set of seven conductivity curves representing measurements of the type shown in Figure 4, with the spacings L_1 , L_2 listed in Table 1.

TABLE 1

Channel	Short Spacing L_1	Long Spacing L_2
	(inches)	(inches)
9	6	9
12	9	12
15	12	15
21	18	21
27	24	27
39	36	39
54	51	54
72	69	72

With these spacings, $\Delta q_j = 3$ inches for all the channels j , which gives approximately matched vertical resolution.

Once derived, the conductivity estimators σ_{Grim}^j may be stored and recorded on a suitable output record medium to produce a conductivity log as known in the art.

As noted above, the dip angle is not required to apply this method.

4.6.4 Data Shifting

The derivative $\Delta v^j / \Delta q_j$ must be evaluated with $h_R + h_T$ held constant. Therefore, depth shifts of the tabular boosted tool voltage data must be performed before and after reconstruction of the two-coil voltages v^j of equation (33). The depth shifts performed before and after reconstruction are hereafter respectively referred to as forward and backward shifting. By shifting the tool voltage data, the midpoint between the receivers

Rn and the transmitter T1 is kept fixed as defined by the voltage data. These depth shifts are measured in units of inches for convenience.

Figures 5 and 6 show the sequence of points in the $h_t - h_r$ plane where the two-coil voltage v^j can be reconstructed, for the tool designs A, B of Figure 1, by applying equation (33). The line segments represent the measured tool voltage data. The reciprocity property of equation (22) is used to reconstruct v at the small circles in Figure 5 for the tool design A. The necessary forward and backward shifts of the tabular data are given in Table 2. As known in the art, a decrease in depth within a borehole is given a negative sign.

TABLE 2

Channel	TOOL-A Shifts (inches)		TOOL-B Shifts (inches)	
	Forward	Backward	Forward	Backward
9	0	4.5	0	4.5
12	-9	3.0	0	6.0
15	3	4.5	0	7.5
21	-12	1.5	0	10.5
27	9	4.5	0	13.5
39	-18	-1.5	0	19.5
54	-18	-9.0	0	27.0
72	-18	-18.0	0	36.0

As shown in Table 2, no forward shifting of the data is needed for the tool design B because the receiver pairs Rn are all below the transmitter T1. At high dip angle (above 60 degrees), these shifts become unimportant and may be omitted.

4.7 Mutual Balance Condition

Figure 7 illustrates an alternative coil configuration that can be synthesized from the tool voltage data. After computing and storing the estimators σ_{Grim}^j for each channel j , they are combined in pairs (using different spacings q_j with suitable weights) to achieve mutual balance. Once derived, the combined conductivity estimator σ_{Grim}^j may be stored

and recorded on a suitable output record medium to produce a conductivity log as known in the art.

Transmitters T1-T4 have the same number of coil turns. The receiver coil Rn turns N are equal and opposite for each synthesized pair:

$$N_2 = -N_1, \quad N_4 = -N_3. \quad (37)$$

The mutual balance condition, equation (27), gives

$$\frac{N_3}{N_1} = -\frac{L_1^{-3} - L_2^{-3}}{L_3^{-3} - L_4^{-3}}. \quad (38)$$

The mutual balance condition produces zero signal in air, canceling the primary field as known in the art. This configuration provides an improved response in the radial direction (perpendicular to the tool axis), but a caveat is that it also increases the noise amplification factor.

Figure 8 illustrates a flow diagram of a method 100 for producing a conductivity log from voltage data developed by the tool when the is disposed in a borehole traversing a formation. The method comprises accessing the voltage data developed by the tool 105; boosting the voltage data 110; reconstructing two-coil voltages from the boosted voltage data 115; processing the reconstructed two-coil voltages 120; and producing the conductivity log from the processed two-coil voltages 125.

4.8 Program Storage Device

It will be apparent to those of ordinary skill having the benefit of this disclosure that the present invention may be implemented by programming one or more suitable general-purpose computers having appropriate hardware. The programming may be accomplished through the use of one or more program storage devices readable by the computer processor and encoding one or more programs of instructions executable by the computer for performing the operations described above. The program storage device may take the form of, e.g., one or more floppy disks; a CD ROM or other optical disk; a magnetic tape; a read-only memory chip (ROM); and other forms of the kind well-known in the art or subsequently developed. The program of instructions may be "object code,"

i.e., in binary form that is executable more-or-less directly by the computer; in “source code” that requires compilation or interpretation before execution; or in some intermediate form such as partially compiled code. The precise forms of the program storage device and of the encoding of instructions is immaterial here.

5

4.9 Logging System

The present invention may be implemented in a well logging system 200 including a well tool 205 adapted to be moveable through a borehole and an apparatus 210 coupled to the tool 205, as illustrated in Figure 9 and described in the ‘605 patent. Certain conventional details are omitted in Figure 9 for clarity of illustration. The apparatus 210 comprises a surface computer (such as the general-purpose computer and program storage device described above) coupled to the well tool 205 by a wireline cable 215 or linked to the tool string’s surface instrumentation as known in the art. The tool 205 may be a propagation or induction well tool that embodies the disclosed coil configurations and conditions. The system may also be implemented in a wireline, or logging-while-drilling (“LWD”), or measurement-while-drilling (“MWD”) operation.

The formation conductivity can be determined in real-time by sending the voltage data to the surface as they are acquired, or it can be determined from a recorded-mode by recording the data on a suitable recordable medium. As known in the art, the voltage data are transmitted from the tool 205 to the surface computer 210 by electronics (not shown) housed in the tool 205. The voltage data may be sent to the surface computer 210 along the wireline cable 215 or by MWD telemetry as known in the art. It will be understood that alternative means can be employed for communicating the acquired data to the surface as the precise form of communication is immaterial to the implementation of the disclosed techniques.

Once received by the surface computer 210, the data can be recorded, processed, or computed as desired by the user to generate a formation conductivity profile. The surface computer 210 is capable of producing a conductivity log from the processed conductivity estimators σ_{Grim}^j . The log can then be recorded on a suitable output record medium. Alternatively, some or all of the processing can be performed downhole and the

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data can be recorded uphole, downhole, or both. It will be understood that the present invention can be implemented in conjunction with any suitable technique for keeping track of the tool 205 depth within a borehole.

5 4.10 Model Examples

Figures 10 and 11 respectively show the radial Born response functions (Born kernels) for the tool design A and for the synthesized conductivity estimators σ_{Grim}^j . The Born kernels give the sensitivity of the measurement to the conductivity in the formation at different radial distances to the tool's axis. The Born kernels were computed for zero
10 background conductivity and normalized to unit peak response. As seen in Figure 11, the response curves for the synthesized estimator σ_{Grim}^j are shallower than for the tool design A measurements, and not as well focused. Turning to Figure 12, it is seen that for the mutual-balanced processing technique, the radial response is considerably improved.

For the well tool designs A, B of Figure 1, reliable radial profiling of the
15 formation conductivity can be obtained out to a radius of 60 inches. Radial profiling out to 24 inches should be possible for the estimator σ_{Grim}^j processed data, and out to 36 inches with the balanced processing technique. However, a caveat is that the balanced processing technique is more sensitive to errors in the measured data.

20 4.11 Processed Examples

In this section, results obtained from computations of test data and actual field data are presented. Figure 13 shows a conductivity log produced by shifting and boosting a computed response of the tool design A using equation (30). The Oklahoma formation was used (a frequently used test problem to evaluate conductivity processing)
25 in the computation. The dip angle is 75 degrees. Horns are present at the bed boundaries, as often seen in field logs at high dip angle. The logs in the low-conductivity layers are filled in by the adjacent conductive layers (shoulder effect).

Figure 14 shows the results obtained with the same data set of Figure 13 after applying the process of the present invention. The curves show good resolution
30 matching, and the accuracy of the logs in the resistive layers is considerably improved.

Because hydrocarbon-bearing layers usually have a relatively low conductivity, correcting the shoulder effect is desirable for quantitative formation evaluation. Figure 15 shows the results obtained with the same data set of Figure 13 after applying the mutual balancing technique. As seen in Figure 15, there is a visible loss of vertical performance with the mutual balancing technique.

Similar results are found for the tool design B. Figure 16 shows a conductivity log produced by shifting and boosting a computed response of the tool design B in the Oklahoma formation. The dip angle is again 75 degrees. Figure 17 shows the results obtained with the same data set of Figure 16 after applying the process of the present invention. Figure 18 shows the results obtained with the same data set of Figure 16 after applying the mutual balancing technique.

Figure 19 shows a conductivity log produced by shifting and boosting a set of raw signals, derived from a tool design B field log, using the least squares equation (29). Figure 20 shows the results obtained with the same raw signals of Figure 19 after applying the process of the present invention. As seen in Figure 20, the processed signals display a dramatic improvement in the vertical resolution, revealing features not clearly seen in the raw data. The processed curves overlay closely, indicating there was no invasion. Figure 21 shows the results obtained with the same raw signals as Figure 19 after applying the mutual-balancing technique. The balanced technique also behaves well with this data set, but the vertical resolution is not as sharp.

While the methods and apparatus of this invention have been described as specific embodiments, it will be apparent to those skilled in the art that variations may be applied to the structures and in the steps or in the sequence of steps of the methods described herein without departing from the concept and scope of the invention. All such similar variations apparent to those skilled in the art are deemed to be within this concept and scope of the invention as defined by the appended claims.

CLAIMS:

1. A method for producing a log unaffected by shoulder effect and dip from data developed by a well tool (205), wherein the tool includes a transmitter and a plurality of receiver pairs, when the tool is disposed in a borehole traversing a formation, the method characterized by:

- a) accessing the developed tool data;
- b) boosting the developed tool data;
- c) reconstructing two-coil voltages from the boosted tool data;
- d) processing the reconstructed two-coil voltages; and
- e) producing the log from the processed two-coil voltages.

2. The method of claim 1, wherein step (b) comprises:

- i) establishing data values associated with formation conductivity values based on theoretical modeling and referencing the tool data within the established data values to determine conductivity values; and
- ii) recording the conductivity values on an output record medium.

3. The method of claim 1, wherein step (b) comprises calculating the following expression:

$$\sigma_b \approx \frac{1}{K_j} (\text{real} V_{meas}^j + \text{imag} V_{meas}^j)$$

where,

V_{meas}^j is a tool voltage data value; and
 K_j is a channel sensitivity factor.

4. The method of claim 1, wherein step (c) comprises shifting the boosted tool data by a predetermined depth shift.

5. The method of claim 1, wherein step (d) comprises interpolating a two-coil voltage to reflect a specific two-coil spacing.

6. The method of claim 1, wherein step (c) comprises calculating the following expression:

$$v^j = (V^j - N_1^j v^{j-1}) / N_2^j$$

where,

v^j represents a two-coil voltage;
 V^j is a tool voltage data value from a tool channel j ; and
 N_1^j, N_2^j are the respective number of turns on first and second receiver coils.

7. The method of claim 6, wherein step (c) comprises estimating an initial value for (v^1) .
8. The method of claim 1, wherein step (d) comprises shifting the reconstructed two-coil voltages by a predetermined depth shift.
9. The method of claim 1, wherein step (d) comprises calculating the following expression:

$$\sigma_{Grim}^j = \frac{1}{k_j} \frac{\Delta v^j}{\Delta q_j}$$

where,

v^j is a two-coil voltage;
 k_j is a sensitivity factor sensitivity factor of a two-coil channel;
 q_j is a receiver-to-transmitter spacing; and
 Δ indicates calculating the difference.

10. The method of claim 9, step (d) further comprising storing the calculated values of (σ_{Grim}^j) .
11. The method of claim 10, step (d) further comprising combining the stored values of (σ_{Grim}^j) to produce a condition of mutual balance.

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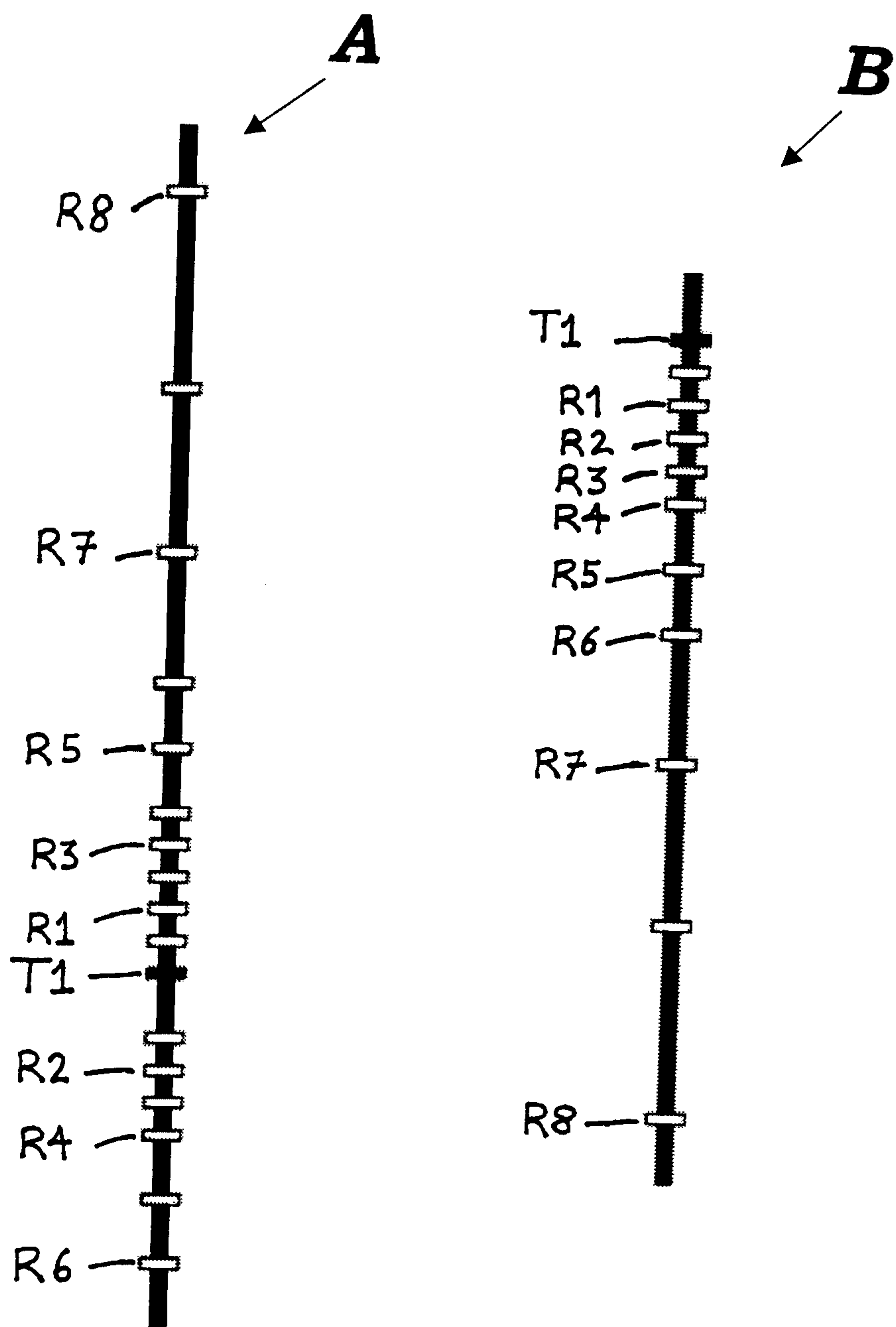
*FIG. 1*

FIG. 2

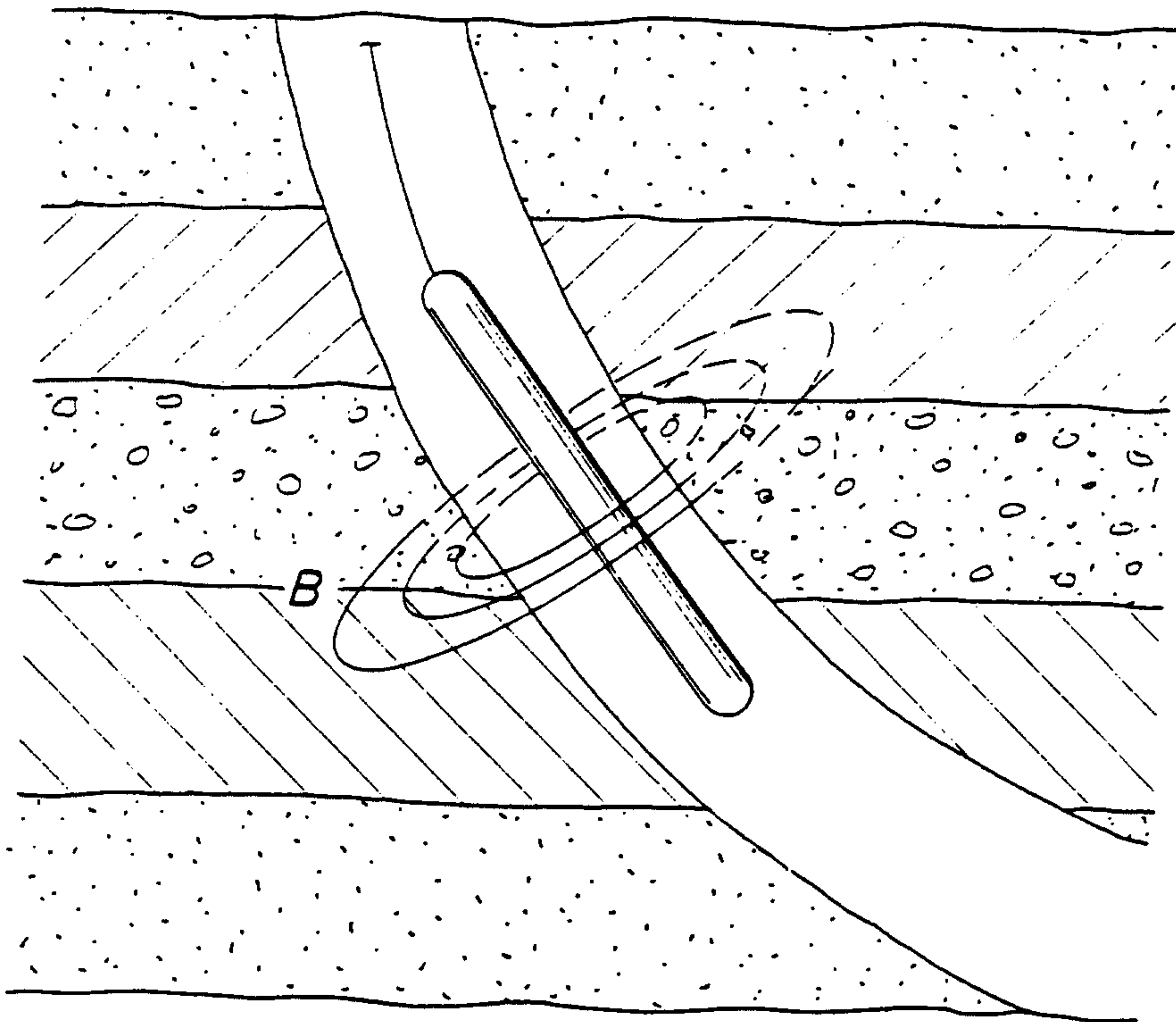
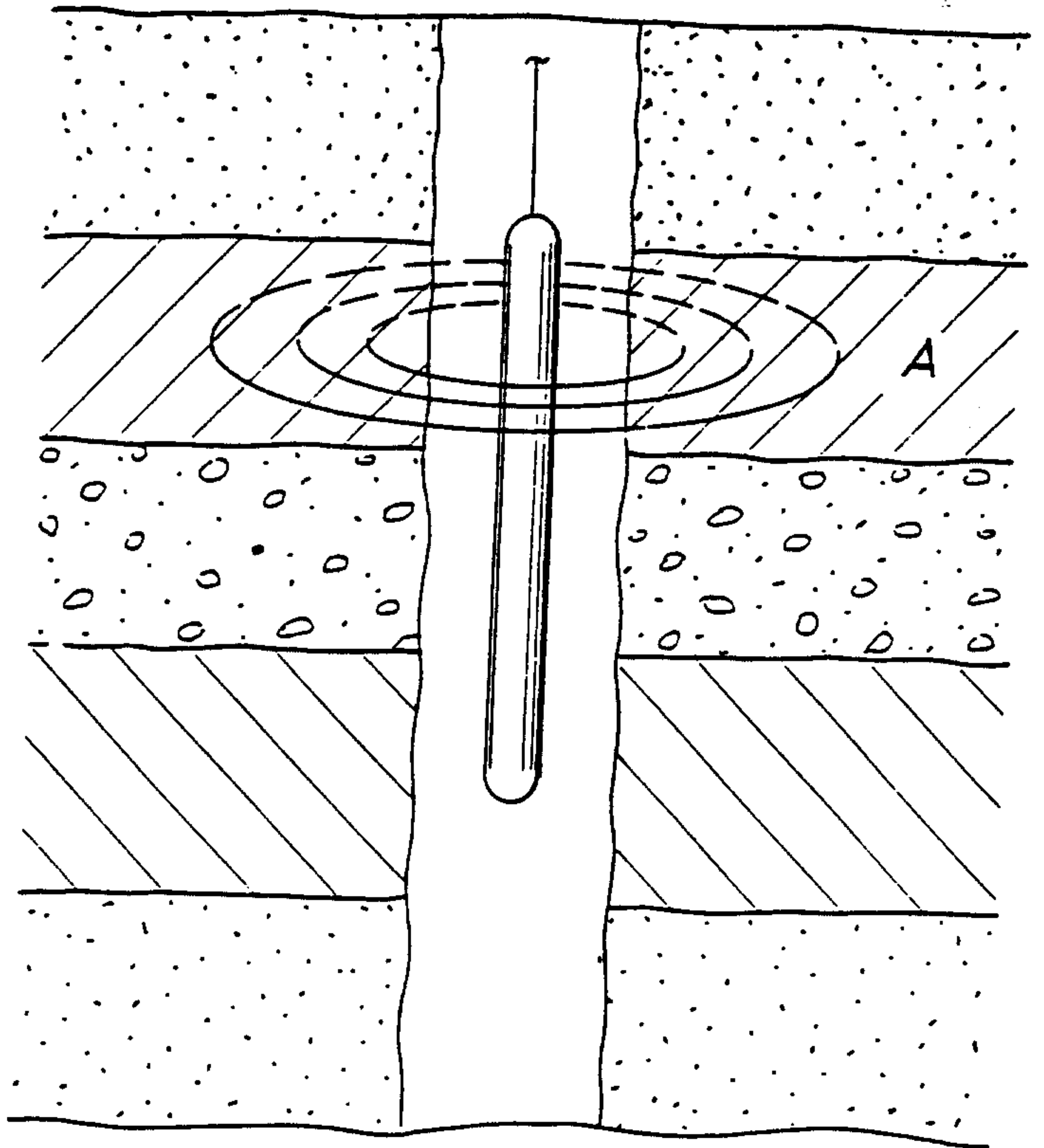


FIG. 3

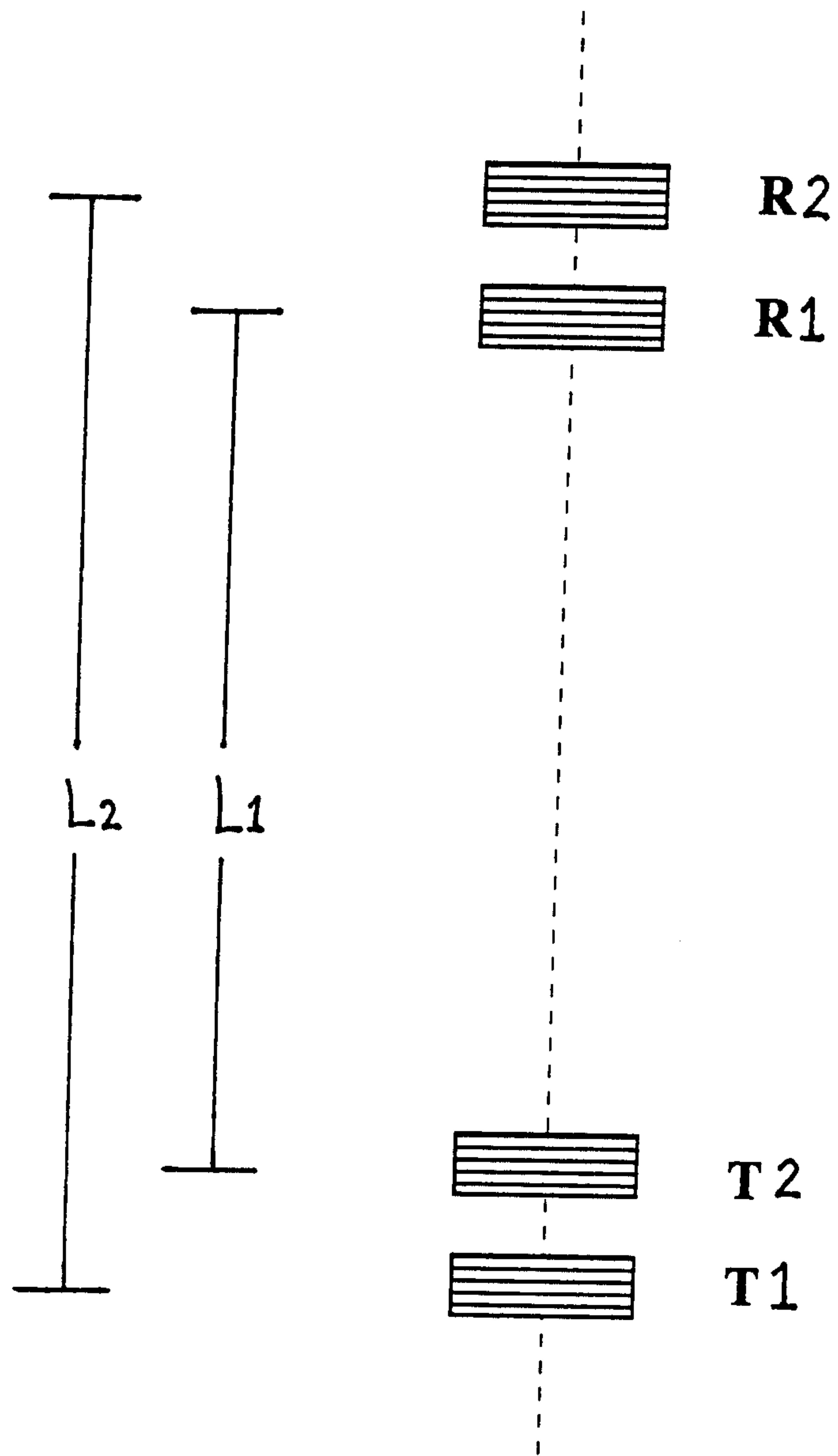
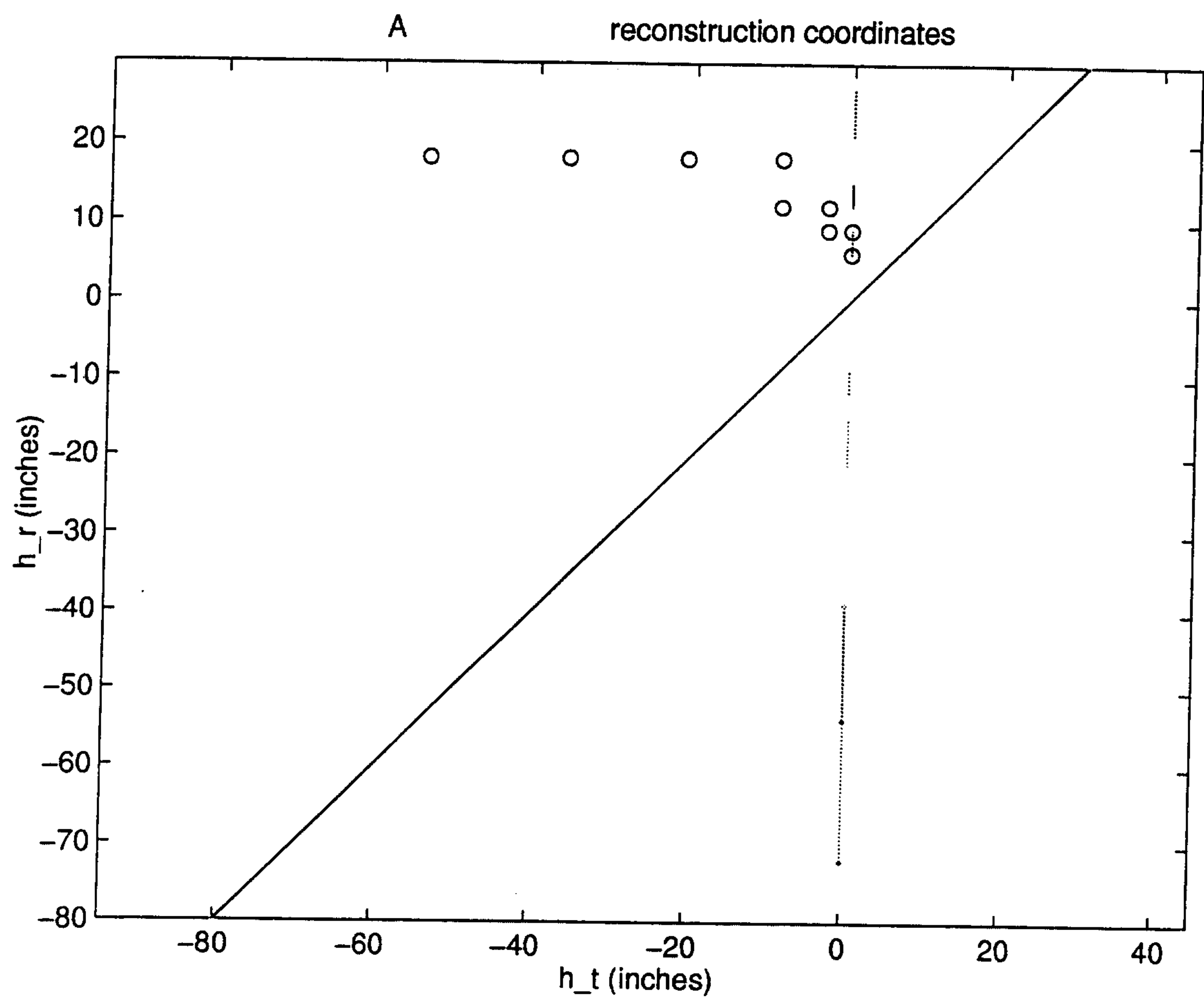
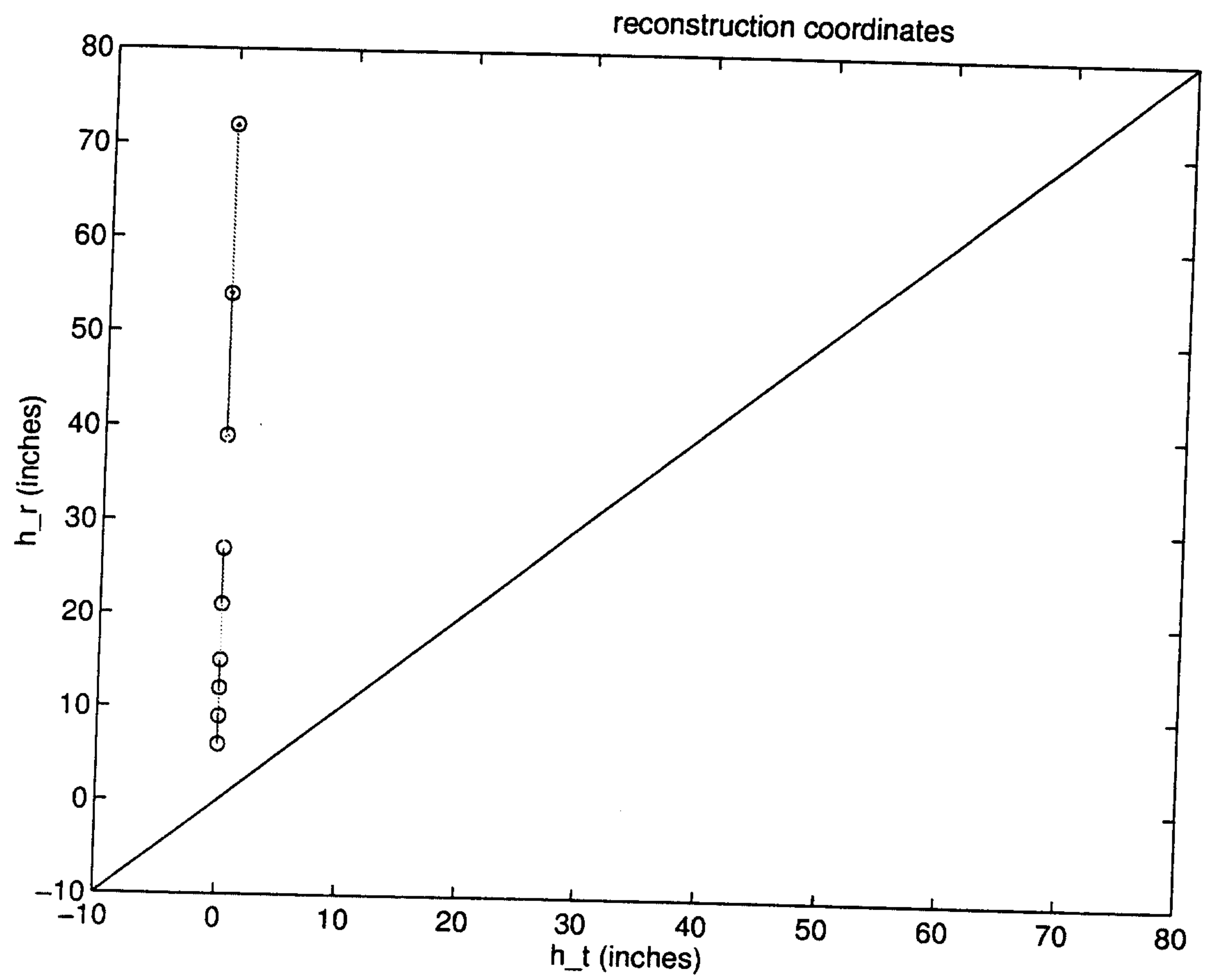
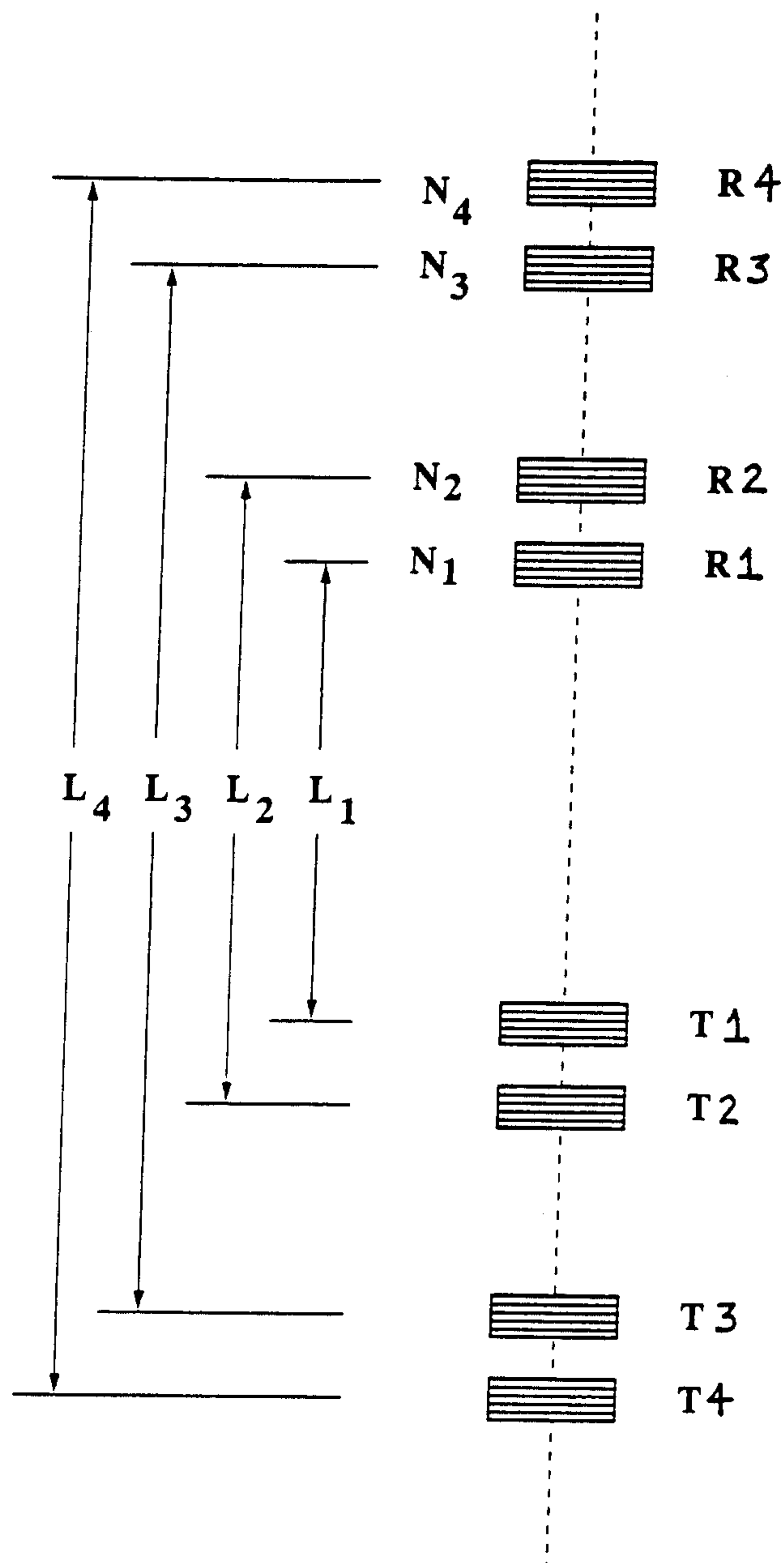
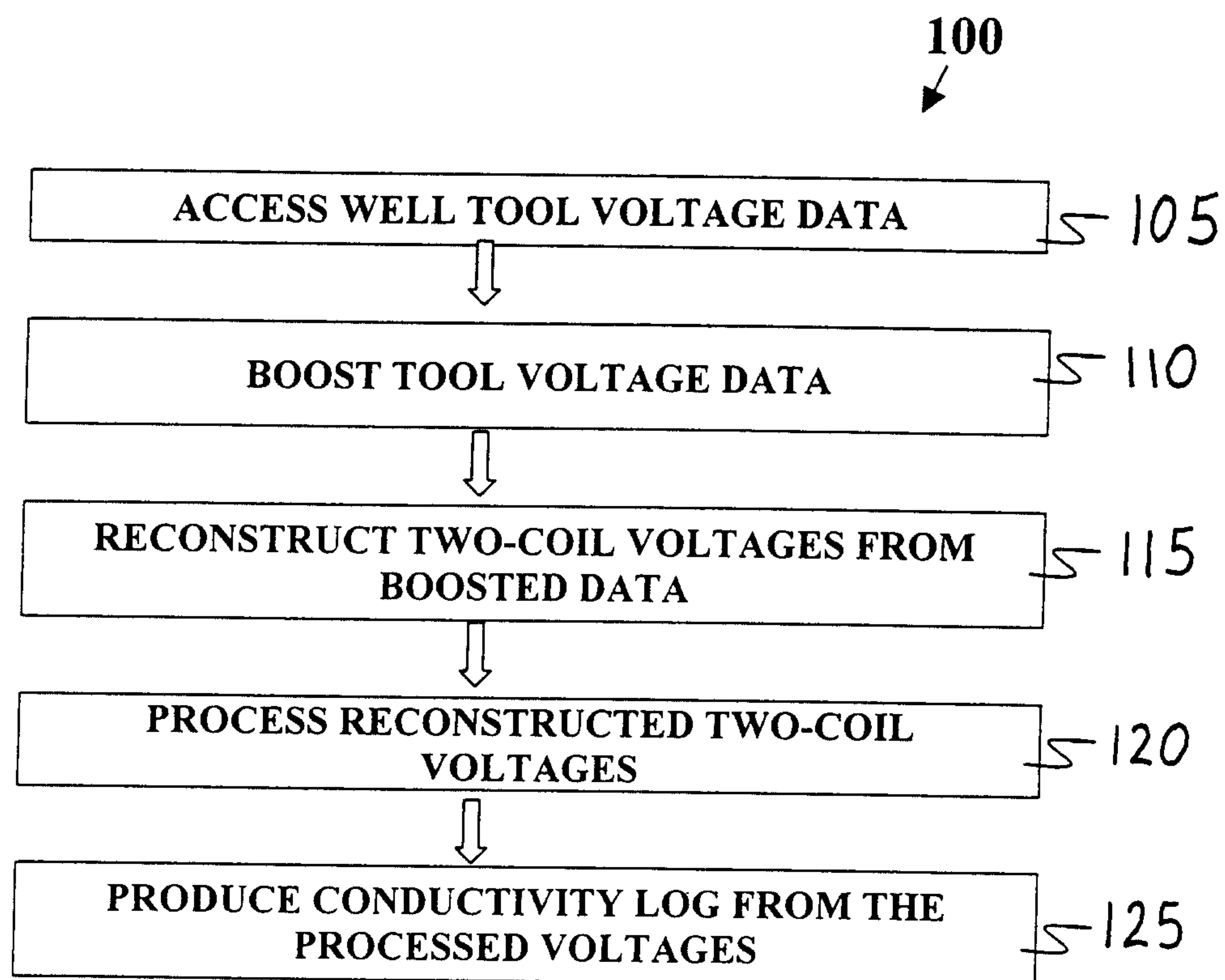


FIG. 4

*FIG. 5*

*FIG. 6*

*FIG. 7*

*FIG. 8*

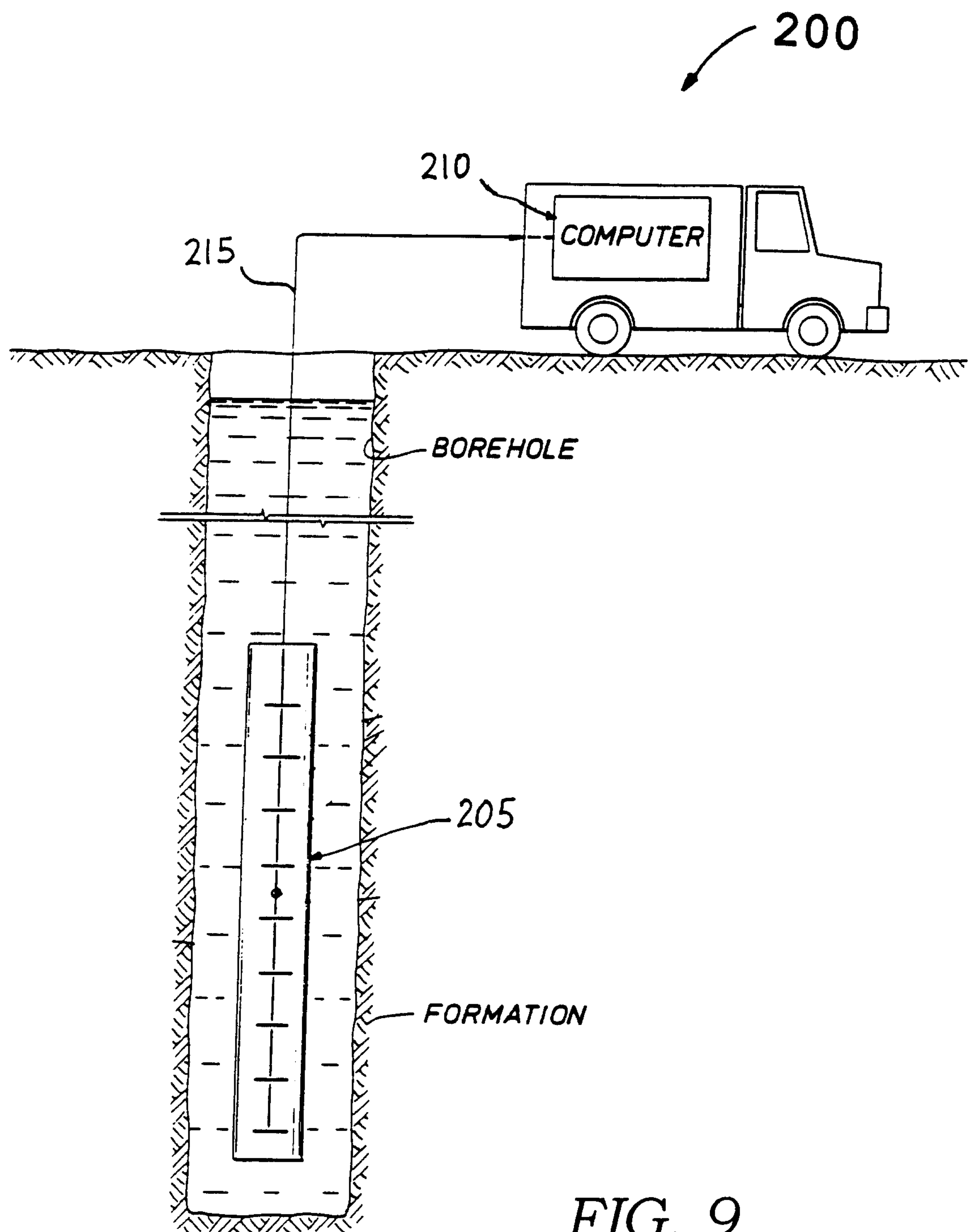
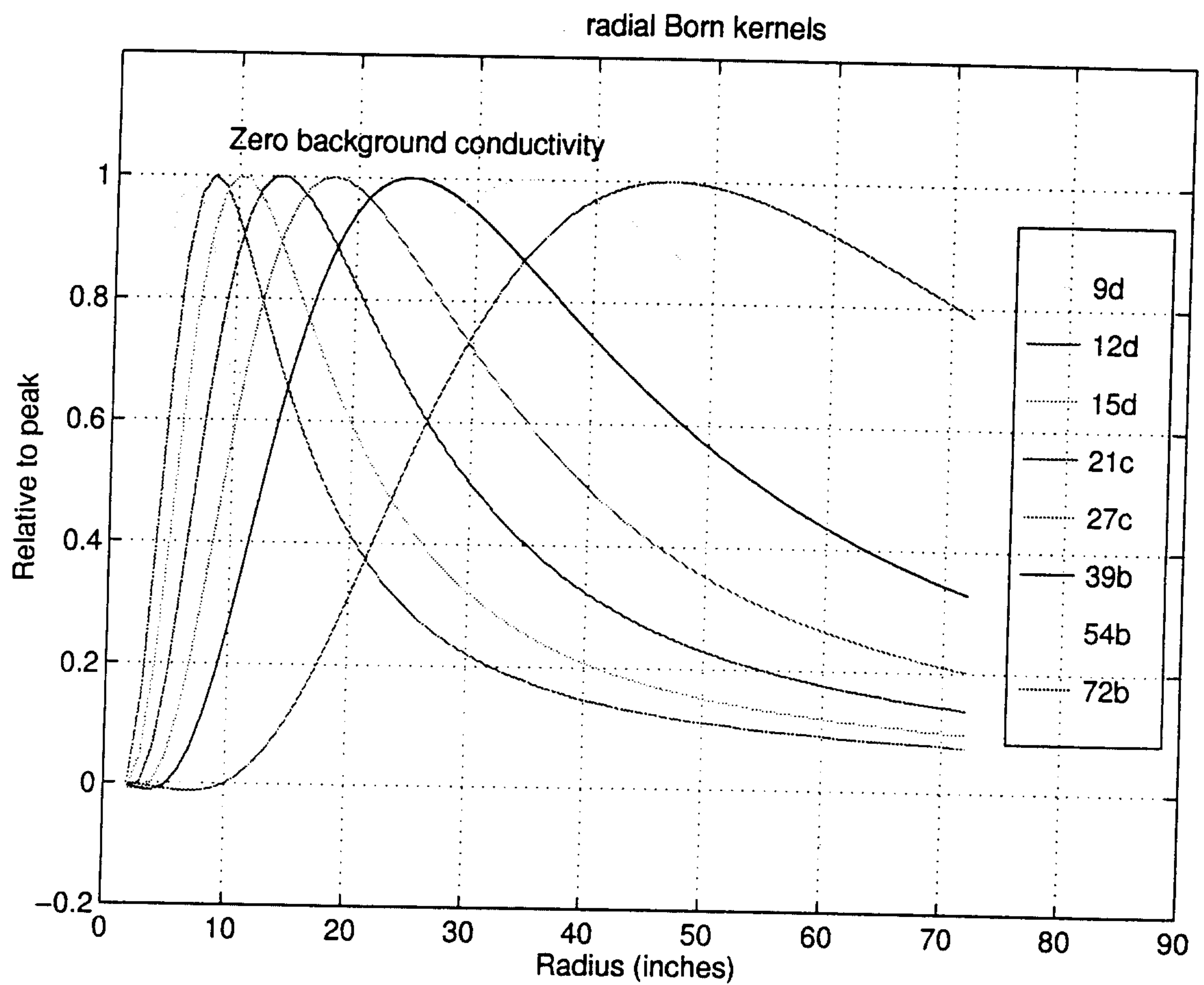
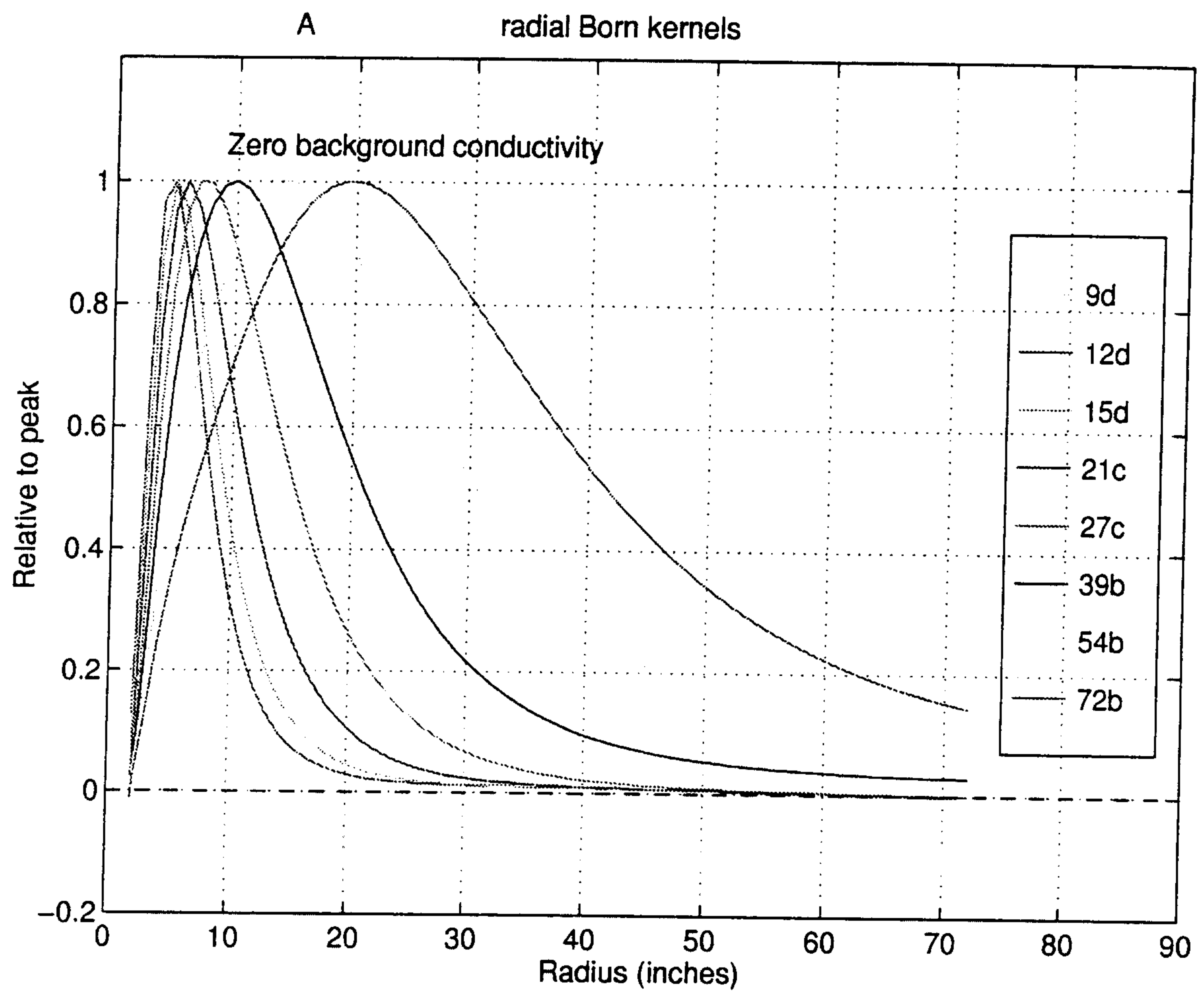
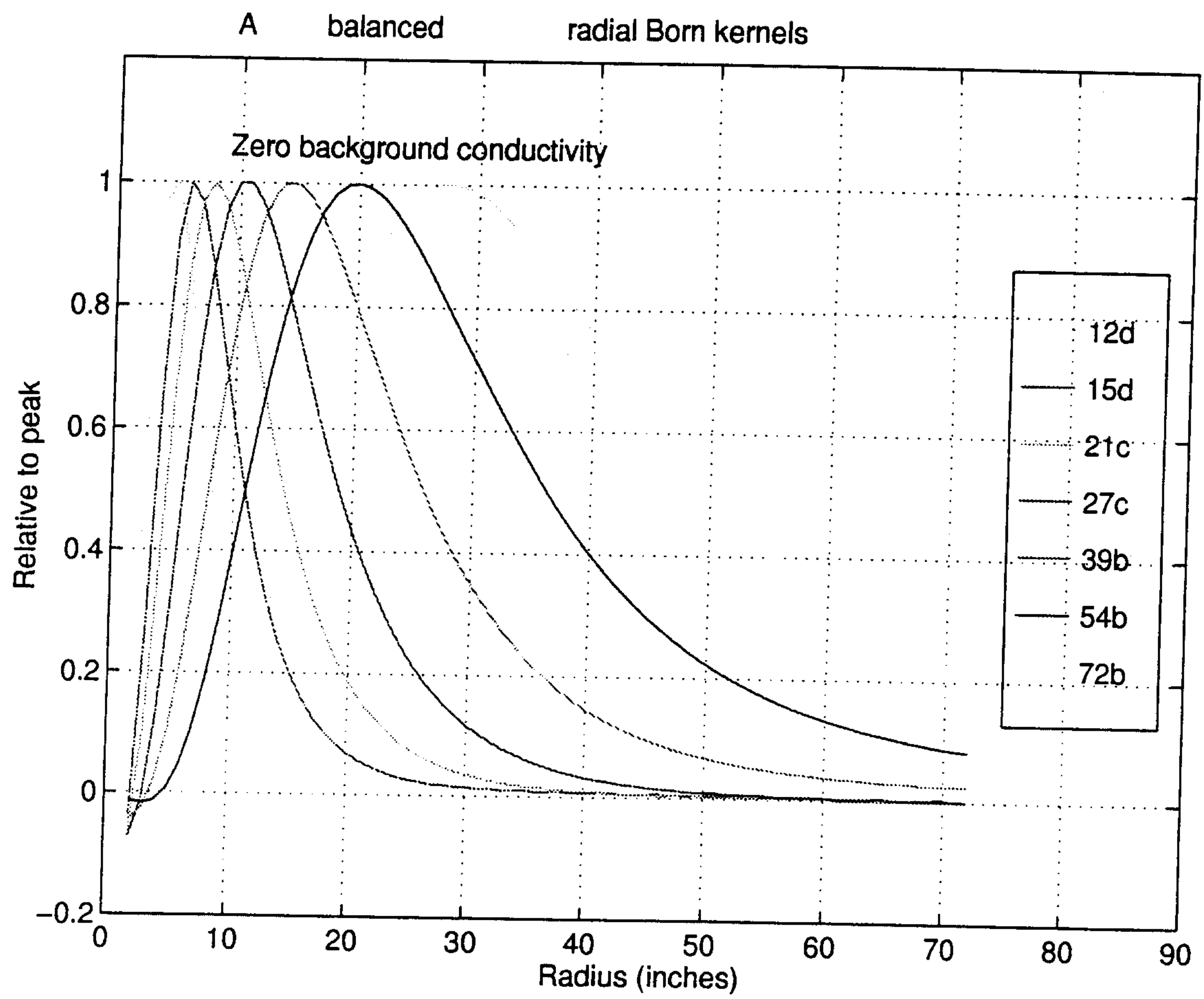


FIG. 9

*FIG. 10*

*FIG. 11*

*FIG. 12*

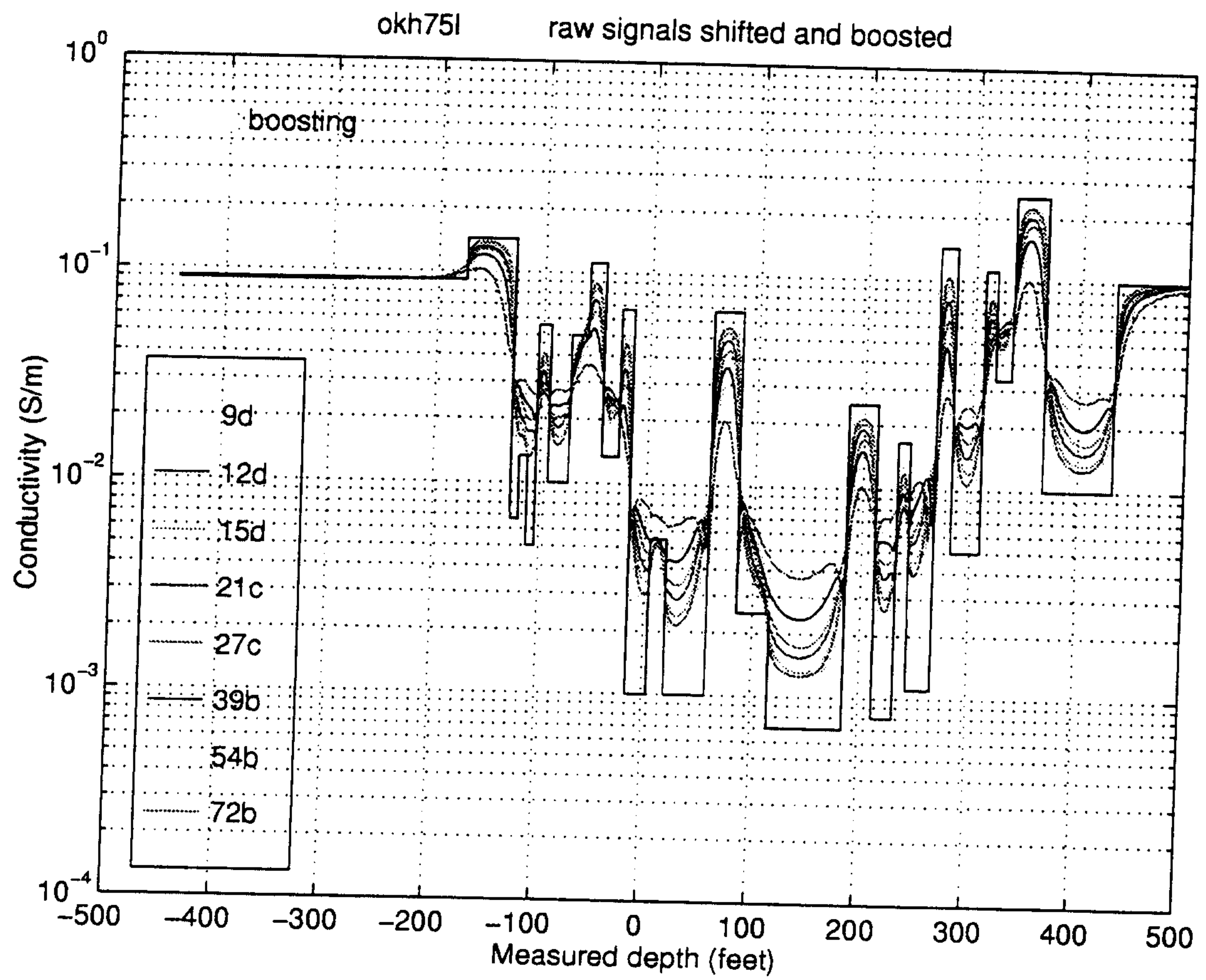
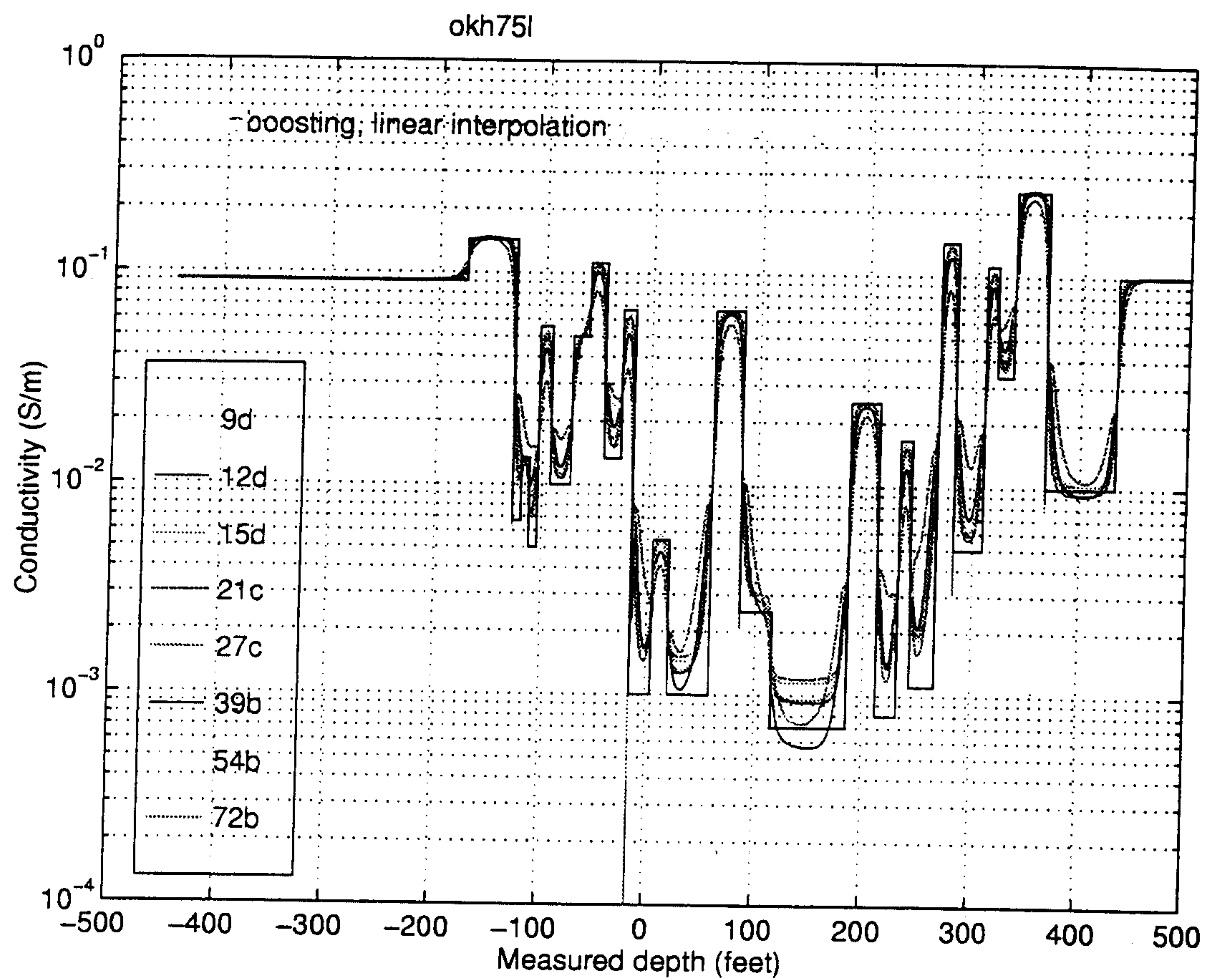
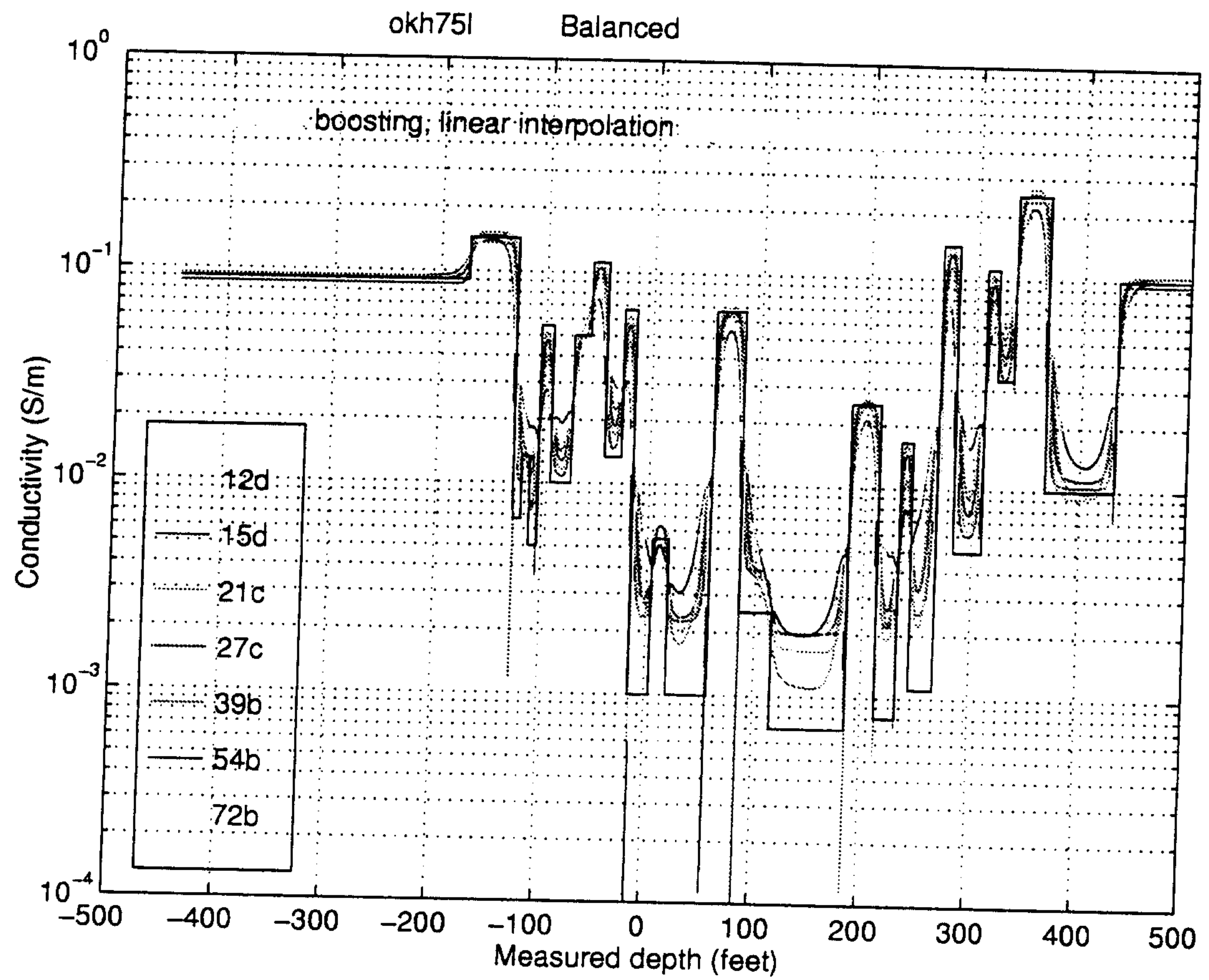
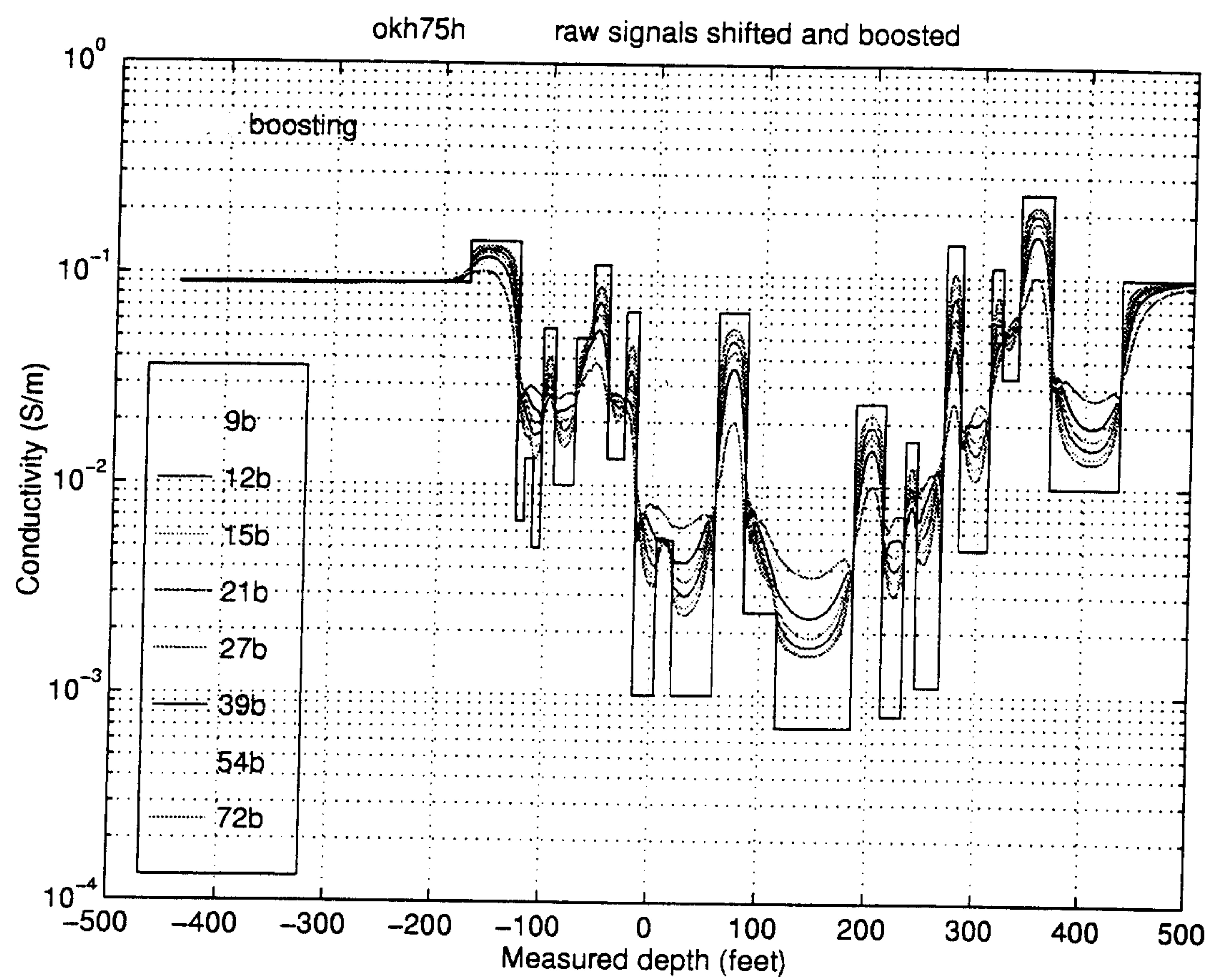


FIG. 13

*FIG. 14*

*FIG. 15*

*FIG. 16*

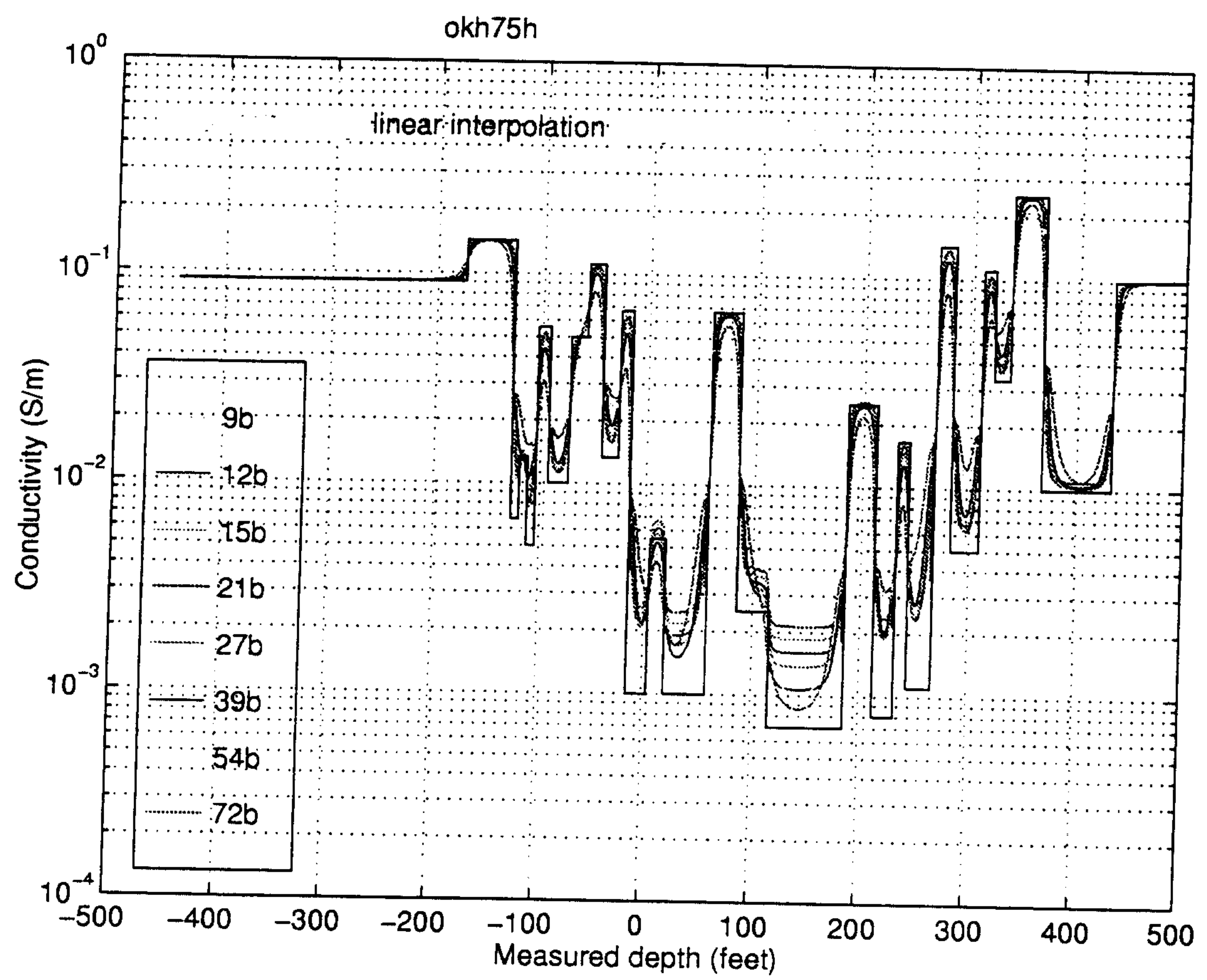
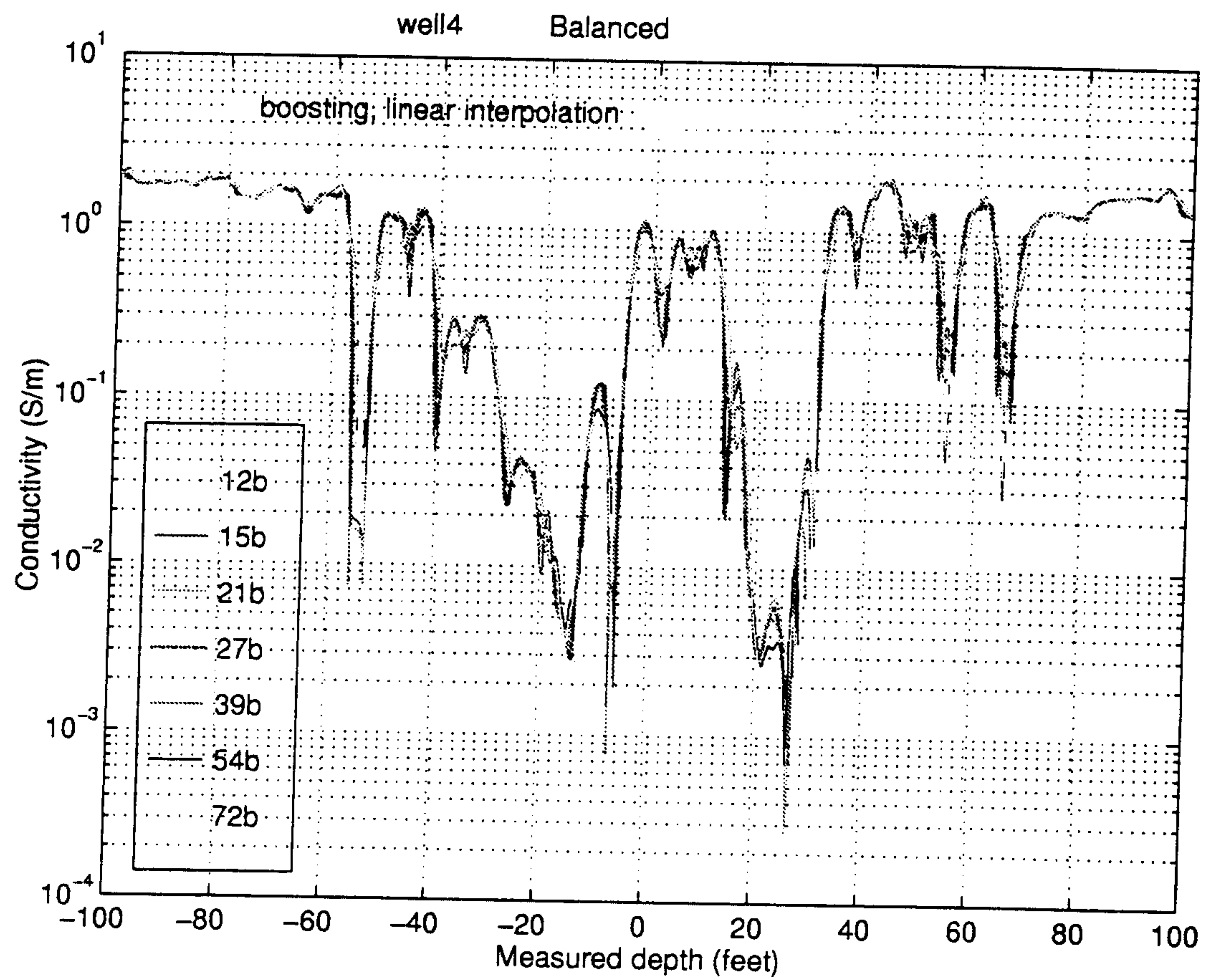
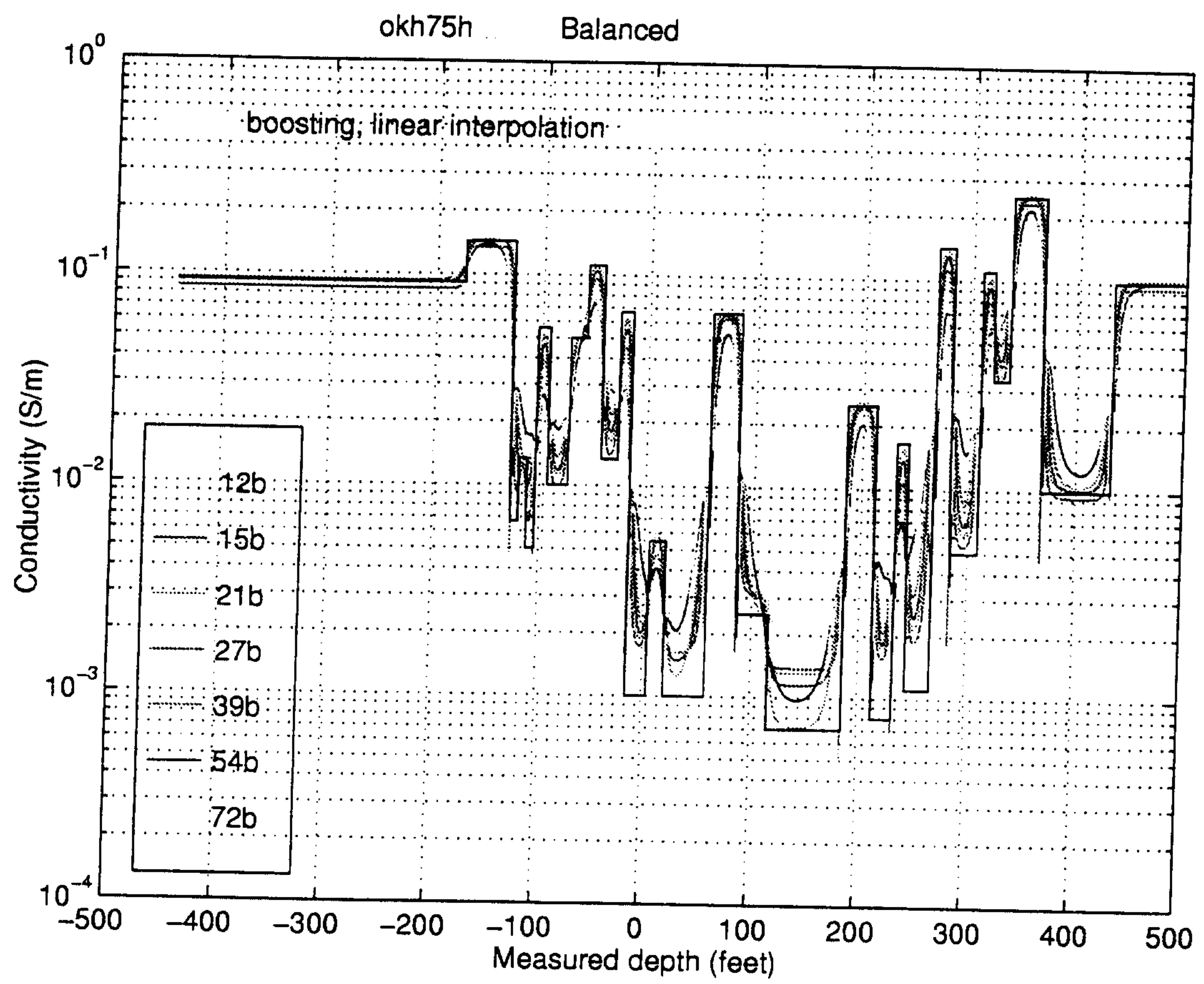
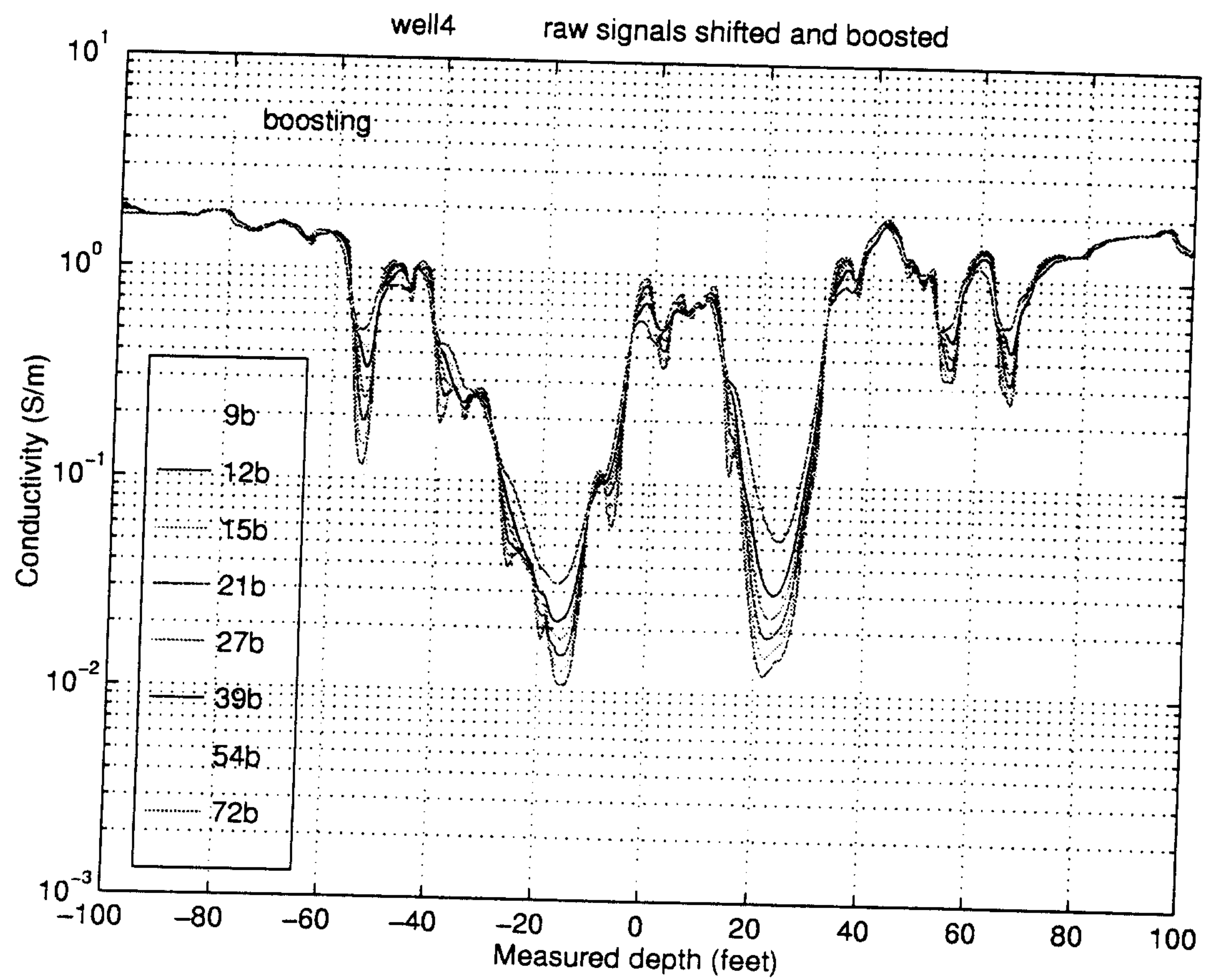
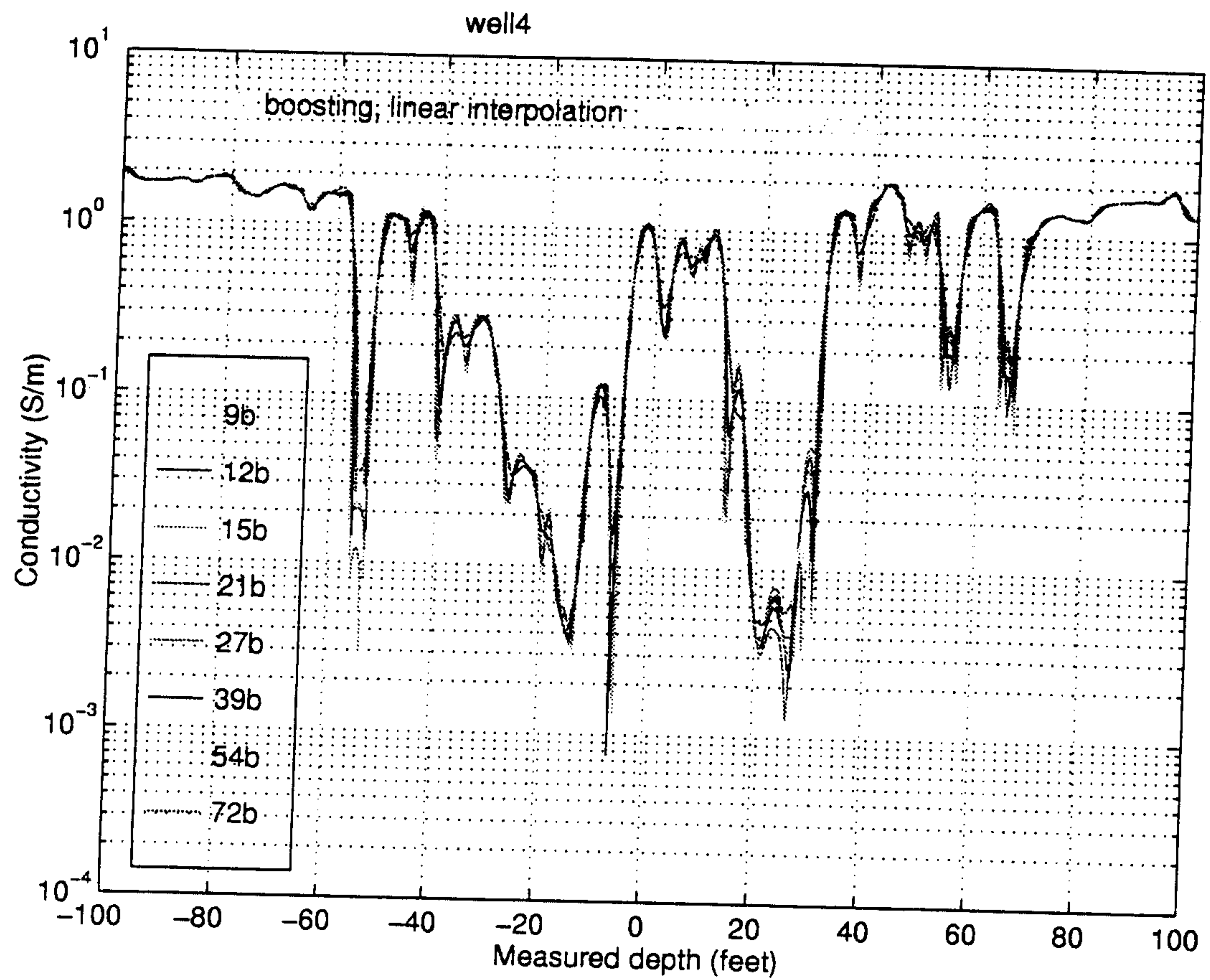


FIG. 17

*FIG. 18*

*FIG. 19*

*FIG. 20*

*FIG. 21*

100



ACCESS WELL TOOL VOLTAGE DATA

105



BOOST TOOL VOLTAGE DATA

110



RECONSTRUCT TWO-COIL VOLTAGES FROM
BOOSTED DATA

115



PROCESS RECONSTRUCTED TWO-COIL
VOLTAGES

120



PRODUCE CONDUCTIVITY LOG FROM THE
PROCESSED VOLTAGES

125