

Robust estimation of the in-phase response from impulse-response TEM measurements taken during the transmitter switch off and the transmitter off-time: Theory and an example from Voisey's Bay.

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ABSTRACT

Modern transient EM systems are now able to take measurements in the transmitter on-time. By combining measurements taken during the transmitter switch-off with those collected in the transmitter off-time it is possible to obtain a robust estimate of the total in-phase response. This total response is comprised of the primary field (which is by definition in-phase) and the in-phase secondary field. If the transmitter loop position is known, and the position and orientation of the receiver dipoles are known, it is possible to estimate the primary field. If this estimated primary is subtracted from the total in-phase response, then an estimate of the secondary in-phase response can be obtained. The secondary in-phase response is extremely useful when exploring for highly conductive bodies, as the response of these bodies is primarily an in-phase response.

On- and off-time PROTEM data collected in a drill-hole proximal to the Reid Brook Zone (one of the Voisey's Bay deposits) shows a strong secondary in-phase anomaly corresponding to a previously unmapped conductor. A drill hole targeted to test this conductor intersected 20.4 m of mineralization, including 8.25 m of massive sulphide.

INTRODUCTION

Highly conductive bodies have EM responses which are dominated by the in-phase component. In the time domain, this means that the measured response will be large when the primary field is large and small when the primary field is small. As most transient EM systems normally measure during the transmitter current off-time (when the primary field is zero), the measured response of very good conductors will be very small (Grant and West, 1965). This is because the off-time response is essentially a measurement of the quadrature response which is very small for these highly conductive bodies.

One solution to this problem, suggested by Grant and West (1965), is to measure the response using a sensor, such as a magnetometer, capable of measuring the magnetic field B directly (rather than its time derivative -- dB/dt). In ground EM, there have been a number of documented experiments using a SQUID magnetometer as the sensor (e.g. Duckworth and O'Neill, 1989). However, we are not aware of SQUID magnetometers being used in practice for the collection of time-domain EM data, most likely because they are difficult to deploy in the field and their high-frequency (or early-time) response is poor.

As the differential equations governing EM induction are linear, an equivalent B -field response can also be obtained by using a dB/dt sensor, but integrating the waveform. In effect this is what is done by the UTEM system (Lamontagne, 1975; West et al., 1984). Another alternative is electronic integration of the dB/dt response measured at the receiver, a suggestion made by Ward (1967).

The UTEM system is an example of a step response EM system, as it measures an equivalent B -field in the transmitter on time. With this system, an estimate of the in-phase response can be obtained from the late-time (channel 1) response.

EM systems that measure the dB/dt response (impulse response) are the most common type of EM system available. This paper shows how impulse response measurements collected during the transmitter switch-off time can be used in combination with the transmitter-off-time data to obtain a robust estimate of the in-phase response and hence increase the sensitivity to good conductors.

MATHEMATICAL FRAMEWORK

The method used to extract the in-phase information from impulse response measurements

is based on a method described by Hughes and Ravenhurst (1996) for removing the quadrature response to estimate the primary field. Subsequently, Bill Ravenhurst of Crone Geophysics and Exploration Ltd. has devised a method for estimating the in-phase response which uses a fairly narrow gate in the transmitter switch off (ramp) time and other samples in the off-time (Watts, 1997). As Crone Geophysics are using a single narrow gate in the switch off, they must make assumptions about the magnitude (and hence shape) of the parts of the switch off that they are not measuring. In the case of the Crone Pulse EM system, the switch off is fairly well controlled, so to a good degree of approximation, they are able to assume that the ramp is linear.

The mathematical analysis below shows that a combination of all the data in the ramp time and all the data in the off time can be used to derive a robust estimate of the primary plus the secondary in-phase response. This robust estimate is independent of any assumption about the functional form of the switch off.

We assume that the secondary-field voltage due to currents induced in the ground, when excited by a unit step in transmitter current, can be written in the form

$$R(t) = B u(t) (1 - H(t)) , \quad (1)$$

where B is defined as the inductive limit (in-phase) response, $u(t)$ is the unit-step-on-function, and $H(t)$ is a dimensionless function characterizing the quadrature response. The function $H(t)$ can have an arbitrary shape, the only constraints being that it must be equal to 1 at $t=0$, and that it tends to zero as t tends to large values. Poor conductors will tend to zero very quickly, and better conductors more slowly. The time derivative of $R(t)$ is given by

$$\frac{\partial R(t)}{\partial t} = B \left(\delta(t) [1 - H(t)] - u(t) \frac{\partial H(t)}{\partial t} \right) . \quad (2)$$

This is the response which would be measured by an ideal impulse-response EM system. Unfortunately, it is not possible to engineer such a system, as most realizable systems switch the current off over a finite period of time, known as the "ramp-time". The response of these systems can be obtained by convolving the impulse-response function with the time derivative of a ramp switch off. The time derivative will be non-zero, with an amplitude equal to $-1/T$ between the ramp start at $t = -T$ and the ramp end at $t = 0$. Elsewhere, the time derivative will be zero. The voltage measured is thus

$$V(t) = -\frac{B}{T} \int_{-T}^0 \left(\delta(t-\tau) [1 - H(t-\tau)] - u(t-\tau) \frac{\partial H(t-\tau)}{\partial \tau} \right) d\tau . \quad (3)$$

In the case when $-T < t < 0$, then

$$V(t) = -\frac{B}{T} [1 - H(t+T)] , \quad (4)$$

and when $t > 0$

$$V(t) = -\frac{B}{T} [H(t) - H(t+T)] , \quad (5)$$

Note that the response for $t > 0$ is actually, the difference of two step responses, suggesting that the response from a realizable impulse-response EM system could be deconvolved to a step response quite easily provided that the switch off and early off-time response can be measured.

The in-phase or inductive-limit response can be obtained by integrating the measured voltage from $-T$ to very late time t_{end}

$$\begin{aligned} \int_{-T}^{t_{end}} V(t') dt' &= \int_{-T}^0 V(t') dt' + \int_0^{t_{end}} V(t') dt' \\ &= \left[\frac{B}{T} \int_{-T}^0 (1 - H(t+T)) dt \right] + \left[\frac{B}{T} \int_0^{t_{end}} (H(t) - H(t+T)) dt \right] \end{aligned} \quad (6)$$

If we define the integral of the step response as

$$I(t) = \int H(t) dt , \quad (7)$$

then we can write equation (6) as

$$\begin{aligned} \int_{-T}^{t_{end}} V(t') dt' &= \frac{B}{T} [T - I(T) + I(0)] + \frac{B}{T} [I(t_{end}) - I(0) - I(T + t_{end}) + I(T)] . \\ &= \frac{B}{T} [T - (I(T - t_{end}) - I(t_{end}))] . \end{aligned} \quad (8)$$

Because $T \ll t_{end}$, we can use a Taylor series expansion,

$$I(t_{end} + T) = I(t_{end}) + \frac{\partial I(t_{end})}{\partial t} T, \quad (9)$$

which simplifies to

$$I(t_{end} + T) - I(t_{end}) = H(t_{end}) T. \quad (10)$$

In the limit as t_{end} tends to large values, $H(t)$ tends to zero, so both sides of the equality in equation (10) are small. This will be true when $H(t)$ at late time is a small fraction of the early time $H(t)$, and because $V(t)$ is the derivative of $H(t)$, this is equivalent to saying that $V(t_{end})$ is small in comparison to $V(0)$. Hence, all but the first term in equation (8) cancel, giving

$$\int_{-T}^{t_{end}} V(t') dt' = B. \quad (11)$$

which is just the inductive-limit or in-phase secondary response.

It is important to note that the above result is independent of the ramp time. Hence, if the sensor and the electronics of the receiver are adequate for measuring the switch off and the early off-time response, then the same result can be obtained by using any ramp time.

The above analysis assumes that the ramp turn off is linear in the interval $[-T, 0]$. The following argument shows that the same result is true for a current switch-off of arbitrary shape.

Assume that the ramp in the interval $[-T, 0]$, is made up on N segments of width Δt_i , where the change in current in each segment is ΔI_i ($i=1, N$). In this case, the integral of the voltage over the on- and off-time is

$$\begin{aligned} \int_{-T}^{t_{end}} V(t') dt' &= B \sum_{i=1}^N \frac{\Delta I_i}{\Delta t_i} \left[\int_{-\Delta t_i}^0 (1 - H(t + \Delta t_i)) dt + \int_0^{t_{end}} (H(t) - H(t + \Delta t_i)) dt \right] \\ &= B \sum_{i=1}^N \Delta I_i. \end{aligned} \quad (12)$$

However, we know that the sum of all the changes in current must add up to the total change in current, which for a unit step off in current must be unity, so

$$\int_{-T}^{t_{end}} V(t) dt = B , \quad (13)$$

which is the identical result to that given in equation (11). Thus, to measure the in-phase response, the length and shape of the switch off are irrelevant.

It is also possible to show that the magnitude of the integral of the measured primary field is independent of the length and shape of the switch off. Once again, the primary field, can be written in a form identical to equation (1), except B is now the primary field value and $H(t)$ is identically equal to zero for all t . The above analysis is simplified, and we obtain the identical result to that in equation (13), without the need for any approximations. Thus, provided that the whole switch off is measured, it is not important that the shape of the switch off be controlled in any fashion. In addition, it is not even important that the shape of the switch off be known. If the ramp is sampled using one window, the ramp shape can even vary from transient to transient; however, if the integration is done on the stacked data, the ramp shape can only vary between stacks (or stations).

The procedure for estimating the primary and secondary in-phase response is thus extremely robust.

FIELD EXAMPLE

It is possible to obtain in-phase information from transient EM measurements collected on the ground, or in drill holes. In this paper, the above methodology will be demonstrated with three-component drill-hole data collected using the PROTEM system in October 1997 by Geotrex-Dighem on behalf of the Voisey's Bay Nickel Company Ltd. (a subsidiary of INCO Ltd.). The PROTEM can be configured to collect data in the switch off by sliding all the 20 channels earlier in time so that the earliest gate is at the start of the ramp switch off rather than the default position which is 85 μ s after the end of the ramp.

The results presented in this paper were measured in drill hole 97_400, which was drilled to

test for a down-plunge continuation of the Reid Brook Zone (Figure 1), a near vertical troctolite dike containing significant nickel-copper-cobalt sulphide mineralization. The hole intersected 9.3 m of weak mineralization at a depth of 881 m (Figure 2).

The axial component results for drill-hole 97_400 are shown on Figure 3. In this paper we have adopted a coordinate system which changes orientation as the drill-hole changes orientation with depth. The axial component is positive up the axis of the drill-hole, the up component is in the vertical plane containing the axial direction, but is perpendicular to the axial direction, with positive up. The transverse component is horizontal and perpendicular to the axial and up axes, so as to make a right-hand coordinate system. The top panel of Figure 3 shows the axial component data from the first nine gates placed inside the ramp. The bottom three panels show the off-time response in the early, mid and late off time. There is a very late-time response centered on about 950 m down the hole.

The data collected during the switch off in the upper panel of Figure 3 shows anomalous responses 135 m down the hole, 235 m down the hole, 260 m down the hole and between 800 and 900 m down the hole. These anomalies are a mixture of quadrature and in-phase responses, as it is possible to get both types of response in the ramp time. There is an off-time response at 880 m due to an in-hole conductor centered just above the hole. This response corresponds to the weak mineralization that commonly occurs throughout the troctolite dike.

The measured response has been integrated and is shown as the dotted trace in the bottom panel of Figure 4. This response is the secondary in-phase (B), plus the integral of the primary field. Note that the narrow responses at 135, 235 and 260 m down the hole are not evident on this trace. This indicates that they have a relatively small in-phase compared with the primary field and are hence poor conductors.

The value of the theoretical primary field alone can be calculated using the subroutine PRIMRY (Macnae, 1980). This routine requires an accurate knowledge of the coordinates of the transmitter loop vertices and the x,y,z location of the hole collar, plus the hole orientation data (normally supplied as depth, dip and azimuth). No assumptions about the functional form of the switch off are required, as explained above. The calculated primary is shown as a solid line on the bottom panel of Figure 4. The difference between the integral of the measured data and the calculated

primary (both traces on the bottom panel) should give an estimate of the secondary in-phase response. This quantity normalized to the total primary at that particular depth in the hole is shown on the top panel. The response is clearly anomalous between 800 and 1000 m down the hole.

The up component response as measured in the on- and off-time is shown on Figure 5. Note that the late off-time data shows an increase from large negative values above 800 m to zero values below 900 m. This indicates there is some type of shielding below 900 m. The estimated secondary in-phase response for the up component is shown on the top panel of Figure 6 to have a cross over from negative to positive, centered on 930 m downhole. The axial and up components together indicate that there is a highly conductive body 120 m away from a depth of 930 m down the hole in a direction below the hole.

Hole 97-412 was drilled to test the interpreted off-hole conductor. The hole intersected 20.4 m of mineralization, including 8.25 m of massive sulphide (Figure 2). The data used to interpret the location of this conductor is not the data presented here, but very similar data collected using the Crone PEM system.

A third component, the horizontal transverse component, was collected on this survey, but this data are not presented here, as the data do not provide further illustration of the robust methodology described in this paper, nor did they contribute significantly to the interpretation of the off-hole conductor (the measured responses were small, implying the conductor was centered in the plane of the drill section).

Near the top of the hole (away from the anomalous zones), there is some discrepancy on Figures 4 and 6 between the calculated primary and the measured data. This could be due to two factors:

- 1) there is a systematic error in the positions of the transmitter loop vertices and the positions and orientations of the receiver dipoles in the drill-hole;
- 2) there are currents induced elsewhere, either from a distant conductor, or from conductive material in the country rock; or
- 3) or a problem with drift or system calibration.

In this case, the transmitter loop and hole collar are surveyed accurately with GPS, which is believed to be accurate to about ± 1 m, and the drill-hole orientation is measured with a gyroscope. The

position and orientation information is thus believed to be quite accurate. The discrepancy is therefore believed to be due to other conductive material in the vicinity of the loop, most likely the weakly mineralized troctolite dike.

Another method for removing the long-wavelength discrepancy described above is to apply a high-pass filter to the data or to use a regional/residual separation method as are commonly applied in gravity exploration (Telford et al, 1976). This same methodology could be applied to removing the primary field itself. This is appealing, as it would not be necessary to calculate the primary field and hence measure the transmitter loop location and the location and orientation of the receiver at each station. Our preference however is to leave the long wavelength data in the profiles, as this information can be diagnostic of other effects such as geometrical errors or the influences of more distant conductors.

CONCLUSION

By combining the switch-off and off-time data it is possible to obtain a robust estimate of the primary and the secondary in-phase response. If the location and orientation of the transmitter and receiver are measured, it is possible to estimate the primary field theoretically, subtract this from the measured in-phase response and hence obtain an estimate of the secondary in-phase response. This in-phase response is extremely useful for detection of "perfect conductors", i.e. those which have a weak quadrature response and a strong in-phase response.

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FIGURE CAPTIONS

FIG. 1. The surficial geology of the area containing the Voisey's Bay massive sulfide deposits

FIG. 2. Interpret geological cross section containing hole 97_400 (from which data are presented in this paper) and hole 97_412.

FIG. 3. The axial-component response in drill-hole 97_400. The top panel shows the response measured in the transmitter ramp time. The bottom three panels are the early, mid and late off-time response. The PROTEM system is operating at 30 Hz. The length of the ramp is 420 μ s.

FIG. 4. In-phase results for the axial component in hole 97_400. The bottom panel is the measured primary plus secondary in-phase (dotted line) and the calculated primary (solid line). The top panel is the estimated secondary in-phase response normalized by the total calculated primary (dashed line). In this plot i denotes the axial component (positive to the top of the hole). The Σ_i denotes the sum over all three components.

FIG. 5. The up-component response in drill-hole 97_400. The top panel shows the response measured in the transmitter ramp time. The bottom three panels are the early, mid and late off-time response. The PROTEM system is operating at 30 Hz. The length of the ramp is 420 μ s.

FIG. 6. In-phase results for the up component in hole 97_400. The bottom panel is the measured primary plus secondary in-phase (dotted line) and the calculated primary (solid line). The top panel is the estimated secondary in-phase response normalized by the total calculated primary (dashed line). In this plot i denotes the axial component (positive to the top of the hole). The Σ_i denotes the sum over all three components.

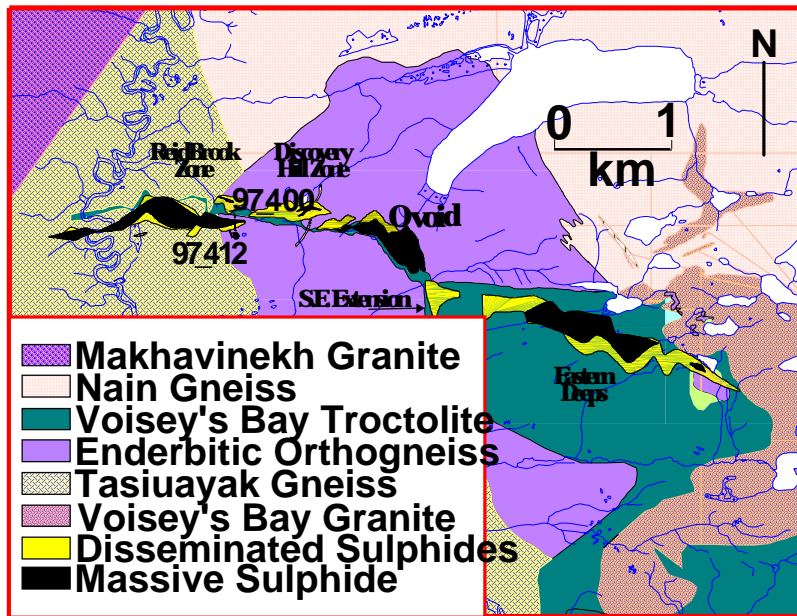


FIG. 1. Smith and Balch

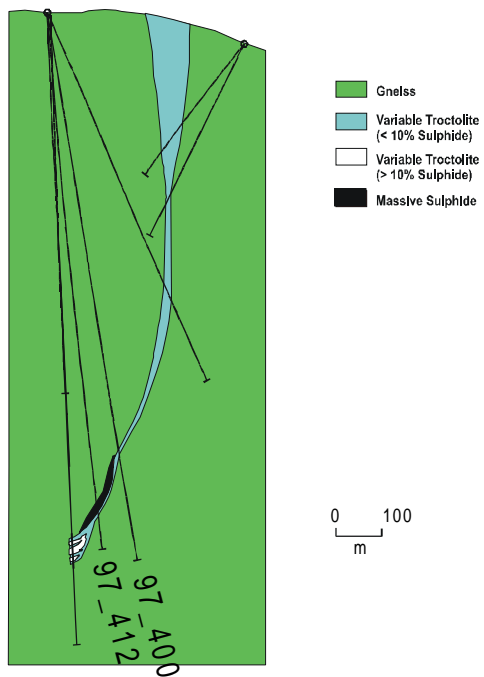
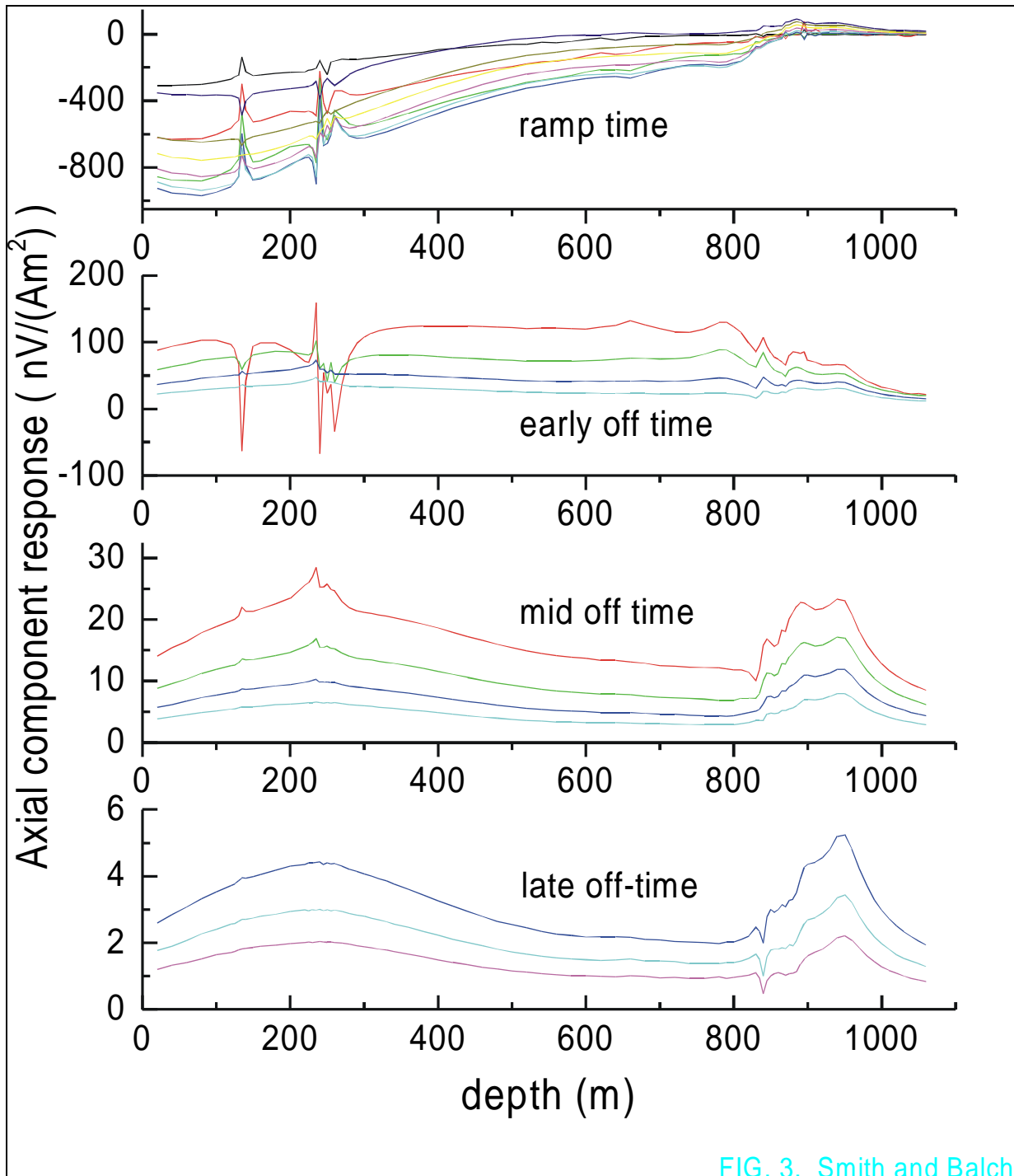


FIG. 2. Smith and Balch



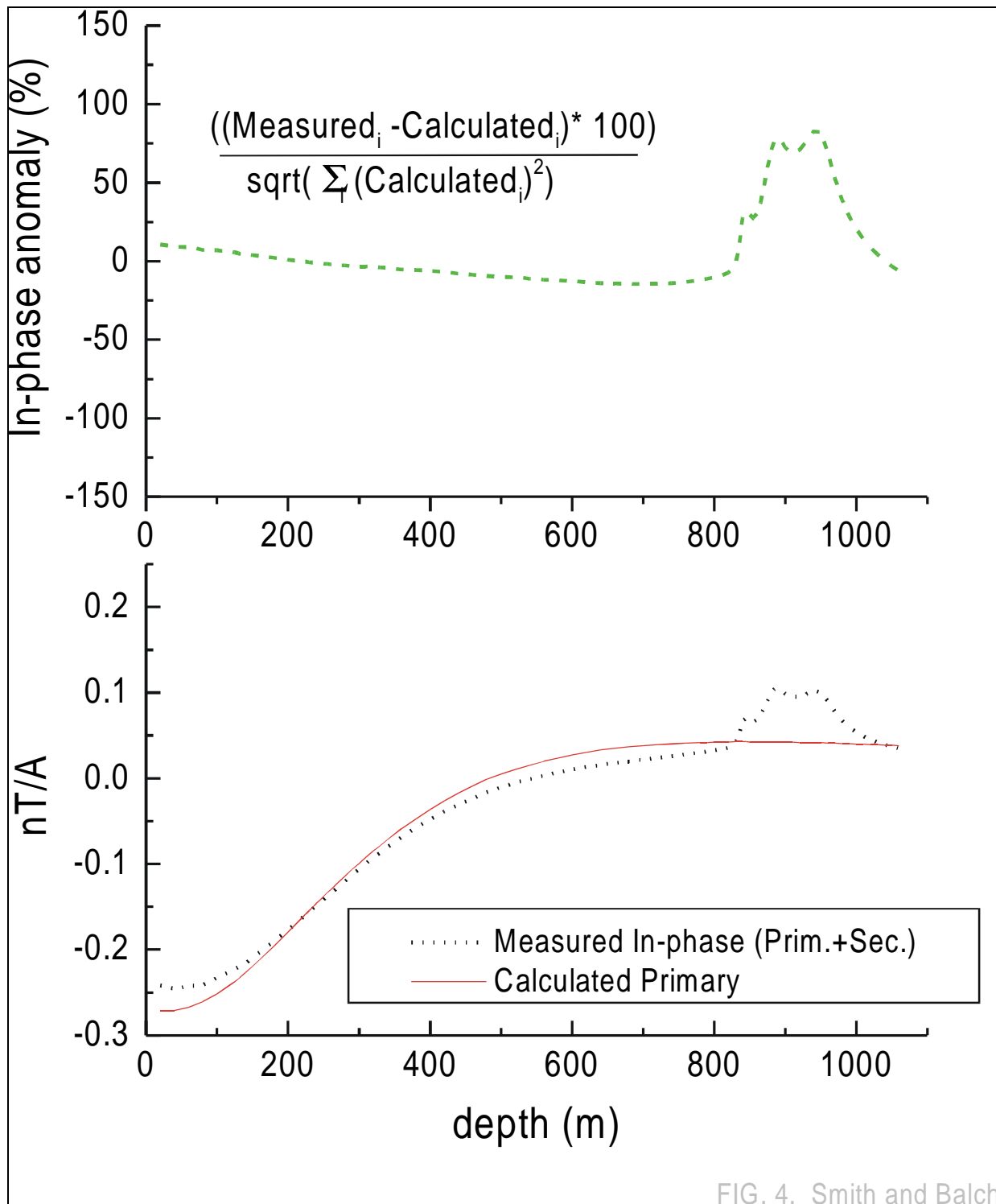
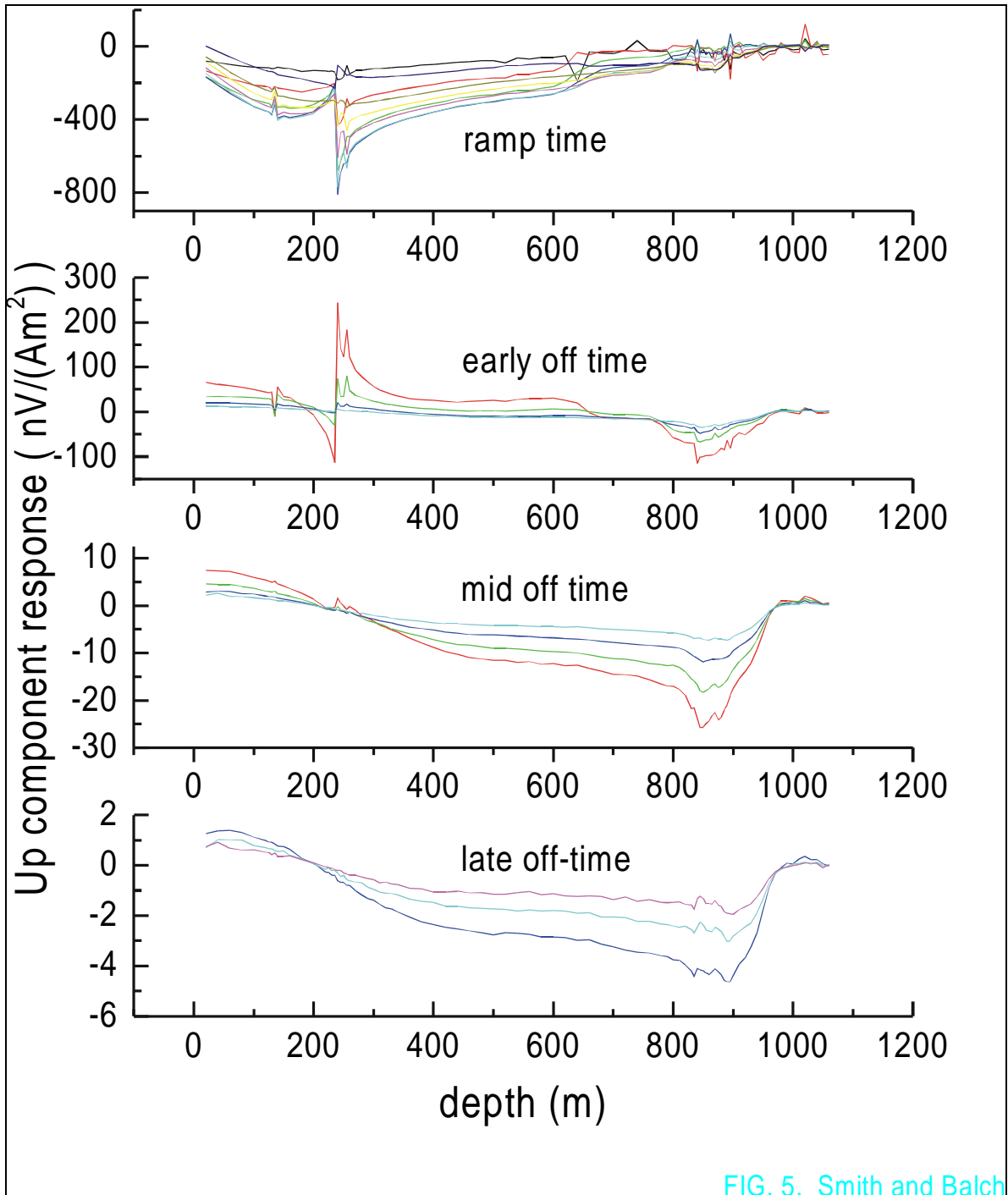


FIG. 4. Smith and Balch



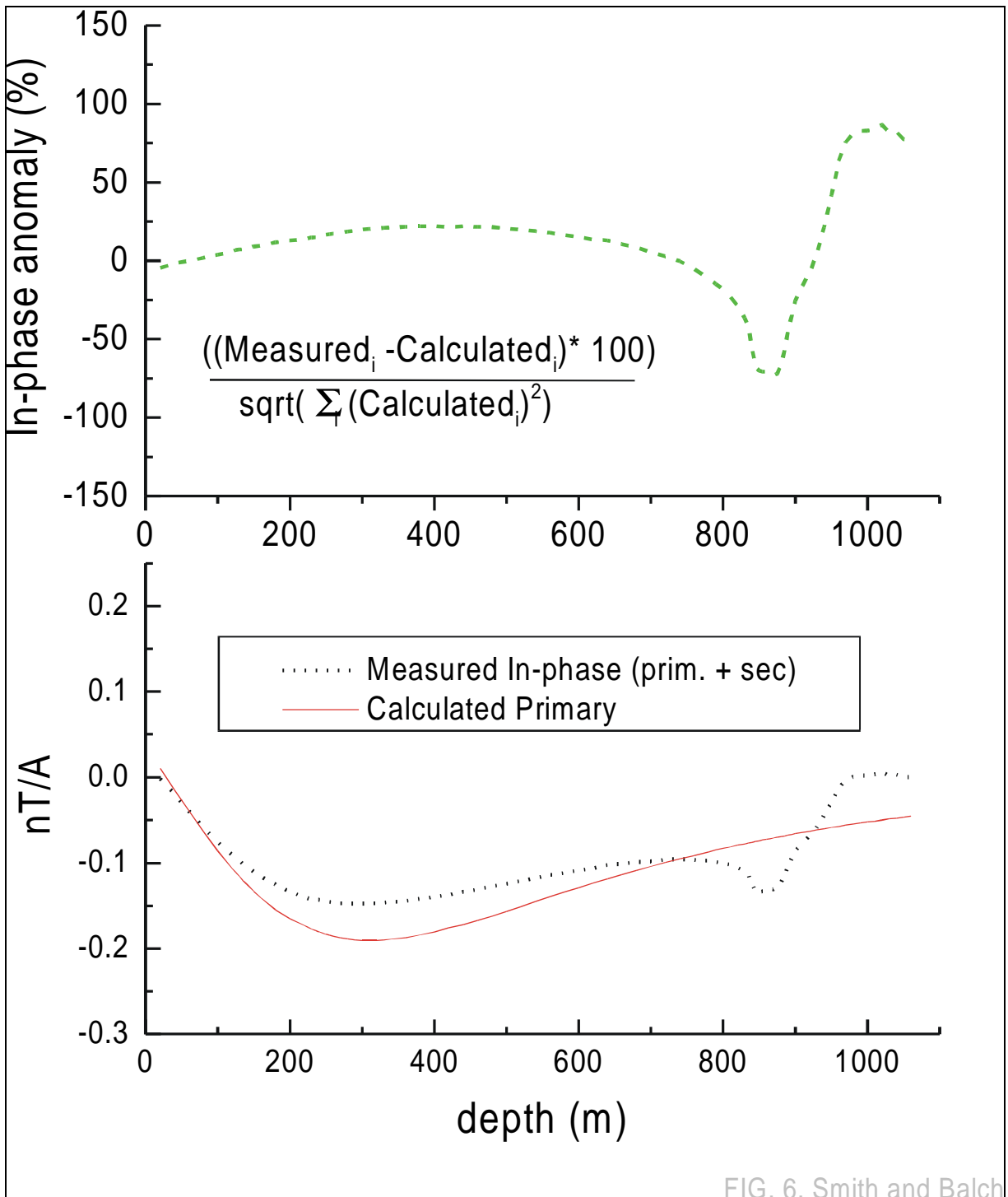


FIG. 6. Smith and Balch