

INSTITUTE OF GEOLOGICAL SCIENCES

**APPLIED GEOPHYSICS UNIT**

REPORT No. 130

**CREST Summary Final Report**

A study of induced polarisation decay curves

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1980

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SUMMARY FINAL REPORT

No 130

Title :A STUDY OF INDUCED  
POLARISATION DECAY CURVES

Project Leader:Dr D.J. Masson Smith

Contractor :Natural Environment Research  
Council  
Institute of Geological Sciences  
Applied Geophysics Unit

Contract No :046-79-1 MPP UK

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## FIGURE

Fig. 1 Curve matching : field curve superimposed on master curve.

## 1. Objective of the research

Conventional induced polarisation surveys measure essentially the magnitude of the IP effect, whether expressed as frequency effect or chargeability. The possibility of deriving additional information from IP measurements has attracted many workers motivated by the need to recognise or remove electromagnetic coupling and the desire to discriminate between causative minerals according to their composition or texture. Pyritic black shales, for example, are a common cause of strong IP anomalies of no economic interest.

Recent advances in complex resistivity measurements (Zonge and Wynn, 1975, and Pelton et al, 1978) have shown that there are significant differences between the spectral responses of different mineralisation types, arising mainly from mineral texture rather than composition: that electromagnetic coupling has distinctive spectral properties which make its removal relatively straightforward; and that the spectral response of small polarisable structures is modified by a function of the geometry.

The objectives of the present study were:

(1) to assess the feasibility of making useful spectral IP measurements in the time domain using relatively simple equipment which a geophysical organisation might be expected to possess; and

(2) to interpret the results of these measurements in terms of geological problems peculiar to the United Kingdom.

## 2. Method and materials

2.1 Theory : The IP phenomenon may be expressed in terms of a very simple equivalent circuit, whose response is known as a Cole-Cole relaxation. The complex impedance of the equivalent circuit is readily obtained; from

$$Z(\omega) = R_0 \left[ 1 - m \left( 1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right] \quad (1)$$

$$\text{where } m = \frac{1}{1 + \frac{R_1}{R_0}}$$

$$\text{and } \tau = \chi \left( \frac{R_0}{m} \right)^{1/2}$$

In this circuit,  $R_0$  simulates unblocked pore paths through which ionic current flows, and  $(i\omega X)^{-c}$  is the complex impedance of metallic-ionic interfaces in series with an additional ionic resistance  $R_1$ . The parameter  $c$  is known as frequency dependence. In real geological situations, the value of  $c$  usually lies between 0.1 and 0.3. From the definition of  $m$  and consideration of the 'capacitive' nature of the element  $(i\omega X)^{-c}$  it is clear that  $m$  is the chargeability defined in the conventional way as the ratio of voltage immediately after to that immediately before cessation of an infinitely long charging current.  $\tau$  is called the time constant and, for  $c = 1$ , has the usual significance of the time constant of an exponential decay.

The values of the resistance (or resistivity) at frequency  $\omega = |Z(\omega)|$  and the phase angle  $\theta$  ( $= \tan^{-1} \frac{\text{Im}(Z)}{\text{Re}(Z)}$ ) can be obtained from (1). This fully describes the frequency domain behaviour of the equivalent circuit; Pelton's field measurements were inverted to give the best values of  $m$ ,  $c$  and  $\tau$  according to this formula.

The time domain response is

$$V(t) = m I_0 R_0 \sum_{n=0}^{\infty} \frac{(-1)^n (t/\tau)^{nc}}{\Gamma(nc+1)} \quad (2)$$

where  $t$  is the time after switch-off of an infinite current pulse  $I_0$ , and  $\Gamma$  is the gamma function. By computing with extended precision, this formula can be evaluated directly for values of  $(t/\tau) < \sim 20$ .

From (2) it can be seen that, for a given  $c$ , we can make a dimensionless plot of  $\log \left[ \frac{V(t)}{m I_0 R_0} \right]$  as a function of  $\log(t/\tau)$ . An experimental plot of  $\log \frac{V(t)}{I_0 R_0}$  against  $\log t$ , shifted vertically by  $\log m$  and horizontally by  $\log \tau$ , will coincide with the theoretical curve. In practice, it is convenient to measure  $V_s$ , the voltage after switch-off, as a fraction of  $V_p$ , the voltage just before switch-off. But since  $V_p = I_0 R_0$  this is equivalent to setting  $I_0 = R_0 = 1$ . A set of master curves can be produced by plotting

$$y = \sum_{n=0}^{\infty} \frac{(-1)^n x^{nc}}{\Gamma(nc+1)}$$

against  $x$ , on bi-logarithmic axes, for different values of  $c$ . The parameters of an experimental curve (of  $\log(V_s/V_p)$  against  $\log t$ ) are then determined by finding the best fit to one of the master curves.  $m$  and  $\tau$

are determined by reading the ordinate and abscissa respectively of the experimental curve at the point ( $\log y = 0$ ,  $\log x = 0$ ) on the mastercurve. The best-fitting curve determines the value of  $c$ .

In practice it was found to be impossible to produce a current pulse long enough to be considered infinite. This result was not expected and forced a change in the curve-matching procedure.

For a finite current pulse of duration  $t_p$ , the voltage measured is

$$V(t) = m I_0 R_0 \sum_{n=0}^{\infty} \frac{(-1)^n}{\Gamma(nc+1)} \left[ \left(\frac{t}{\tau}\right)^{nc} - \left(\frac{t+t_p}{\tau}\right)^{nc} \right] \quad (3)$$

Here  $(t_p/\tau)$  is an additional variable and the reasoning above applies only if we make several plots of  $\log\left(\frac{V(t)}{m I_0 R_0}\right)$  against  $\log(t/\tau)$  for different values of  $(t_p/\tau)$ . For each chosen value of  $t_p/\tau$  we construct a set of master curves for different  $c$ . Typical master curves are shown in Fig. 1.

2.2 Field measurements : Measurements were made on outcropping mineralization of different styles and habit, using a short electrode array of a few metres.

The measurement technique was to set up a suitable array using non-polarising Cu-CuSO<sub>4</sub> electrodes, sustain a steady current flow until no further change was detectable at the receiving electrodes, and then after switch-off measure the decay voltage on a pen recorder. The current source was either a Huntec LOPO battery providing 36V DC or a Huntec 2.5 kW transmitter modified to give a continuous pulse when higher power was required. The TOA pen recorder used for voltage measurement had a wide range of input sensitivities and chart speed settings and a sufficiently high input impedance to be connected directly to the electrodes. The 150 mm chart width combined with ~0.5 mm mechanical hysteresis meant, however, that the resolution was limited. The requirement of sampling a rather wide voltage range at time intervals ranging from fractions of a second to many minutes is not easily met. The recorder used had the advantage of simplicity and portability but the absence of useful information at less than ~0.5 second after switch-off combined with uncertainty in the zero reference level caused data analysis problems.

A total of 41 analysable recordings were made at 18 sites in England, Scotland and Wales.

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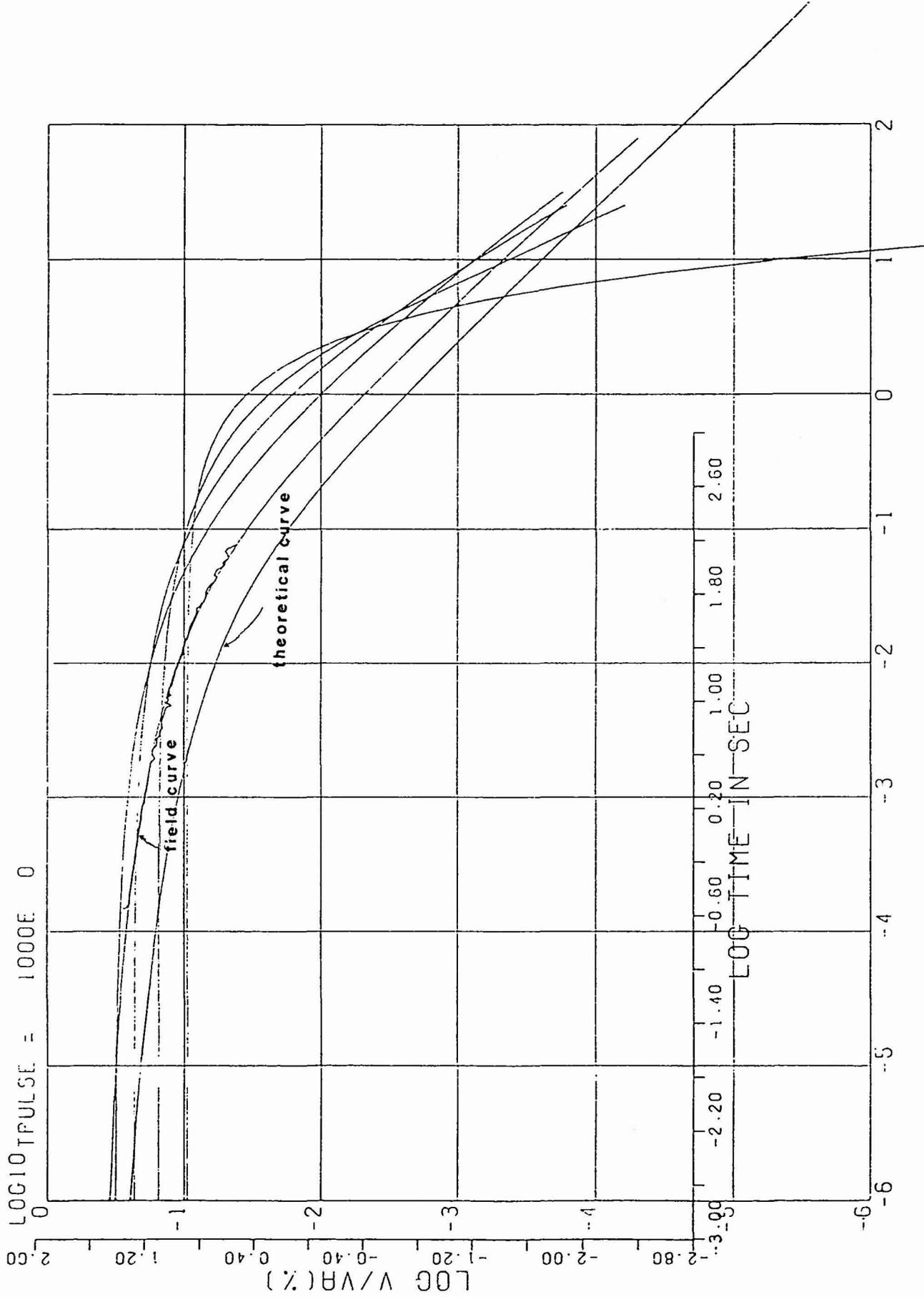


Fig.1 Curve matching : field curve superimposed on master curve

### 3. Analysis of results

3.1 Field curves : The field curves were manually digitised and replotted on the same scales as the master curves after correction for chart recorder sensitivity, speed and zero level. In most cases good matches could be obtained to the master curves for  $c = 0.2$ . In some cases the chosen zero level was evidently wrong as a good fit could not be obtained to any curve, and several different values were tried until the results were satisfactory.

Although at best a very close fit could be obtained, a fundamental problem was that the theoretical curves for  $c = 0.2$  and different values of  $(t_0/\tau)$  were very similar in shape and offset horizontally by amounts such that several different estimates of  $\tau$  would give reasonably consistent results. In fact the uncertainty in the derived values of  $\tau$  was at best about one order of magnitude.  $c$  and  $m$  were more closely defined.

All but two results could be fitted to curves for  $c = 0.2$ , the exceptions being  $c = 0.3$  and  $0.4$ .  $c$  appears not to be significant in a mineral discrimination context.

$\tau$  varied from  $10^0$  to  $10^7$  seconds. Shorter values down to  $10^{-3}$  seconds as reported elsewhere were not seen, but might not be recognised as an anomaly at all with the equipment used.  $m$  varied between 34% and 100%.

Attempts to recognise diagnostic features of different styles of mineralisation show that fine-grained dark shales are clearly distinguishable from all other types by virtue of a very long time constant and high chargeability. The few measurements on rocks of large grain size showed no particular grouping. These observations appear to conflict with previous results (Pelton et al, 1978) which show that increasing grain size corresponds to increasing time constant. Rocks containing carbon cannot be distinguished directly from metal sulphides nor massive mineralisation from other types.

3.2 Theoretical study : Because of the impracticability of generating a current pulse of effectively infinite length it might be imagined that conventional IP equipment using a repetitive input waveform and recording decays at times up to a second or so would give increased high-frequency information. A short theoretical analysis of the decay curves to be expected from a Cole-Cole model was carried out.

Assuming the transmitted waveform can be analysed as a Fourier sine

series, we can say that for unity current,

$$V(t) = \text{Im} \sum_{n=1}^{\infty} \frac{2}{\omega T} \cos\left(\frac{\omega T}{4}\right) \cos\left(\frac{3\omega T}{4}\right) Z(\omega) e^{i\omega t} \quad (4)$$

where  $Z(\omega)$  = impedance  
 $\omega$  =  $n\pi/T$  (frequency)  
 $\text{Im}$  = imaginary part  
 $T$  = waveform period

We can substitute the Cole-Cole impedance  $Z(\omega) = 1 - m \left( 1 - \frac{1}{1 + (\omega\tau)^c} \right)$  in (4) and evaluate the response over a suitable interval to give the decay curve for different values of  $m$ ,  $c$  and  $\tau$ . Variations of  $m$ ,  $\tau$  and  $c$  to a 2 seconds on - 2 seconds off cycle showed that as  $m$  decreases from 1.0 to 0.5, the decay curve decreases in amplitude by more than 50%. Further a change of  $\tau$  from a value typical of most rocks to a value typical of black shales causes a distinct change in curve shape, but an associated and very small change of  $m$  makes the curves almost identical. This suggests that evaluation of  $m$  and  $\tau$  from conventional decay curves is not feasible. Electromagnetic coupling can however be recognised.

## 5. Conclusions

The time-domain response of the Cole-Cole model has been explored, for single current pulses of infinite and finite duration and for a conventional repetitive pulse train.

In practice, it is impossible to produce a pulse of sufficient length to be regarded as infinite. Finite pulses can be analysed by a somewhat inelegant curve-matching procedure and values of three independent parameters of the model  $m$ ,  $\tau$  and  $c$  can be obtained. The fourth parameter  $R_0$  (D.C. resistivity) of the model has been kept in the background because its behaviour is already familiar. It may be noted however that the resistivity measured by conventional prospecting equipment on bodies of high  $m$  and  $\tau$  may be only a few per cent of  $R_0$ .

Field measurements on selected outcrops in the UK showed a clear distinction between dark shales and other rock types and a tendency towards high chargeability for a given time constant for rocks of large effective grain size; no other systematic grouping was evident.

Commercial equipment using a repetitive waveform is unlikely to be able to perform any useful discriminatory function except for the recognition of electro-magnetic coupling. The measured 'chargeability' is not simply related to any of the parameters of the Cole-Cole model.

5. References and communications

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