A controlled-source, time-domain electromagnetic survey over an upthrust section of Archean crust in the Kapuskasing Structural Zone*

R. D. Kurtz, J. C. Macnae and G. F. West

1 Geological Survey of Canada, 1 Observatory Crescent, Ottawa, Ontario, K1A 0Y3 Canada
2 Lamontagne Geophysics Ltd, 24 Mowat Avenue, Toronto, Ontario, M6K 3E8 Canada
3 University of Toronto, Department of Physics, Toronto, Ontario, M5S 1A7 Canada

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SUMMARY
A pilot controlled source electromagnetic survey was conducted in the Kapuskasing Structural Zone to test the application of the UTEM technique for determining the electrical conductivity structure of the Earth's crust to depths of up to 10 km. In general, the data are consistent with the results of an earlier broadband magnetotelluric (MT) survey and indicate a quasi-layered earth below a variable overburden zone with conductances between 0.1 and 0.5 S. At some depth below 10 km, conductivity appears to increase in agreement with the MT interpretation and provides confidence that the static shift of the MT data was corrected. A weakly conductive layer, located at depths greater than 2 km, is possibly associated with a feature of the Ivanhoe Lake Cataclastic Zone (ILCZ), a major fault zone along which up to 30 km of the Earth's crust has been thrust to the surface. There was no clear evidence in the UTEM data for a conductive zone extending to the proposed surface strike location of the ILCZ. A conductive anomaly at depths of 1-2 km may extend east of the present survey area and suggested that a subsequent UTEM survey must expand the coverage to the east.

Key words: Canadian Shield, electromagnetic, Kapuskasing, upthrust crust, UTEM

INTRODUCTION
The Kapuskasing Structural Zone (KSZ) in northern Ontario has been selected as one the principal transects of project LITHOPROBE, a multidisciplinary geoscientific research programme designed to investigate the nature and evolution of the lithosphere in Canada (Candel 1981; Clowes 1984; Clowes et al. 1984). The KSZ has been identified as an upthrust section, up to 30 km thick, of the Earth's crust bounded to the east by a major thrust fault known as the Ivanhoe Lake Cataclastic Zone (ILCZ) (Percival & Card 1985, and references therein). The KSZ has been subdivided into three zones on the basis of geological and geophysical results and are referred to, from south to north, as the Chapleau, Groundhog River and Fraserdale-Moosonee blocks. Near the centre of the Chapleau block the upthrust cross-section is over 100 km wide, and is characterized by a transition from low-grade greenstone facies rocks in the west to high-grade granulite facies immediately west of the ILCZ. The area provides a unique opportunity to study the physical properties of exposed lower crustal materials, especially their electrical properties. The continental crust in many areas of the world is characterized by a significant increase in electrical conductivity at mid to lower crustal depths (Jones 1981). Studies by Dowling (1970), Koziar & Strangway (1978), Sternberg (1979), Connerney, Nekut & Kuckes (1980), Duncan et al. (1980), Kurtz (1982), and Kurtz, Ostrowski & Niblett (1986) have shown this to be the case for Shield regions of North America. The cause of the enhanced conductivity has not been firmly established and theories range from concentrations of specific mineralogical assemblages such as graphite to the presence of free water or other fluids.

The initial electromagnetic (EM) study in the KSZ was conducted in 1984 by Woods & Allard (1986) and consisted of a large-scale geomagnetic depth sounding (GDS) investigation of the gross electrical conductivity structure of the Chapleau and Groundhog River blocks. However, no overall anomalous response was detected across the KSZ from which they concluded that lower crustal conducting zones must be related to intrinsic conditions at lower crustal depths. A high resolution, broadband, tensor MT survey consisting of 26 soundings across the Chapleau block coinciding, in part, with the survey discussed in this paper was conducted by Kurtz et al. (in preparation) in 1986. The electrical conductivity structure of the mid and upper crust

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was observed to be remarkably uniform with only a shallow (less than 600 m thick) conductive anomaly required to model the MT data collected across the ILCZ at a location 28 km north of the present survey. However, a pilot seismic extending at least 10 km in a horizontal direction. The reflection profile (Cook 1985), coincident with the present survey, revealed an event dipping at 35°–38° west and extending at least 10 km in a horizontal direction. The reflector was not traced to the surface but was associated with the ILCZ.

This paper discusses the results of a survey undertaken in 1986 December with a UTEM system (West, Macnae & Lamontagne 1984). The first aim of the survey was to investigate the applicability of UTEM, originally designed for mineral prospecting, to determine the Earth conductivity structure to depths of interest in crustal studies. The second aim was to investigate whether any small or poorly conducting features associated with the ILCZ could be detected at depth, as no obvious features had been resolved by natural source methods. Third, the survey was to provide a comparison with the electrical conductivity structure from the interpretations of Cavaliere, Bailey & Desbiens (1986) and Kurtz et al. (in preparation). The data collected on these two MT surveys indicate considerable ‘static shift’ (Jones 1988) and provide evidence for local lateral heterogeneity. Static shift is the phenomenon where individual apparent resistivity versus frequency curves from closely spaced stations are very similar in shape, but differ greatly in absolute amplitude. The physical cause of static shift is the (quasi-static) electric charge distribution that is induced where regional currents cross lateral boundaries and thus primarily affects the electric field component (Poll, Weaver & Jones 1989). If the MT data are static shifted, it is impossible to define unambiguously the absolute conductance of the Earth or the depth to conductivity boundaries (Jones 1988). However, the relative conductivity structure of a layered sequence can be firmly established. The MT data indicate that a conductive but inhomogeneous zone (likely glacially transported overburden) is present above a very resistive upper crust, which overlies a more conductive lower crust and upper mantle.

CONTROLLED SOURCE SYSTEMS

Detailed electromagnetic soundings using controlled source systems can be obtained by analysis of the response from fixed transmitter/receiver configurations as a function of time or frequency (a common application of which is central-loop TEM sounding; Kaufman & Keller 1983), or by analysis of the response at one delay time or frequency as a function of geometry (geometrical sounding). Because of the diffusive nature of EM fields, time-domain data are usually sampled in time windows whose delays are spaced equally on a logarithmic scale. By combining time and geometrical sounding methods, particularly with the use of multiple receiver/transmitter combinations, data redundancy can be created which allows for greater constraints in the conductivity-depth section through averaging (or stacking). To obtain an optimum conductivity estimate for a given depth and location, the weights for the soundings used in the averaging procedure are determined by the sensitivity of the sounding to current induced at that depth and location. Although it is a recent development which is currently the object of research, this stacking appears to produce reasonable soundings even in the presence of considerable lateral heterogeneity (Macnae & Lamontagne 1987). Soundings obtained by techniques that utilize inductive (closed loop) sources and magnetic coil receivers, such as UTEM, are less affected by the electric charges that cause static shift in the electric component of an MT sounding.

A UTEM survey which combined geometrical and time-delay sounding was conducted over the proposed surface strike of the ILCZ west of Foleyet, Ontario, along the Warren–Carty Township road. Two large loops, numbered 2 and 3 (Fig. 1), with sides approximately 2 x 3 km were used to obtain a very large and distributed peak transmitter dipole moment of $6 \times 10^6 \text{Am}^2$ in order to maximize the small secondary fields arising from deep current penetration. Three smaller loops, numbered 11, 12, and 13 were deployed to study the near-surface structure around the geologically inferred location of the ILCZ (Percival 1981; Percival & Card 1983). These smaller loops were also to be used to investigate the lateral homogeneity of the area.

DATA PRESENTATION

The data collected with the UTEM system in this survey consisted of the time derivative of the total vertical magnetic field as a function of delay time after a ramp change in the triangular current waveform produced by the transmitter. These measured signals are mathematically identical to magnetic field measurements from a transmitter carrying a square wave current. In the remainder of the paper, data will be referred to as magnetic field measurements with an implicit assumption of a square wave current. The data collected east of loop 2 at a 100 m station spacing are presented in profile form in Fig. 2. On this plot, the vertical components of the magnetic field at 10 time-delay windows are presented as secondary fields expressed as a percentage of total primary magnetic field. The data are presented on two vertical scales with early delay times on the top axis and later delay times on the bottom axis.

The secondary magnetic fields decay to zero some time after the step change in the primary field. To allow for repeat measurements and signal stacking, the step change is repeated; the base frequency for this experiment was chosen to be 31 Hz, which allows the observed secondary fields to decay completely before the next transition. In the absence of strong magnetic susceptibility responses and provided that no appreciable secondary field persists to late delay times, the total measured field at the latest time channel (12.8 ms) is a measure of the primary field $P$. Differences between $P$ and the theoretical primary field calculated using the survey geometry and transmitter current can usually be attributed to geometrical error between actual survey station/loop locations and the nominal ones used in data reduction. Vertical scales in Fig. 2 (and 4) are expressed as the percentage of the primary field estimated from the latest delay-time channel.

RESPONSE CHARACTERISTICS

The fields generated by the transmitter and by current induced in the Earth are geometrically complicated
functions of location which result in difficulties with presentation and interpretation. However, the response expected from a number of structures chosen to represent simplified geological models have been obtained by both numerical and scale-modelling techniques and these type-curves are used as an aid in interpretation. A number of examples are given in West et al. (1984) and Macnae (1986).

The early delay-time responses shown in the upper diagram in Fig. 2 are quite variable and are characteristic of shallow conductive anomalies which are discussed in the next section. Based on the observed statistics of data repeatability, local variations along the profile at later delay times (lower diagram) can be attributed mainly to sferic noise rather than to conductivity variation. In general, however, the vertical component of the secondary magnetic field recorded outside large transmitter loop 2 shows an underlying pattern of migration of the zero crossover location from one channel to the next at early delay times and smoother, decaying broad positives at late delay times. These responses are typical of a quasi-layered conductive earth as demonstrated in Fig. 3 by examples that show type curves for the computed response of a 20-channel UTEM system over a half-space (Fig. 3a) and over a near-surface thin layer (Fig. 3b). Outside the transmitter loop, the vertical component of the secondary magnetic field shows crossover responses that migrate with time away from the transmitter loop as the secondary centre of maximum current density in the earth diffuses downwards and outwards. At later delay times the response is completely positive on the measured profile. Changes in the conductivity of the half-space or conductance of the thin layer will cause timing changes, with the basic amplitude pattern as a function of location unchanged (West et al. 1984). Note the more rapid change in anomaly characteristics with time for the thin-sheet as opposed to the half-space.

**SHALLOW ANOMALIES**

**Large transmitter loops**

While the UTEM survey data show lateral variations at early delay times that are not consistent with a uniform layered earth at shallow depths, it is possible to obtain an estimate for the average of the surface conductance, \( \sigma d \) (where \( \sigma \) is conductivity and \( d \) is thickness), of a uniform overburden layer whose response most closely matches that of the data without going through an inversion process (Macnae 1986). Essentially, this is a curve matching procedure which exploits the invariance of the response.
Figure 2. Vertical component magnetic field data measured at stations separated by 100 m along the Warren-Carty road east of transmitter loop 2. A, B and C indicate locations of conductive anomalies discussed in the text. Dashed curves labelled I, II and III are computed responses for a surficial thin conductor of 0.13 S at delay times of 0.05, 0.2 and 0.8 ms.

Figure 3. (a) Twenty-channel UTEM vertical magnetic field response measured over a halfspace of 0.01 S m⁻¹. The transmitter loop is 400 m on a side and is located between -400 to 0 m. (b) The vertical magnetic field response over a thin layer with conductance of 1 S.

A closer examination of the early delay time data in the profile shown in Fig. 2, suggests three lateral inhomogeneities that are annotated A, B and C. The sharpness (or short spatial wavelength) of these features is consistent with the response of near-surface conductive anomalies. Interpretation of such features is usually performed using simple rules developed from scale or computer forward modelling, as formal inversion techniques have not, as yet, been developed for complex responses such as these.

Localized overburden conductors would tend to produce mainly a negative depression in the vertical magnetic field whereas a steeply dipping feature such as a fluid-filled fault or shear zone would lead to a reasonably symmetric crossover response (Macnae 1986). The region marked A is predominantly a local negative, with little positive response near the transmitter, and is therefore likely a localized flat-lying overburden conductor. The response at B is approximately symmetric with positive and negative peaks when compared with the local background level. This may well be the response from induction in a steeply dipping conductive zone, although current gathering into a long linear overburden feature cannot be excluded. C has similarities to both zones A and B. Due to the relatively small amplitudes of responses B and C compared with the primary field, however, they cannot represent the response of a half-plane type conductor, such as a uniformly conductive steeply dipping fault zone with considerable strike length. Rather they are consistent with a conductive feature of relatively limited depth extent. Responses generated by loops 2 and 3 along other sections of the survey line were obtained with 250–500 m station spacings and are not shown in raw data format. In general, the lateral variation in the near-surface conductivity structure is present throughout the survey line.
Small transmitter loops

A 1.3-km-long section of the Warren–Carty road was profiled by receivers spaced at 50 m with signals from three smaller transmitter loops (Fig. 1) to investigate the region around the geologically inferred location of the ILCZ. An example of the data is shown in Fig. 4. An estimate for the average overburden conductance of 0.25 S along a 1-km section west of Highway 101 is locally greater than the 0.13 S estimated from loop 2 over a longer profile. The data in Fig. 4 show detectable anomalous responses only at the earliest delay times (0.025–0.1 ms) and again are typical of near surface overburden variations. A zone of apparent higher surficial conductivity is marked C and another zone appears to extend west of position D. The survey line was too short to define completely anomaly D; however, its location indicates its source is probably the same as anomaly B in Fig. 2. The UTEM data give no evidence for large, steeply dipping features in this vicinity.

Interpretation of finite patches of conductive overburden is described in West et al. (1984) and in more detail in Macnae (1986). Estimates of the time rate of decay of the vertical magnetic field observed over the isolated feature C (same as conductor C on the loop 2 data) gives a conductance estimate of 0.5 S. Feature D has a similar estimated conductance. From the loop 2 data, the region labelled A has an estimated conductance of 0.4 S. While it is not possible to estimate the local surface conductance of the less conductive overburden patches, these are certainly much less than the 0.25 S ‘average’ obtained when data are fitted to a uniform surface conductor. With this wide variation in the conductance of near-surface overburden, it is not surprising that the MT data were collected with electrodes in, or near, zones of varying conductivity and therefore the apparent resistivity curves show considerable static shift.

Fig. 5 shows an apparent resistivity pseudosection calculated from scalar audiomagnetotelluric (AMT) data for electric field measurements in a north–south direction. The AMT data were collected along the Warren–Carty road from Highway 101 to 1.5 km west. UTEM anomaly C is associated with a minor, high-frequency decrease in apparent resistivity. Anomalies B and D are more pronounced on the pseudosection and show a response typical of a thin vertical conductor the top of which does not extend to the surface. The pseudosection for tellurics east–west (not shown) displays a weaker anomaly at location B but the anomaly at location C is similar in the telluric north–south and telluric east–west pseudosections. Therefore the AMT and UTEM data for anomaly C may be interpreted as a surficial zone of increased conductivity.

Five UTEM stations were surveyed along Highway 101, using loop 12 as a source, to investigate the variation in observed response in a NNE–SSW direction. The data appear symmetrical about station 400 south (Fig. 6), and would indicate that the structure is uniform in the direction parallel to the strike of the ILCZ. A more detailed station spacing is required to confirm this conclusion.

**DEPTH IMAGE PROCESSING (DIP) RESULTS**

The discussion so far has focused on the electrical variability of the overburden and the apparent lack of response from a larger conductive anomaly. Especially noteworthy is the absence of a significant conductor associated with the presumed location of the ILCZ, a result which is consistent with the interpretation of the MT survey data (Kurtz et al. in preparation). To obtain information on the deep Earth structure, a conductivity-depth section was obtained by transforming the data using a Depth Image Processing (DIP) program (Macnae & Lamontagne 1987). DIP is a
Figure 5. Audiomagnetotelluric apparent resistivity pseudosection for electric field measurements in a north–south direction. Dots indicate the locations and frequency for which data were obtained. Contour units are $\Omega$m. The approximate location for the Ivanhoe Lake Cataclastic Zone (ILCZ) as proposed by Percival (1981) and Percival & Card (1983) is indicated at the top of the figure.

Figure 6. Normalized vertical magnetic field data collected along Highway 101. Station 400 S is a point of symmetry with respect to transmitter loop 12.

forward data transform which produces a stable estimate of the conductivity-depth section that (if no averaging is used) has a one-to-one relationship to input data. A comparison of imaged conductivity with the true conductivity structure for a number of models is given in Macnae & Lamontagne (1987). DIP is stabilized in that similar input data will produce similar imaged sections, thus facilitating the visual analysis of large datasets. The program only fits layered Earth models to field data and as a result cannot be regarded as a true section of the ground beneath the survey line, but rather is an approximation that has been shown to be reasonably correct if the Earth structure is quasi-layered (Macnae & Lamontagne 1988).

The deep penetration data (late time channels) from loops 2 and 3 were processed and the results are presented in Fig. 7. Before describing the section, it is important that several caveats be noted. For a good interpretation of data collected in areas containing lateral inhomogeneities, DIP requires data to be collected from transmitter loops both over and on either side of any area of interest (i.e. three-fold coverage). The DIP software has been optimized for this situation. To obtain stable transformation of single-fold (or at best two-fold) data collected in this survey, considerable lateral averaging was required during the fitting process. The resulting section is thus most reliable in areas where the
Figure 7. Structural section produced by the Depth Image Processing (DIP) technique and represents the smoothest quasi-layered resistivity distribution that fits the data. The hatched areas show the regions of the section for which the resistivities are not well constrained. The resistivity image in the upper right quadrant is only approximately layered and estimates of depths and resistivities must be viewed with caution. The section begins at Highway 101 and extends west along the Warren–Carty road. Contours are labelled in kΩm.

The structure is predominantly layered and conductive (darker shading). Features which do not appear layered on the image section may not be correctly estimated in terms of conductivity or in depth; they do however reflect real changes in the data. The features in the upper right quadrant of Fig. 7 may not be reliably rendered.

Surficial layers with conductances in the 0.1–0.5 S range were fitted in the processing but are not shown in Fig. 7 as their thicknesses are not resolved and the depth scale is not appropriate to display shallow features. A somewhat deeper conductive zone with resistivity less than 6000 Ωm is shown at depths of 1.5 km between stations 1 W and 4.5 W. A zone with resistivity of approximately 6000 Ωm and a total conductance of about 0.13 S appears to lie at a depth between 2 and 3 km under the western part of the survey line, and may dip gently to the west. If it is identified correctly as a layer, the true dip may be different than shown because of the fitting procedure and lateral averaging. Below 10 km resistivities appear to decrease to less than 6000 Ωm but at this depth (due to geometrical errors) the data do not tightly constrain the fitted model.

Generally in the remainder of the upper crust the resistivity is estimated to be more than 10 000 Ωm. When the electrical structure in an area has large resistivity contrasts, the secondary magnetic fields induced by the comparatively small currents flowing in resistive horizons tend to be negligible compared with the magnetic fields of current flowing in the more conductive parts. In this case, the presence of the resistive horizons can be inferred (from the absence of current) and a lower limit on the resistivity defined. With the irregular near-surface changes in conductivity observed here, the UTEM data cannot define an upper limit on the resistivity of the 2 km immediately below the overburden from the limited data collected in this survey. However, 10 000 Ωm is a well-constrained minimum value for the upper crust resistivity.

It is important to consider the resolution of features plotted on the DIP section. Observed amplitudes at a receiver station are used to estimate the depth D of an equivalent current image source. The conductivity is then estimated using the inverse acceleration estimated by the second derivative \( d^2t/dD^2 \). With the standard three-fold coverage of most sounding surveys (Macnae & Lamontagne 1987) reasonable uniform resolution of conductivity as a function of depth D can be obtained. In this survey, where data were only collected from two adjacent transmitter loops, a cone of limited resolution extends under the common side of the loops (below 5 W, Fig. 7). As well the resolution of the location of shallow features is limited both immediately under the transmitter loop wires and at large distances away from them. If a receiver station is located at a distance \( x \) from the nearest side of the transmitter loop, with a noise envelope of <1 per cent, depth to the centre of induced current and derived conductivities are constrained to within 20 per cent only in the range \( 0.2x < D < 5x \). The hatched areas below 2.2 W and 6.7 W in Fig. 7 show which...
part of the section has data falling outside these limits. The UTEM data in this case are able to detect unambiguously the presence of conductors at depths of 1.5 and 3 km in Fig. 7. At the current state of development of DIP processing, it is not possible to quantify the error in the fitted section when the real Earth is non-layered. For truly layered earths and optimized field data acquisition parameters, depths to conductors can be estimated to better than 10 per cent and the cumulative conductance to better than 20 per cent.

The UTEM DIP section in Fig. 7 was simulated with a model (based on the MT interpretation) having horizontal layers, listed in order of increasing depth, of 3000 Ωm (300 m thick), 40 000 Ωm (12 km), 4000 Ωm (23 km) and 900 Ωm (195 km) over a half space of 100 Ωm. A conductive zone of 0.125 S was embedded in the 40 000 Ωm layer at a depth of 1 km to the east and 2.4 km to the west with the offset occurring at 6 W to represent the conducting zone shown in Fig. 7. The 2-D response of this model shows a maximum splitting between the B and E polarization apparent resistivity curves of 3 per cent (on a logarithmic base 10 scale) and of 2° for the phase curves. If the assumption is made that the anomaly can be represented as a horizontal layer at a depth of 1 km, then the 1-D apparent resistivity curve would change by 6 per cent (logarithmic base 10 scale) at 300 Hz and the phase by 9° (at 1000 Hz) from the response of a model without the conductor. The conductive zone could be observed in high quality MT data but the observed variability and static shift effects make it difficult to identify the conductor using standard MT techniques.

CONCLUSIONS

The results from the UTEM survey indicate that controlled source EM sounding can play a part in investigations of the Earth's crust. This test survey suggested operational improvements for a more detailed survey conducted in 1987 August, also, in part, along the Warren–Carty road (Bailey, et al. 1989). In particular a higher base frequency was required to quantify the upper crustal resistivity, and more systematic geometrical coverage was required to minimize the effects of conductive overburden on the deeper interpretation. Results from these surveys, when combined with data from a major seismic reflection survey (conducted in late 1987) will provide constraints on the nature of seismic reflectors. Moreover, it will be possible to compare fault zone characteristics at depth with those determined at the surface. No large conductive structure can be associated with a surface expression of the ILCZ on the west side of Highway 101 and a major goal of the subsequent UTEM survey was to extend the profile over 10 km to the east.

The DIP section in Fig. 7 defines structure that is possibly related to the ILCZ. The anomaly at depths greater than 2 km has a conductance of 0.13 S or less and was not evident in the MT data. The seismic reflection survey (Cook 1985) provided a minimum depth estimate to a reflector of 3 km at 2.5 W (Fig. 7) and dipping to at least 7 km at 9 W, much deeper than 2.5–3.3 km estimated for the depth to the UTEM conductor. Other, unidentified reflectors were observed in the preliminary seismic survey and may in fact be more closely related to the conductive zone. The recent (Autumn 1987) seismic reflection survey imaged reflectors that delineate a major thrust surface (A. G. Green, private communication) coincident with the UTEM conductor.

It is perhaps premature to speculate on the cause of the UTEM conductor until results for the second UTEM survey and the high-resolution seismic reflection survey become available. However, it is worth noting that rock porosity is one of the prime factors controlling resistivity in fluid saturated rocks at low temperatures. Assuming the material in the conducting zone has a bulk resistivity of 5000 Ωm and is saturated with fluids of salinity comparable with sea-water, Archie's law gives an estimate for the porosity of 0.7 per cent.

The interpretation of the UTEM data corroborated and extended the electrical models derived from the MT data. In the MT interpretation Kurtz et al. (in prep.) observed a moderately conductive (0.1–0.2 S), but laterally variable overburden layer above a resistive upper crust. The two most conductive anomalies observed along the AMT profile coincided with UTEM anomalies B (and D) and with C. Anomaly C is located in a low marshy area, but anomaly B is located at a higher elevation and the surface was very dry. Anomaly B could be the response of a steeply dipping conductor, not extending to the surface, and striking approximately north–south and should be the target of further field work.

The MT model for the upper crust had an estimated resistivity between 30 000 and 50 000 Ωm. The UTEM survey set a well-constrained lower limit of 10 000 Ωm but no upper limit could be determined from this particular dataset. To correct for static shift in MT soundings, the resistivity of this layer could be better defined by a higher base frequency (earlier sample times) and better geometrical survey control. A decrease in resistivity at mid-crustal depths was suggested by the DIP and degrees well with a similar decrease beginning at 12 km observed in the MT interpretation.

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