Lateral variations of conductivity structure across Southern Scotland and Northern England

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ABSTRACT

High-frequency (100–0.01 Hz) magnetotelluric (MT) soundings have been carried out along a 140 km profile across Southern Scotland and Northern England, where previously longer-period soundings had been undertaken. Examples of the results of the processing of data from 15 sites along the profile and of the application of a number of 1D inversion procedures are presented. The latter include the joint inversion of d.c. resistivity and MT data at Rookhope where borehole stratigraphy is also available. Although the data were severely contaminated by near field sources at some sites, and the station spacing was too large in parts of the traverse for good resolution of model parameters, by incorporation of results from the earlier studies it is possible to obtain a preliminary 2D model of the electrical resistivity structure of the upper crust in this region. Significant differences have been found in the three main geological zones crossed by the survey—the Alston Block, the Northumberland Basin and the Southern Uplands of Scotland. In the discussion, special attention has been paid to four sites in the neighbourhood of the Southern Uplands Fault, for which the data have been subjected to tensor decomposition. This has revealed two dominant regional azimuths, one of which dominates at the shorter periods and corresponds to the strike of the Southern Uplands Fault and the other, at longer periods, which corresponds to the strike of the well-known Southern Uplands magnetovariational (MV) anomaly. Moreover, in this region, the electrical resistivity models indicate the presence of a highly conducting zone beginning at a depth of about 4 km at Station CAP, which is located on the axis of the MV anomaly, and extending to a depth of at least 25 km. The depth to this conducting zone increases both to the north and the south of the MV anomaly axis, resulting in a structure which has many features in common with those along parallel traverses in SE Scotland and in Ireland. In discussing the implications of the Irish model, another researcher proposed either metamorphosed sediments and/or serpentinised island arc crust as being possible sources of the high conductivity and other geophysical and geological data. The probability that the arguments in that study are equally applicable to Southern Scotland is currently under consideration.

1. Introduction

In the past two decades, many geological and geophysical studies have been carried out in Southern Scotland and Northern England to obtain information about the structure of the Earth's crust in this region of the Iapetus suture (McKerrow and Cocks, 1986). For determination of the electrical conductivity structure, two electromagnetic induction techniques have been used—the magnetovariation (MV) and magnetotelluric (MT) methods. From the pioneering studies of Edwards et al. (1971) and Jones and Hutton (1979a,b), which revealed respectively the presence of a major conductivity anomaly striking NE–SW across Southern Scotland and the existence of low conductivity in the lower crust, there have been major advances in instrumentation, field logistics, data processing, modelling and inversion techniques. This has resulted in a succession of further studies in the region (Fig. 1) both along a central traverse AA' between the Midland Valley of Scotland and the Weardale granite of the Alston Block in Northern England and

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along a shorter parallel traverse XX' to the NE. In all cases, they aimed at supplementing and improving some aspect of the prior work. For example, as was the norm for MT studies in the 1970s, those of Jones (1977) were restricted to the period range 10–3000 s, data recording was on paper chart recorders, and state-of-the-art modelling was confined to 1D structures. By the late 1970s, the bandwidth of MT soundings was being extended into the audio frequency range (AMT), with the first experience of AMT in the UK being that undertaken in Northern England by Novak (1981). Although the total sounding capability for his study was increased to 0.001–3000 s there was unfortunately a gap of two decades around 1 s, as a result of instrumental and funding constraints at that time. The real-time data acquisition system SPAM (Dawes, 1984), and additional induction coil magnetometers to cover the intermediate sounding frequencies, then became available, with their first deployment in the UK being in the Duns area of Sule’s traverse XX’ (Sule, 1985;
Fig. 2. An example of the data resulting from application of classical processing techniques to observations made at Site CAP. (a) Apparent resistivity and phase vs. frequency variations in the measured directions (north–south and east–west). (b) Apparent resistivity and phase vs. frequency variations in the principal directions. (c) Skew vs. frequency. (d) Azimuth of the major impedance vs. frequency.
Sule et al., 1993). The results presented in this paper are concerned with the extension of the long-period soundings of Jones and Novak into the audio range. Although it had already become clear that satisfactory structural resolution could only be achieved with much closer station spacing than used in the former studies, it was decided to supplement the existing soundings before undertaking a more closely spaced array. As a result of the relatively large station spacing and severe noise contamination at some frequencies, only tentative deductions can thus be drawn from the study; nevertheless, the results not only substantiate the conclusions of the earlier workers, but for the first time provide information about the upper-crustal structure along the traverse and a preliminary 2D model. Since the completion of this study, an additional eight soundings have been made in or near the southern part of AA' by Parr (1991), who has also reprocessed many of the present data using a constrained robust processing algorithm (see Parr and Hutton, 1993), and 2D inversions of these new and reprocessed data have been undertaken by Livelybrooks et al. (1993). Additional soundings, and the application of robust processing and 2D inversion, are only now being undertaken for the more northerly part of AA'—near the Southern Uplands Fault. For this region, in addition to the initial processing and modelling of Harinarayana (1988), the impedance tensors of two of his sites (CAP and DZR) and additional soundings at LIB and GLK (P.C. Jones, personal communication, 1992) have recently been subjected to tensor decomposition using the Groom and Bailey (1989, 1991) procedures. This small but more intensive study con-

Fig. 3. The Kao and Orr dimensionality indices D1, D2 and D3 vs. frequency for (a) Site CAP, (b) Site DZR, (c) Site WHI and (d) Site LAM.
Fig. 4. 1D Occam's Razor inversions for the decomposed impedance tensor (with a fixed azimuth of N50°E) at Site CAP for the E-pol and H-pol directions. The resistivity-depth profiles are on the right of the plots of the decomposed responses (dots) and the model responses (thin solid lines).
firms the indication provided by the previous modelling of the initial data that a major conductive feature exists in the upper crust in the neighbourhood of the axis of the previously detected MV anomaly. Moreover, comparison of the results from the northern part of AA' with those from XX' (Sule and Hutton, 1986; Sule et al., 1993) and from a traverse across the Midland Valley of Ireland (Whelan et al., 1990) provide preliminary evidence of common features in the electrical resistivity structure across corresponding geological zones of Scotland and Ireland.

2. Data acquisition and processing

The data were acquired using two types of equipment—the real-time acquisition system SPAM of Dawes (1984) with an operating range of 128–0.031 Hz and a long-period MT system with digital recording on magnetic cassettes and operating range 5–190 s. In both cases, the magnetic sensors were the CM11E induction coils of Société ECA (Paris). The electric field sensors comprised pairs of copper electrodes for the former system and non-polarising lead/lead-chloride electrodes in the latter. The site locations of this study are shown in Fig. 1, together with the locations of other MT soundings discussed. Unfortunately, data at several stations, e.g. NEW, were corrupted with noise, and the static shift detected at Site SML could not be corrected owing to the large station spacing in this region of the traverse AA'. As a result, the data from these sites could not be incorporated in the final models. The reduction of the noise in the CRK data using digital filters has been discussed by Fontes et al. (1988).

A full description of the processing, event selection, analysis and averaging procedures applied to data from all the sites except LIB and GLK is given, together with the results, by Harinarayana (1988). The procedures follow those developed by Sims et al. (1971). For the additional soundings at LIB and GLK and two neighbouring sites, the data have been robustly processed using the methods of Egbert and Booker (1986), and for all four sites they have been subjected to tensor decomposition. As an example of the initial procedures, the processed results from Site CAP are shown here in Figs. 2a–d, in which the following parameters as a function of
frequency are plotted: (a) apparent resistivity and phase in each of the measured directions (north–south and east–west); (b) apparent resistivity and phase in the principal directions; (c) skew; (d) azimuth of the major principal impedance.

The dimensionality indices D1, D2 and D3 of Kao and Orr (1982) are shown in Figs. 3a–d for Sites CAP, DZR, WHI and LAM, respectively. These indices are normalised weights which have been shown to be more reliable indicators of the contribution of 1D, 2D and 3D effects than the more widely used skew parameter. Although Figs. 2 and 3a indicate that the CAP sounding can be regarded as 1D throughout, in general the data from the other sites showed more evidence of 2D and 3D contributions—at least over part of the sounding ranges—as shown in Figs. 3b–d for DZR, WHI and LAM.

Fig. 4 shows an example of the results of the decomposed CAP data together with an Occam model (Constable et al., 1987). Although the decomposition at this site confirms the one-dimensionality of its responses and provides a model comparable with those previously obtained (see Figs. 5), the decomposition of the responses from

### TABLE 1

Decomposition parameters of the data recorded at four northerly sites on the traverse AA' (regional azimuth angles are quoted as positive east of grid north)

<table>
<thead>
<tr>
<th>Period range (s)</th>
<th>Niblett–Bostick depth range (m)</th>
<th>Average regional azimuth (deg.)</th>
<th>Twist angle (deg.)</th>
<th>Shear angle (deg.)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A (deg.)</td>
<td>B (deg.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site CAP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2E—0.3 to 3.7</td>
<td>600—4500</td>
<td>7–80</td>
<td>0–83</td>
<td>−8 to −2</td>
<td>−6 to 4</td>
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<tr>
<td>3.7 to 23.3</td>
<td>4500—6500</td>
<td>29</td>
<td>69</td>
<td>−38 to −6</td>
<td>−25 to −6</td>
</tr>
<tr>
<td>Site GLK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.7E—0.3 to 7.3E–03</td>
<td>600—1100</td>
<td>39</td>
<td>42</td>
<td>10.5</td>
<td>5.5</td>
</tr>
<tr>
<td>1.45E—02 to 0.1178</td>
<td>1100—2500</td>
<td>39</td>
<td>88</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>0.16 to 1.78</td>
<td>2500—6000</td>
<td>52 to 63</td>
<td>39 to 60</td>
<td>−18 to 33</td>
<td>−18 to −6</td>
</tr>
<tr>
<td>4.0 to 12.8</td>
<td>6000—10500</td>
<td>44</td>
<td>50</td>
<td>−35</td>
<td>−15</td>
</tr>
<tr>
<td>Site DZR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.45E—02 to 0.1</td>
<td>1500—5000</td>
<td>46</td>
<td>57</td>
<td>18.5</td>
<td>12.5</td>
</tr>
<tr>
<td>0.2 to 2.0</td>
<td>5000—20000</td>
<td>45</td>
<td>51</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td>2.0 to 5.8</td>
<td>20000—30000</td>
<td>51</td>
<td>69</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>Site LIB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.16E—03 to 18.28</td>
<td>100—10000</td>
<td>37</td>
<td>42</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21 to 55</td>
<td>28 to 52</td>
<td>2 to 30</td>
<td>−12 to 6</td>
</tr>
</tbody>
</table>

Effectively 1D data; regional azimuth not resolved
Poorly resolved decomposition parameters; indication of data becoming 2D
Well resolved
Data galvanically distorted by structure above; channelling angle 40
Noisy data; parameters not well resolved
Fairly well resolved
Data typical of 2D regional tensor considerably distorted by galvanic scattering
Parameters not well resolved; data associated with large error bars
Fig. 6. Joint inversion (D Guill and Vezzoli) of d.c. resistivity and MT data from Site ROO. The joint inversion of MT responses (a) and resistivity responses (b) is shown in (c), and the inversion of the MT responses alone is shown in (d). The smooth curves in (a) and (b) are model (c) responses. The block diagram models (i) for ROO Limestone: (o.d.: G.W., Gr. White Shale; Gr. granite).
the other three sites leads to deductions which could not have been drawn from the previous procedures. A summary of the main results of the decomposition is given in Table 1 and is discussed in section 3.2.

3. 1D modelling

3.1. Traverse AA' data—initial modelling

Because, as stated above, the data were 2D or 3D for at least part of the sounding range at almost all the sites except CAP, the apparent resistivities and phases derived from the determinant impedances were also obtained at all sites, and 1D models were derived from these averages to provide a starting model for subsequent 2D modelling. Two different 1D inversion algorithms were initially applied to data from the complete traverse—a Hedgehog modification (G.J.K. Dawes, personal communication, 1981) of the Monte Carlo inversion of Jones and Hutton (1979b) and the inversion scheme of Jupp and Vozoff (1975). The starting model, based on the Bostick transform (Bostick, 1977; Jones, 1983), was the same in both cases. As an example of those procedures, their application to the determinant responses at Site CAP is shown in Figs. 5a–c. The good agreement between the models (Figs. 5b and 5c) obtained with the different algorithms is typical of the 1D modelling for the study as a whole. An example of a joint inversion of the results of a large spread d.c. resistivity sounding (Habberjam and Thanassoulos, 1979) and those from the MT sounding at ROO about 2 km distant is shown in Figs. 6a–e. As expected, the joint inversion (Fig. 6c) improved the resolution of the uppermost few hundred metres but it resulted in only minor adjustments to the deeper structure obtained from the MT data alone (Fig. 6d). It also provided an estimate of the depth to the known Weardale granite which was in better agreement with the borehole stratigraphy than that obtained from the resistivity data alone (Fig. 6e). Similar joint inversions at EDG and LAM were less successful, partly as a result of the lack of overlap in the penetration depths of the two methods.

An attempt to collate previous long-period MT sounding data from Sites CAP, LAM, EDG and BOW adjacent to Site CRK with the higher-frequency data of this study has unfortunately been limited by difficulty in retrieving the full tensor impedances of these earlier soundings. However, by combining the E-pol responses of the previous long-period sounding at CAP with the determinant responses for the nearby CAP site of this study, Harinarayana (1988) has shown that although a very good conductor at approximately 4 km depth can be inferred from the present study, the longer-period data are essential for indication that its thickness is at least 20 km. At LAM, by a similar collation, he found that the penetration depth is increased from about 20 km to the order of 100 km, although the deep structure in the resulting 1D model can only be regarded as a first approximation, owing to its multi-dimensionality (see Fig. 3d) at frequencies less than 1 Hz.

3.2. Results of tensor decomposition and 1D modelling—Southern Uplands Fault data

Examination of Table 1 confirms that most of the data recorded at CAP are effectively 1D. The data recorded at Sites GLK, DZR and LIB, however, are 2D, with two regional azimuths dominating these data sets. With the exception of the longest periods at Sites CAP and DZR, regional azimuths of between 42 and 52° are prevalent. At these sites, however, the dominant regional azimuth changes to approximately 69° for the longest periods. The data at the four sites were decomposed using the values in Table 1, and the invariant was calculated using the Berdichevsky average of the subsequent principal impedances (Berdichevsky and Dmitriev, 1976). The E-pol ($R_{xy}$) and H-pol ($R_{yz}$) responses were obtained by decomposing the data using the methods of Groom and Bailey (1989) with a fixed azimuth of N50°E.

1D modelling of the decomposed data sets has been undertaken using the inversion routines developed by Fischer and Le Quang (1981), Fischer et al. (1981) and Constable et al. (1987). For comparison with the models derived initially, the
The former are shown here (Figs. 7a and b) for the E-pol responses at Sites CAP and DZR. 1D models for the data recorded at LIB show that the surface layers of the Midland Valley are relatively conductive (approximately 55 \( \Omega \) m) to a depth of about 1.5 km in comparison with the top.

Fig. 7. 1D Fischer Minim models for the decomposed E-pol \( (R_{xy}) \) responses from (a) CAP and (b) DZR. For CAP, the r.m.s. fit is 2.49 and for DZR 1.34.
layers in the 1D models of the data recorded at Sites GLK and DZR in the Southern Uplands, which have average resistivities of at least 600 Ω m. These contrasting electrical structures come into contact at the Southern Uplands Fault, which strikes approximately N49°E within this area. Regional azimuths approximately equal to this value start to dominate data with skin depths equal to the distance to the Fault from Sites DZR and GLK.

The dominant feature of the 1D models of data recorded at CAP (Figs. 4, 5 and 7a) is the onset of a highly conductive layer (2.2 Ω m) at 4.0 km, whereas the decomposition analysis of the longest periods recorded at CAP (data with Niblett–Bostick depths greater than 5.5 km) gives some indication that the data become 2D with an azimuth of approximately 69°.

Although the data at DZR are strictly 2D, it is of interest that Fig. 7b shows a conductive bottom layer of 10 Ω m at depths greater than 10.5 km and that Table 1 shows that the longest periods recorded at this site have a regional azimuth of 60° as for GLK. This azimuth is very close to the Southern Uplands MV anomaly direction of 72° in this area (Banks et al., 1993). It is thus proposed that the bottom conductive layer detected in this region by this study is also associated with the MV anomaly.

4. 2D modelling

Before 2D inversion, pseudo-2D sections were obtained by collating 1D models for each site along the 140 km traverse from the Weardale granite of Northern England to the Southern Uplands Fault of Scotland. Two such sections were obtained—one for the average responses and the other for the E-Pol responses with an assumed average strike of N75°E. The latter is presented here as Fig. 8, and a schematic interpretation is given in Fig. 9a. As a result of the inadequacies of the sounding density, especially in the northern half of the traverse, and to poor data quality at many sites, only major features in the resistivity structure can be detected—the Weardale granite, the relatively conducting Northumberland Basin overlying a thinned upper-crustal resistive basement, and the thicker more resistive basement of the Ordovician rocks of Southern Scotland. As found in the earlier studies of Jones and Hutton (1979a,b), the lower crust is relatively conducting and there is further evidence that the depth to this conductor in Southern Scotland dips to the south from the neighbourhood of the Southern Uplands Fault. Owing to lack of broadband data in the central portion of the traverse, Jones's 1D model (1977) for the long-period data set at NEW have been

Fig. 8. The compilation of 1D inversions (Jupp and Vozoff) of the E-pol responses (average strike 75°) for the whole traverse. The model for NEW is from Jones and Hutton (1979a). (Note that the depth scale is logarithmic.)
Fig. 9. (a) A schematic resistivity model for traverse AA'. The structure assumed near the centre of the traverse reflects results published by Beamish and Smythe (1986). (b) The 2D inversion.

included in Fig. 8, and the features traced across this part of the section in Fig. 9a have also been influenced by the interpretation of average resistivity and phase data from three long-period soundings (Beamish and Smythe, 1986) which extend from the Northumberland Basin to the Southern Uplands near CRK. Bearing in mind the restricted sounding range and the considerable anisotropy of their data and the large station spacing, the 10 km thick northward-dipping conductor in the lower crust proposed in Beamish and Smythe must be regarded as tentative. It will be noted, however, that the depth to the lower-crustal conductor under the Northumberland Basin at Sites LAM and EDG differs from that under the granite batholith at Sites ROO and HIL, being about 10 km and 20 km, respectively.

As the geological strike varies from about N60°E in Southern Scotland to N90°E in Northern England, the impedance tensors were rotated through the average value of N75°E before the application of Hill's 2D inversion (Hill, 1987). This scheme applies a biased linear estimation algorithm using singular value truncation and
Fig. 10. Examples of the fit of the model responses to the observed responses for the following sites along the traverse AA': (a) DZR; (b) CAP; (c) CWR.
Fig. 11. (a) Site locations in the region of the Southern Uplands Fault (S.U.F.). The thick solid lines indicate the locations of the geological faults and the dashed line the zero contour of the MV anomaly mapped in Fig. 1. (b) A compilation of 1D models of upper-crustal electrical resistivity across the Southern Uplands Fault and the MV anomaly in central Scotland. The values in the models are resistivities (in Ω m) with those for Site GLK in parentheses. (c) The 2D model of upper-crustal electrical resistivity across the Southern Uplands Fault and the MV anomaly in SE Scotland—traverse XX' of Fig. 1 (Sule et al., 1993). (d) Part of the 2D model of crustal electrical resistivity across Ireland (from Whelan, 1989). The arrowhead on the left-hand side of the figure indicates the location of the extension of the Southern Uplands Fault in Ireland.
ridge regression iteratively, with the iteration using the Brewitt-Taylor and Weaver (1976) procedure for the forward calculation. In many respects, the procedure is similar to that of Jupp and Vozoff (1977), but it has the advantage that both the position and the resistivity of each block can be considered as variables during the iterations. The final 2D model is shown in Fig. 9b, with examples of the fit of the model to the observed apparent resistivities and phases at three sites in Figs. 10a–10c. Only certain gross features of this model are accepted as meaningful on account of inadequacies in the station spacing, data quality, sounding bandwidth and the variation in strike direction along the 150 km traverse.

5. Discussion

As more recent work (see Parr and Hutton (1993) and Livelybrooks et al. (1993)) has resulted in both 1D and 2D models derived from a more dense array of sites over the southern part of the same traverse and with the application of more recently developed robust processing algorithms, further reference to this part of the traverse in this paper is restricted to a summary of those features which were first identified by the 1D and 2D models of this study. These are as follows:

1) there is a different upper-crustal electrical conductivity structure in each of the three geological zones—the Alston Block, the Northumberland Basin and the Southern Uplands of Scotland—crossed by traverse AA',

2) In the Alston Block, at a depth of about 400 m, the resistivity increases to about 10 K \( \Omega \) m; this value is compatible with the presence at that depth of the known Weardale granite (Dunham et al., 1965).

3) The Northumberland Basin is identified by relatively conducting (60 \( \Omega \) m or less) uppermost layers of maximum depth 3 km, overlying basement rock of resistivity of approximately 300 \( \Omega \) m.

4) The upper-crustal resistivity of 370 \( \Omega \) m in the Southern Uplands of Scotland is unexpectedly low by comparison with results obtained by Sule and Hutton (1986). This may be due to the inadequacy of data in this region.

5) The lower crust along the whole traverse has low resistivity (typically less than 100 \( \Omega \) m) along the whole traverse, in agreement with the results of earlier studies (Hutton et al., 1980), and there is further support for variation along the traverse in the depth to this conducting zone. A particularly interesting feature is the shallow depth to the conductor about 7 km south of the Southern Uplands Fault. The thickness of the conducting zone is not well resolved.

Although further soundings are now being undertaken in the region of the Southern Uplands Fault, the application of tensor decomposition to the Sites CAP, DZR, LIB and GLK has yielded valuable support for the presence of a major conductive feature in the crust in the region of CAP and significant new information about the presence of two dominant strike directions. Although in the 2D model of Fig. 11 the conductive feature is required to satisfy the responses at CAP only, the decomposed 1D models for CAP, DZR, LIB and GLK confirm the presence of the conductor at shallow depths (3–10 km) over a section of the traverse of the order of 10 km. The current field studies are providing additional confirmation of the presence of this feature. As the early MV studies of Edwards et al. (1971) had already located—without depth control—a major conductivity anomaly striking NE–SW across Southern Scotland, and the subsequent shorter-period and denser MV observations of Jones and Hutton (1979) had more precisely located its axis as passing through CAP (see Fig. 11a) it seems reasonable to regard the model structures shown in Figs. 9b and 11b as more quantitative expressions of the MV anomaly. The determination of two dominant regional strike directions, one of which can be associated with the strike of the Southern Uplands Fault and the other, at longer periods, with the strike of the MV anomaly, is further evidence of the common source of both the MT and MV anomalies. It is also significant that the parallel MT traverse of Sule and coworkers (Sule and Hutton, 1986; Sule et al., 1993) shows a similar crustal resistivity model with a good conductor at comparable depths, again cen-
tred near the axis—less accurately located in this region—of the MV anomaly (Fig. 11c). From the mapping provided by the MV techniques (for the most recent study, see Banks et al., 1993), it seems likely that similar conductivity models will be found across the whole of the axis of this Southern Uplands anomaly. The apparent similarity between the two resistivity models across the Southern Uplands Fault in Scotland and across its extension in Ireland (Fig. 11d) are being examined, and the relevance to the Scottish models of the possible sources of the high conductivity (metamorphosed graphitic sediments and/or serpentinitised island-arc crust) discussed by Brown (1993) for the Irish model are being considered.

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References


