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AUDIOMAGNETOTELLURIC/MAGNETOTELLURIC SOUNDINGS OF THE BROADLANDS-OHAAKI GEOTHERMAL FIELD

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Abstract

AMT/MT soundings at 11 sites on a south-north line across Broadlands-Ohaaki geothermal field clearly detect the upper surface of the geothermal reservoir. Depth to the reservoir varies from 100m to around 450m. The low resistivity region associated with the reservoir appears to extend well to the south of the field at a depth of about 1km. In contrast, the northern boundary of the field is relatively abrupt. There is evidence of a second conducting region, possibly marking the base of the crust, at a depth of 15-20km.

Introduction

Magnetotelluric (MT) sounding and its high frequency extension audiomagnetotelluric (AMT) sounding have, for many years, been widely used in the study of the electrical conductivity structure of the Earth. For a review of recent studies see Hjelt (1988). The MT and AMT techniques depend upon the fact that continually occurring small changes in the geomagnetic field induce electric currents in the electrically conducting Earth (e.g. Parkinson, 1983). At any given location the relationship between the horizontal components of the electric and magnetic fields can be interpreted in terms of the local electrical conductivity structure. The process of electromagnetic induction in the Earth may be regarded as a diffusion of electric and magnetic fields into the Earth with a depth of penetration which is dependent on the period of the field variations. It is thus possible to obtain, from measurements made at the surface, a profile of the variation of electrical conductivity with depth.

In more recent years AMT and MT have been used in both North America (e.g. Gamble et.al., 1984) and Europe (e.g. Berktold, 1983; Hutton et. al., 1989) in the study of geothermal areas. Whiteford (1975) explored the use of AMT in New Zealand for this purpose but his initial work was not followed up. Indeed it is only recently that MT sounding has been much used in New Zealand for looking at deeper structural problems (Ingham, 1987, 1988b). The equipment used in these latter two studies has now been extended to incorporate frequencies up to 1kHz which allows much greater resolution of the near surface electrical conductivity structure.

During December 1988 AMT/MT measurements in the frequency range 1kHz to 0.01Hz were made at 11 sites on a roughly south-north line across the Broadlands-Ohaaki geothermal field (Fig. 1). The hatched area in Fig. 1 indicates the boundary of the field as defined by Risk et. al. (1977) from resistivity measurements. Also shown in Fig. 1 are the locations of those drillholes which are pertinent to the discussion of the AMT/MT results. Due to development of the field, data could not be obtained from the area to the north-west of the Waikato River (Fig. 1) where the majority of the surface geothermal manifestations occur and where the main productive part of the field is situated. Site 9, however, is located in a region, which like the productive part of the field, was noted by Macdonald and Hatherton (1968) as having near surface temperatures more than 5°C above the ambient.

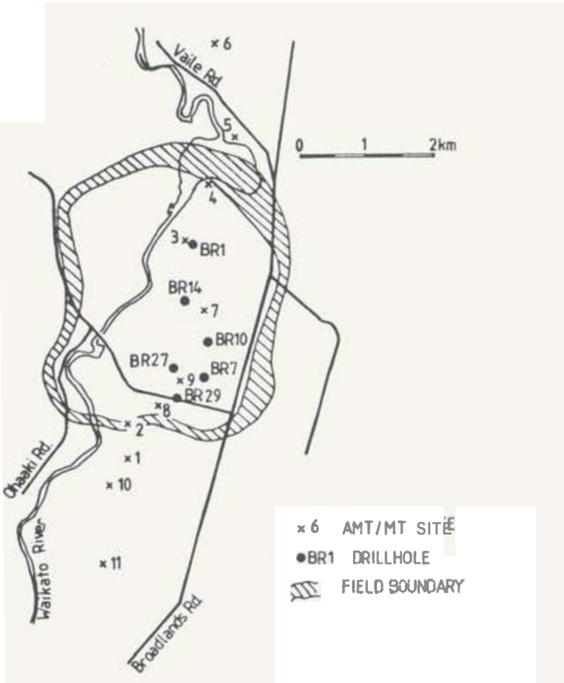

Fig.1 Broadlands-Ohaaki geothermal field.

Data analysis, results and modelling

Time variations in the north and east electric and magnetic fields at each site have been analysed using standard spectral techniques to yield maximum and minimum apparent resistivity and phase curves, azimuthal directions of the principal impedance and various dimensionality indices. The apparent resistivity (ρ_{det}) and phase (ϕ_{det}) curves derived from the "determinant" impedance of Ranganayaki (1984) have also been calculated for each site. These parameters are of importance as the determinant impedance is independent of the orientation of the impedance tensor and can be regarded as being responsive to the one-dimensional electrical conductivity structure beneath the measurement site.

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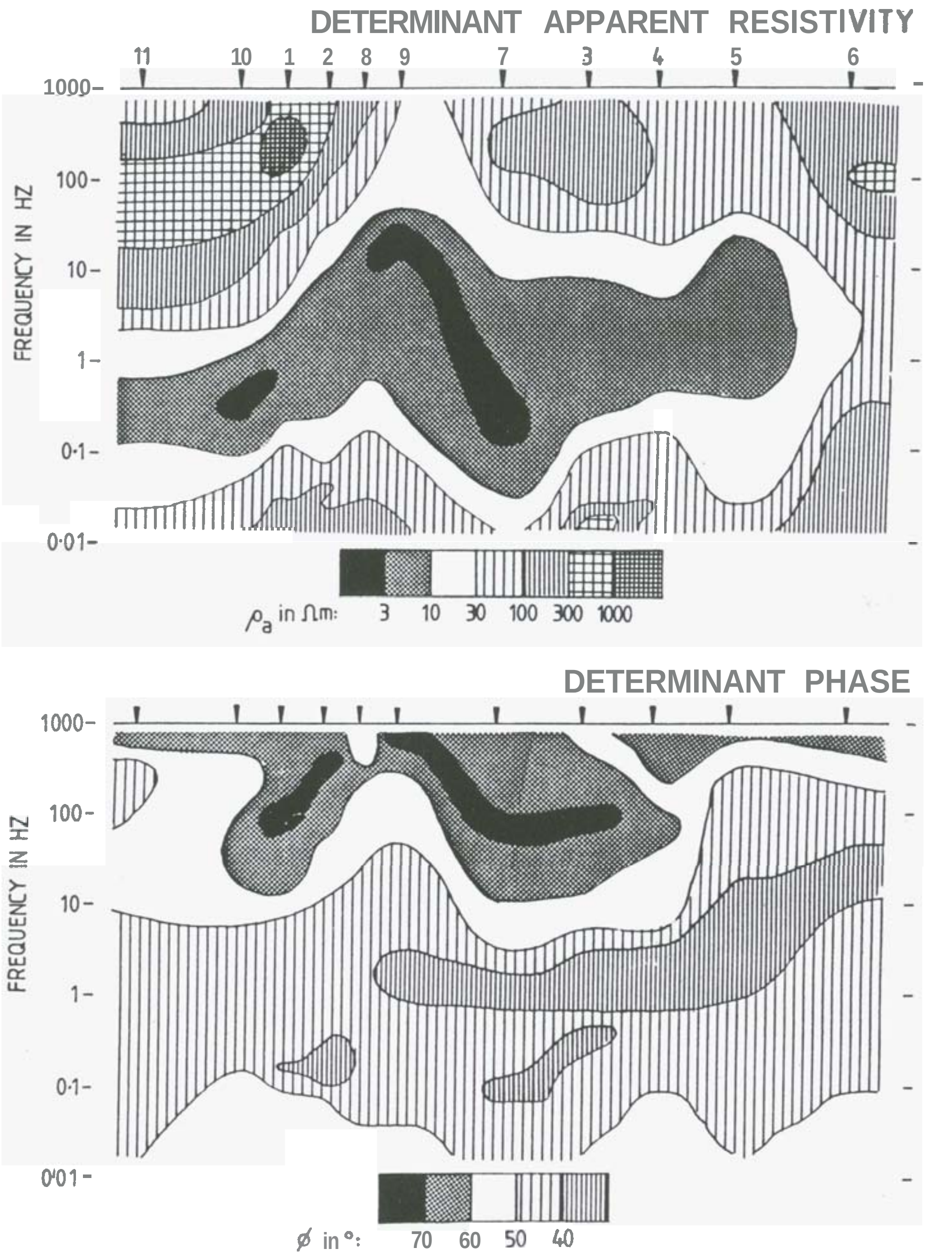

Fig.2 Determinant apparent resistivity and phase pseudo-sections for the Broadlands-Ohaaki AMT/MT data.

ϕ_{det} is of additional importance because it is unaffected by the phenomenon of static shift caused by near-surface inhomogeneities (Jones, **1988**). Static shift appears as a frequency independent "vertical" shift in the apparent resistivity curves and if uncorrected can consequently lead to erroneous interpretation. The phenomenon can be regarded mathematically as the multiplication of the (2x2) impedance tensor by a (2x2) real, frequency independent matrix. This changes the magnitudes of the impedance tensor elements but not the phases. As they are unaffected by static shift, pseudosections of ϕ_{det} are now commonly presented as a first indication of conductivity structure (e.g. Jones et. al., **1988**). A phase of greater than 45° indicates a change with depth from resistive to conductive structure. Phases less than 45° indicate that structure becomes more resistive with depth.

Pseudosections of both ρ_{det} and ϕ_{det} for the traverse shown in Fig. **1** are presented in

Fig. 2. Although it is not possible to relate the frequency scales directly to actual depth, because the skin depth at a particular frequency depends upon the resistivity, several conclusions can be drawn from the pseudosections. Firstly, the apparent resistivity pseudosection shows no indication of the measurements having been affected by static shift. It indicates a generally resistive surface structure with more conductive material beneath and resistive material again at still greater depth. In the ϕ_{det} pseudosection, at all frequencies down to 10Hz, phases are generally above 45° confirming the transition from resistive to conductive material relatively close to the surface. The most conductive region appears as phases greater than 70° at very high frequencies around site 9, indicating that, as expected, the depth to the geothermal reservoir is smallest in this area. To the north of the field boundary phases are lower, showing more resistive material, whilst to the south there is some suggestion of a continuation of the main conducting zone at deeper depths (i.e. lower frequencies). It is also interesting that at the lowest frequencies the phase again starts to rise suggesting a second conductive layer.

Although nearly all geophysical structures are in reality three-dimensional there are many instances where valid interpretations can be obtained using two or even one-dimensional methods. In the case of the Broadlands-Ohaaki AMT/MT data all the dimensionality indices and the generally low degree of anisotropy between the maximum and minimum apparent resistivity curves indicate that, despite the apparent three-dimensionality of the geothermal field, a one-dimensional interpretation at each site is not inappropriate. Wannamaker et. al. (1984) have stressed the potential dangers of one-dimensional interpretatioh when a near surface conductor exists which is laterally

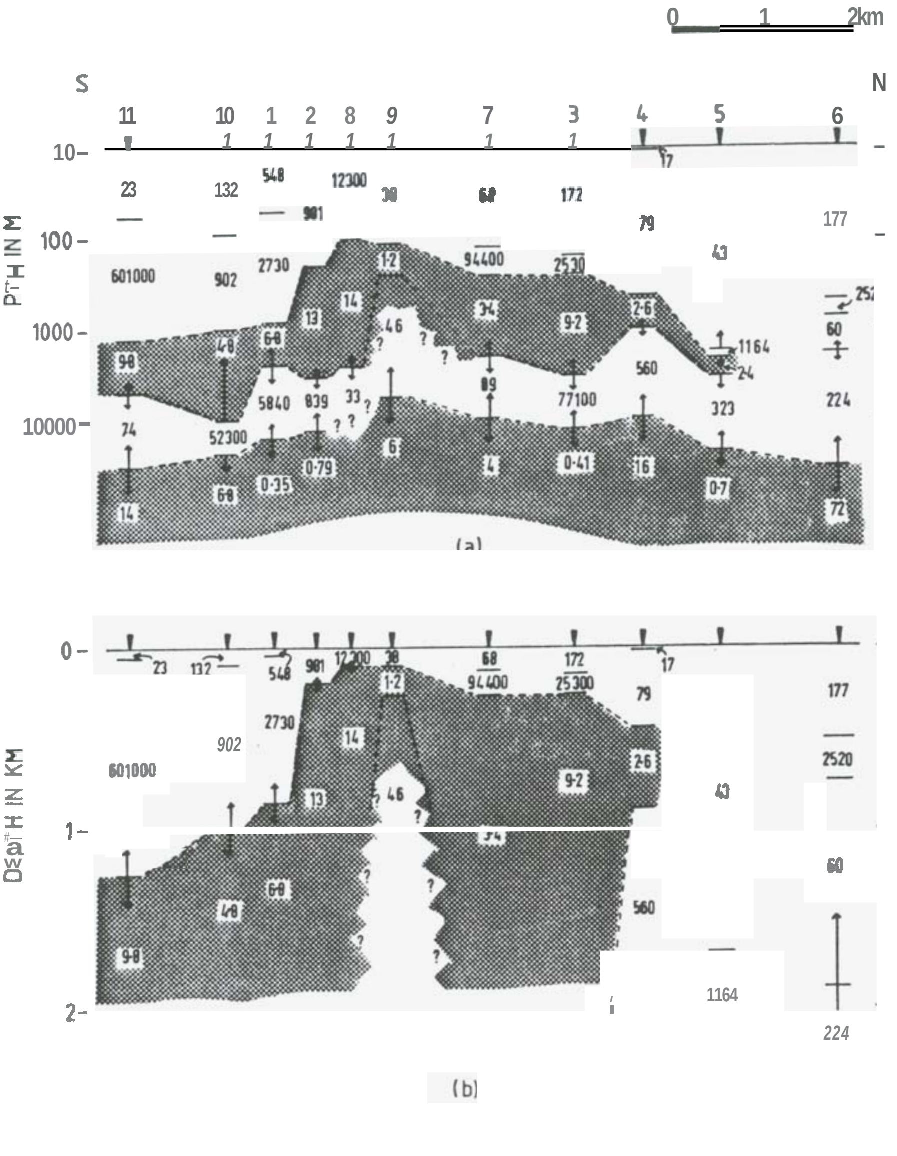

Fig. 3 Compilation of 1-d models. The principal conducting regions are stippled. (a) Complete models (b) Upper 2km only.

non-infinite. Such situations, in which grossly erroneous interpretation may arise, appear to be characterized (Ingham, 1988a) by apparent resistivity curves which show a continual decrease with increasing period and no rise in apparent resistivity at even the lowest frequencies. As can be inferred from Fig. 2 the results obtained in this study show no such characteristics. Consequently at nine of the eleven sites one-dimensional models have been fitted to the invariant apparent resistivity and phase (i.e. ρ_{det} and ϕ_{det}) curves. At sites 4 and 8, where the phase data are not well constrained, models have been fitted to the apparent resistivity data only.

Shown in Fig. 3a as a south-north cross-section of the geothermal field is a compilation of the one-dimensional models for the eleven sites.' The resistivities of the different layers are marked and the principal regions of low resistivity are stippled. The depth scale is logarithmic. In Fig. 3b the upper 2km of the section is shown in more detail with a linear depth scale.

The gross structure of the field along the traverse is clearly depicted in Fig. 3a. The main low resistivity zone rises closest to the surface beneath sites 8 and 9. Indeed, beneath site 9 resistivities are relatively low at all depths. To the south of the field the conductive zone can be seen to dip to around lkm depth, whilst to the north it loses its character close to the northern boundary of the field as determined by the resistivity measurements. Uncertainties in the resistivity boundary increase with depth due to the difficulty in penetrating the conducting zone associated with the geothermal field. Nevertheless, as was suggested by the phase pseudosection, there is a clear indication of a second low resistivity zone at greater depth. The depth to this zone appears to be of the order of 15-20km and it can tentatively be associated with the base of crust.

The actual depth to the geothermal reservoir is most clearly seen in Fig. 3b. Depths to the low resistivity associated with the field are very well determined. Beneath sites 8 and 9 low resistivities occur at l00m depth whilst slightly to the north the depth of the reservoir is 250m dipping at the northern edge of the field to around 450m. At the southern boundary of the field beneath site 2 the conducting zone is placed at 200m depth. Further south the zone plunges rapidly to around lkm depth but still shows low resistivities of the same order of magnitude. The thickness of the conductive zone is not well constrained but, as an average value, low resistivities seem to exist to around 2-3km depth. However, the modelling procedure is sensitive to the Conductance of the low resistivity zone rather than its thickness and actual resistivity and it is thus possible that the zone has lower resistivity and smaller thickness than the model values indicate.

Discussion

A geological cross-section for that part of the field which lies within the resistivity boundary of Risk et. al. (1977) is shown in Fig. 4. The section is based upon that of Grindley and Browne (1968) but has been extended using the drillhole logs reported by Browne (1971) and Wood (1983). The extrapolations of the upper surfaces of the Broadlands Dacite and the Ohaaki Rhyolite come from the seismic, gravity and magnetic work of Henrys (1987) as reported by Henrys and van Dijck (1987). Also shown, and constructed from the drillhole data, are the 150, 200, 250 and 275°C isotherms. The upper surface of the low resistivity zone identified by the AMT/MT measurements is shown by the dashed line.

The AMT/MT results are generally in excellent agreement with the other information available. The top of the low resistivity region is approximately parallel to, and some 100-200m above, the upper surface of, in the south, the Broadlands Dacite, and in the northern part of the field, the Ohaaki Rhyolite. It is consistent therefore with the upper aquifer which was identified by

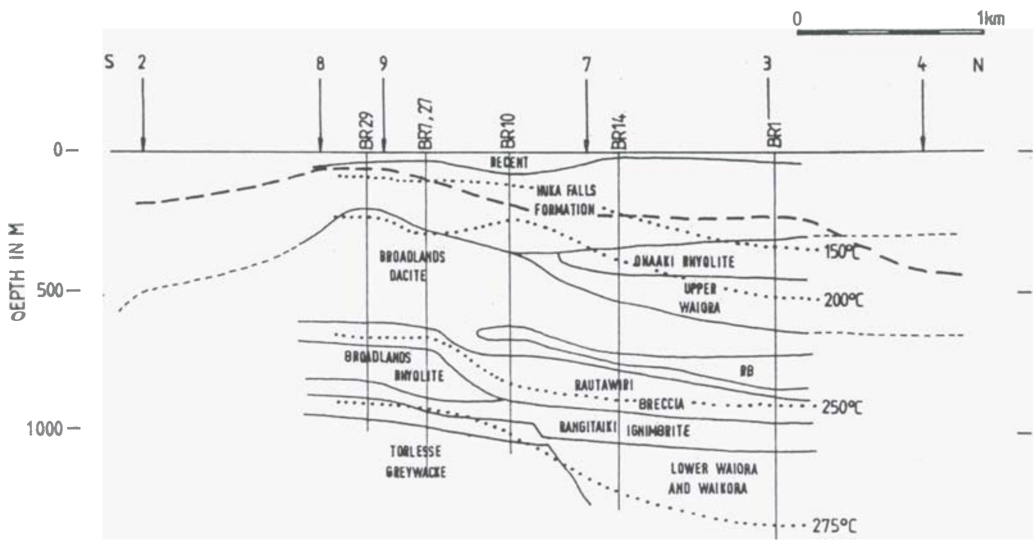

Fig. 4. Geological section across the Broadlands-Ohaaki geothermal field. Dotted lines are isotherms and the upper surface of the high conductivity zone as identified by AMT/MT is shown as the heavy dashed line.

Donaldson (1968) to lie above these bodies. The AMT/MT results do not apparently detect the impermeable basement beneath 750m-1km depth. The base of the conducting region is modelled as at around 2-3km depth. This difference may in part be due to the relatively large uncertainties in the low frequency phase data and to the fact that any rise in resistivity which occurs is muted by the high temperatures. Nevertheless allowing for the uncertainties in this depth and maintaining the same conductance of the low resistivity layer it is possible that beneath the field the base of the conducting region is indeed as shallow as 1km.

The results of Henrys (1987) indicate that south of site 2 the upper surface of the Broadlands Dacite dips rapidly to beneath 500m. This coincides with the observed dip of the low resistivity zone to much greater depths. It seems reasonable therefore to infer that the southern boundary of the field does not in fact mark the termination of the low resistivity zone but its rapid plunge to much greater depths. This low resistivity region at 1km depth certainly exists as far as 2km south of the field boundary and it is interesting to note that results, not presented here, from a single site some 15km to the south also show a similar feature.

At the northern boundary of the field there is an apparently similar increase in depth to the low resistivity region, followed, further to the north, by a significant increase in resistivity. The depth of 2km to the low resistivity region beneath site 5, just to the north of the field boundary, may in fact itself be a product of two-dimensionality close to the field boundary in a similar manner to side-swipe effects in seismics.

Conclusions

(1) AMT/MT measurements from 11 sites across the Broadlands-Ohaaki geothermal field clearly define the upper surface of the geothermal reservoir. The minimum depth of the reservoir is 100m in the south-central part of the field.

(2) At the northern boundary of the field the low resistivity zone associated with the reservoir terminates abruptly.

(3) Immediately to the north of the southern boundary of the field, as determined by resistivity traversing, the top of the low resistivity zone is at around 200m depth. As far as 2km further south low resistivities occur at a depth of around 1km.

(4) The thickness of the low resistivity zone appears to be 2-3km but could be as thin as 1km.

(5) A second conducting region exists at around 15-20km depth and can tentatively be associated with the base of the crust.

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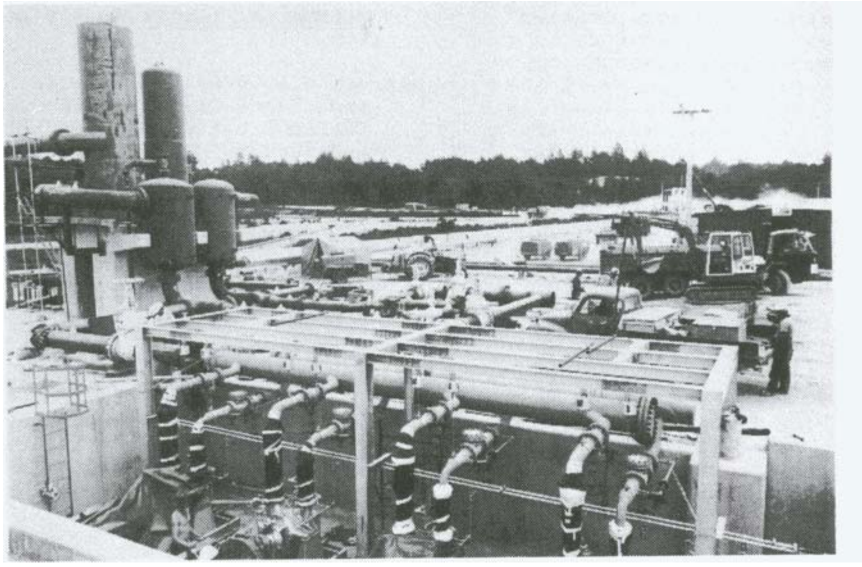

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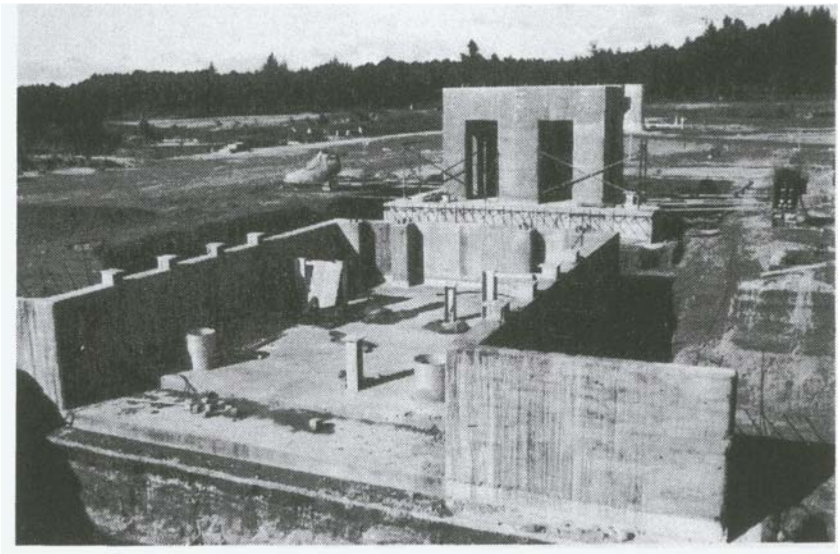

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