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THERMAL ENERGY STORAGE IN PERMEABLE FORMATIONS IN THE UNITED KINGDOM

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CONTENTS

SUMMARY

A substantial amount of theoretical and experimental research into Aquifer Thermal Energy Storage (ATES) has been carried out in the USA, China and to a lesser extent in France, West Germany, Switzerland, Japan, Denmark, Sweden and Britain. A review of literature relating to these studies is presented which indicates the high potential of ATES, especially in confined aquifers, as a means of energy conservation. Combined analytical and numerical modelling of the hydrothermal anomalies resulting from recharge of heated water into aquifers, enable extrapolation and predictions to be made which can result in a reduction of the cost of field experiments necessary in a practical study. Extrapolation of the hydrochemical processes from field experiments to the different temperatures and pressures of full scale projects will not, however, always be possible.

In order to investigate the feasibility of ATES in the United Kingdom, consideration is given to modelling and field studies involving the injection of water between 30-120°C into a confined aquifer and its subsequent storage and recovery. The purpose of a field experiment would be to provide practical experience in the operation of ATES, to assess the potential of ATES as a means of energy conservation in the UK, and to provide data for calibration of a numerical model. A brief review of aquifers in the UK is presented and the hydrogeology of those suited to a preliminary ATES study described. The confined Permo-Triassic Sandstones of the Midlands and the Lower Greensand of the Cambridge area appear suitable for large and small scale experiments respectively.

The possibilities and the manner of using an aquifer for thermal energy storage will depend on the details of the application and on the detailed properties of the aquifer; as in all applied geotechnology the latter are site specific and require careful assessment in each application.
However the known properties of aquifers which might be suitable for use for energy storage in the UK are broadly similar to and no less favourable than those in known projects overseas where this use of aquifers is being proposed and investigated. Technically suitable formations are conveniently located with respect to important industrial and population centres, though this necessarily means that there may be competing uses for the aquifers, including water supply.

1. INTRODUCTION

The possibility of aquifer thermal energy storage (ATES) was first proposed in the West by Kazmann (1971) and Meyer and Todd (1973) although a recent report (Sang, in Tsang (Ed) 1980(b)) states that practical use of ATES commenced in China in 1963. The use of aquifers to store thermal energy has many potential advantages.

1) Given suitable hydraulic and thermal conditions the possibility exists of being able to inject, store and recover large quantities of heat in natural formations. Above-ground storage vessels for amounts of thermal energy equivalent to those suggested for full scale ATES operation (Meyer et al., 1972, Meyer et al., 1977), with appropriate insulation together with the land required would be prohibitively expensive.

2) Seasonal operation of an aquifer heat store would enable waste thermal and/or solar energy to be captured during summer and used in winter.

3) If an aquifer is used, water (a readily available material of high thermal capacity) could be used to inject and recover the thermal energy from the system.

4) The storage and re-use of waste industrial heat would reduce thermal pollution at present caused by the discharge of surplus thermal energy.

5) The demonstration of a satisfactory aquifer storage/recovery technique would encourage the development of a "total energy system" concept enabling the generation of electricity together with useful heat in the most efficient way.

This report considers injection temperatures in the range from 30°C up to about 120°C. This temperature range only overlaps with the lower end of the range used in Meyer and Todd's theoretical calculations (op. cit) but the majority of experimental work carried out by subsequent investigators (detailed later) has been within this range.

It is evident that the lower the temperature of injection of storage water the lower will be the temperature of the recovered water. Hausz (1975) succinctly illustrated that lowering the source temperature (or raising the sink temperature) reduces the thermal efficiency of the system. With regard to the temperature of the injected source water, Winn (1977) states that injected water temperatures need to be at least 120°C and preferably 170°C, when storage efficiences (the ratios of energy recovered:energy injected) would be 60-70%. Also, Meyer (1976), one of the original proponents of ATES, suggests that heat storage wells should not be intended to receive and store the vast quantities of tepid cooling water discharged from power stations but rather to handle much smaller amounts of water at high temperatures.

In the higher temperature regime, two-phase fluid flow will occur unless local pressure is maintained above saturation pressure. For example, at 175°C saturation pressure is 9.2 atmospheres (.93MN m^{-2}) and a local hydrostatic head of at least 85 metres will be required to prevent flashing (Meyer et al., 1977). Difficulties related to higher temperatures indicate strongly that initial field experiments to investigate ATES should principally concern the lower-temperature regime; data adequate to develop and verify computational procedures can be gathered in this way. However, subsequent investigations should include higher-temperature operation because of its important potential payoff (Meyer et al., (op. cit.).

This report will describe successful ATES and recovery experiments carried out at injection temperatures within the range 30°-80°C; the possibility of using heat pumps to upgrade the heat recovered should be borne in mind. It will also review the available published work on ATES since 1973 and will consider the general prospects for injecting water in the temperature range 30-120°C into suitable permeable formations in the United Kingdom.

2. PUBLISHED EXPERIMENTAL AND PROPOSED STUDIES

A number of field experiments have been carried out to investigate the practicality of ATES in both confined and phreatic conditions. Much of the work so far reported has been carried out in the United States (approximately 50% of reported studies). An indication of the importance that the USA government attach to the potential of ATES is given by the Dept. of Energy report on the Multi-Year Plan for Thermal and Mechanical Energy Storage Program (DOE, USA 1979). The Thermal and Mechanical Energy Storage Program of the Energy Storage System Division of the United States DOE has been set up to develop reliable, efficient inexpensive energy storage technologies to support other DOE end-use divisions in their substitution and energy saving missions. Thermal energy storage is considered a priority area of the program and ATES a priority in the thermal sector. A total budget of $271.9M has been planned for the 5 year period 1979-84 of which 23.5% of the total ($63.9M) is allocated to ATES.

Several experiments have been reported from both France and West Germany (approximately 15% of reported studies each) with individual experiments reported from Switzerland, Japan, Denmark, Sweden, Britain and a recently reported large scale experiment in China.

A brief resumé follows of the available literature relating to field experiments into ATES - items 1-2 and 4-7 are largely based on a report by Tsang (1979).

2.1 University of Neuchatel, Switzerland. 1974. (Mathey, 1977; Mathey and Menjoz, 1978)

This experiment involved a small amount of hot water injected into a shallow, phreatic, sand-gravel aquifer for later recovery. The cycle involved injection of 494 m^3 at 51^{o}C over a period of 223 hours (equivalent to an energy injection rate of approximately 10^5 watts), storage for a period of 4 months and partial recovery of injected heat by pumping at 406 l/min for 28 days (16370 m^3). Because of the high permeability of the aquifer and the low injection rate, natural convection in the aquifer caused hot water to spread under the groundwater surface, resulting in a large heat loss. Consequently not only did the use of numerical methods to forecast the extension of thermal disturbance prove difficult but also only 40% of the heat was recovered after abstracting more than 30 times the injected volume. Mathey concluded that if summer recharging of a phreatic aquifer is required, the aid of a thermal pump for heat enhancement would be necessary.

2.2 The Campuget experiment, Gard, France. 1977-78. (Cormary <u>et al</u>., 1978)

Carried out by the Ecole des Mines de Paris this project also involved a shallow phreatic aquifer; the influence of rainfall during the experiment was noted. Here again, the natural convection effect was large and heat loss significant. Energy recovery was only 30% of that injected.

Such results suggest that more efficient ATES may be achieved in deeper confined aquifers having low vertical permeability, although some success in the storage of low grade heat in unsaturated Chalk has been reported - see Note 3.

2.3 Institute of Geological Sciences, Unsaturated Chalk Experiments, U.K., 1979. (Day <u>et al</u>., 1980)

Simple physical model experiments were carried out which demonstrated that low grade heat derived from hot water can be stored for significant periods in unsaturated permeable material at shallow depths and subsequently utilised without artificial plumbing or further energy input. The experiment enabled the behaviour of heat plumes in unsaturated repacked chalk (chosen for its favourable thermal characteristics) to be studied; results confirmed that conduction is the principal mechanism of heat movement although, under the particular constraints of the model, convection in the vapour phase may have played a minor part.

2.4 Bonnaud, France. 1976-77. (Fabris and Gringarten, 1977, Sauty et al., 1978)

This experiment was carried out jointly by the Bureau de Récherches Géologiques et Minières, the Centre d'Etudes Nucléaires de Grenoble and the Ecole des Mines de Paris. The aquifer was confined, 4 m thick and at about 4 m depth. Detailed data were taken for two series of heat storage experiments from a central well surrounded by 11 observation wells. The first series of experiments consisted of three successive injection and production cycles in 1976 and the second consisted of four cycles during 1977. The rate of energy injection was of the order of 1.3 x 10^5 watts. Large thermal dispersion was observed which may be expressed in terms of an exceptionally large apparent thermal conductivity of 12 cal/m/s/~~d~~°C

2.5 Auburn University, USA. 1978-79. (Molz et al., 1978; Papadopulos and Larson, 1978; Molz et al., 1979, Tsang, 1980a)

Two series of experiments were carried out in a sand aquifer at the Mobile Site in Alabama, one in 1976 and the other in 1978-79. The experiments involved one injection/abstraction well and 14 observation wells. The first series of experiments involved the storage of waste hot water at 36.4°C from a nearby power plant. Clogging of the injection well was experienced, probably due to fine particulates that passed the filters. The second involved storage of water pumped from a more shallow aquifer and heated to 55°C. Heat energy was injected at a rate of 1.2 x 10^6 watts over a period of 79 days and stored for 50.5 days. With periodic backwashing, no significant injection well clogging was experienced. Detailed data were collected to validate numerical models. A storage-recovery factor of 65% was found. Such clogging as did occur in this experiment resulted from swelling of clay particles in the aquifer resulting from the relatively low concentration of cations in the supply water.

In the summer of 1980 a series of three injection-storage recovery cycles is planned. A doublet system of fully screened injection and supply wells 250 m apart will be constructed and about 55,000 m^3 of water will be withdrawn from the supply well, heated and pumped into the injection well for each of the cycles. Injection temperatures will be 55°, 90° and 125°C for the first, second and third cycle respectively and after a storage period of 2 months water will be withdrawn via the injection well and returned to the supply well. New observation wells will also be constructed and aquifer tests carried out. Hydrodynamic dispersion will be studied by a tracer experiment and land subsidence and rebound will be monitored throughout the study.

2.6 Yamagata Basin, Japan. 1977- . (Yokoyama _et al._, 1978; Yokoyama in Tsang (Ed), 1980(b))

This experiment, conducted by the University of Yamagata, involved two dual purpose wells and one observation well. In summer, cooling water was withdrawn. After direct cooling, waste water was sprinkled on the roof for heat collection by conduction and radiation. The water was then filtered and further heated by a heat exchanger and recharged through the second well. The process was reversed in winter. A storage-recovery factor of about 40% was determined.

Current field experiments on the University campus include the storage of cold water in a shallow aquifer. Problems were encountered in maintaining a low temperature in the aquifer, probably due to the injection of an insufficient amount of water. Additional studies include efforts to determine analytically optimum well locations in areas of natural groundwater flow and this work has resulted in an optimum method which yields a seasonal recovery rate of 50% in spite of the natural groundwater gradients.

At the Nihon Chikasui Kaihatou Co Ltd., an ongoing project involves monitoring the quality of injected water for the duration of the storage period. It is reported that to date no evidence of contamination in water injected in 1974 has been detected.

2.7 Texas A & M University, USA. 1978-79. (Reddell *et al.*, 1978)

This experiment will investigate the use of a cooling pond in winter to chill water from 21°C to less than 10°C and to study the storage of the chilled water in an aquifer for several months and its subsequent use for air-conditioning in summer. Results are not yet available.

2.8 Krefeld experiment, W Germany. 1975-76. (Werner and Kley, 1977)

Water at a temperature of 45°C was injected into a shallow phreatic sand and gravel aquifer over a period of 64 days, the distribution of temperature in the surrounding space measured and its variation with time observed. No attempt was made at recovering the heat energy, the objective being to establish a physical basis for the technical problems of heat storage in aquifers. In the undisturbed aquifer a natural groundwater flow of 1 cm per day was present and an available pore volume of 23% measured. A total quantity of 430 m^3 was injected at 45°C over a period of 64 days equivalent to an energy injection rate of 1.1×10^4 watts.

The propogation of heat during this time remained limited to a radius of 20 m. A theoretical model was developed to simulate the field experiment and good agreement between model and experiment was demonstrated. It is suggested that the model is an extrapolatory procedure and thus makes expensive large-scale field experiments almost superfluous.

2.9 RISØ experiments, Denmark. 1980. (Reffstrup and Würtz, 1979)

The RISØ National Laboratory of Denmark plan to combine a pilot field study using ATES in a confined aquifer with a fully 3-dimensional model developed from two existing 2-dimensional models. A proposed pilot plant is described. The aquifer is approximately 30 m thick and the distance from the centre to the four outer relief wells is also approximately 30 m. The storage volume is thus approximately 10^5 m^3 x porosity. The test period is planned to cover 2 cycles for injection/storage/recovery over a period of 2 years. The periods for injection and recovery are each planned to be 4 months. For a temperature from the combined heat and power plant of 80°C and a temperature of the water of the relief wells of 46°C the efficiency in the second cycle is calculated to be 80%. In the first cycle where the initial temperature in storage is approximately 8°C the efficiency is approximately 36%. The storage capacity is about 10,000 GJ (2 TCal). It is estimated that the volumetric flow rate in the pumping periods will be approximately 30 m^3/hour and the heat flow rate about 1MW.

2.10 Technical University of Denmark, Laboratory experiments on the mixing of hot and cold water in aquifers (Ambo, 1980)

A series of laboratory experiments were carried out at the Institute of Hydrodynamics and Hydraulic Engineering of the Technical University of Denmark, to investigate the physics of the non-isothermal flows resulting from ATES. The experiments demonstrated that density differences play a dominant role in determining the dispersion coefficient and thermal conductivity. Only to a smaller degree was classical hydrodynamic dispersion found to affect the flow.

2.11 Hot and cold water storage in a doublet system, Bureau de Récherches Géologiques et Minières, France. 1980- . (Menjoz and Sauty in Tsang (Ed), 1980a).

Theoretical research into the operation of doublet systems has been carried out by BRGM (Fabris and Gringarten, 1976). Recently, interest in doublet systems has been enhanced by the possibility of storing winter cold and summer heat alternatively for later use. Two systems have been considered: (1) a sweep system where waves of alternatively warm and cold water are injected through one of the wells in such a manner that the warm and cold waves reach the production well at the right season; (2) a hot well and cold well system where each well is used successively for injection or production depending on the season. Theoretical studies are now to be followed by investigation of the feasibility of heating and cooling offices by using groundwater heat pumps in the Paris area. A volume of 212,000 m^3 per year will be injected and then abstracted through each of the hot and cold wells of the doublet system. The system should be operational in 1981.

2.12 Industrial waste heat storage, Royal Institute of Technology VBB-SWECO, Switzerland. 1979-80. (Hyden in Tsang (Ed), 1980a)

A combination of finite element groundwater modelling and analytical and numerical heat flow modelling has been used to simulate the storage of waste heat in industrial cooling water at approximately 35°C in Quaternary deposits 5 to 15 m thick and its subsequent use to heat 200 small houses. The waste water source is equivalent to 10 $GW_{(th)}$ and the simulation involved three months of injecting 16 l/s of water at 30°C, using a five-well injection-withdrawal scheme, followed by a storage period of three months and a retrieval of 16 l/s over the following three months. The simulation showed an approximate heat loss of 56% of which 5% was vertical heat loss. The results indicate that a low-temperature district heating scheme involving ATES could be economically viable provided the transmission line between heat source and user is not too long.

2.13 Model research into heat propagation in porous media, Institut für Wasserbau und Wasserwirtschaft, Federal Republic of Germany. (Rouvé and Pela in Tsang (Ed), 1980a)

A finite element model has been constructed to solve the problem of heat flow in porous media. Comparison of results from the numerical model with a physical model has shown that the employed procedure can be used with a sufficient degree of accuracy to calculate the heat and mass transfer in a porous medium.

2.14 An ATES characterisation study and systematic parameter study of recovery factor, Lawrence Berkeley Lab., California, USA. L979- (Tsang, 1980a)

This study concerns parameter sensitivity in the numerical simulation of the Auburn field experiment (see Note 4). It includes:
(1) the selection of key dimensionless parameter groups which characterise the hydrothermal processes that determine the storage-recovery

ratio; (2) validation of the uniqueness of these groups using the "CCC" model (see Section 3); (3) modification and generalisation of these groups wherever necessary. The project objective is the development of a general approximate graphical or semi-analytic technique to predict energy recovery factors for given aquifer and storage conditions. To date three groups of parameters have been considered: (1) vertical heat loss to the confining units; (2) radial heat loss due to smearing and tilting of the thermal front, and (3) the characteristic tilting time of the thermal front due to buoyancy flow.

A linear flow model developed by Lund University is being used to investigate the recovery factor for a series of conditions by varying aquifer thickness, storage volume, thermal conducitivity of the aquifer and of the upper aquiclude. It has been found that, beyond a certain point, increasing injection volume does not substantially improve the recovery factor.

One element of the Thermal Energy Storage Program of the US DOE - mentioned in the first paragraph of this Section - is the Seasonal Thermal Energy Storage Program managed by the Pacific Northwest Laboratory. The objective of this Program is to demonstrate the economic storage and retrieval of thermal energy on a seasonal basis (Minor, 1980). The following four experiments are part of this program.

2.15 Pacific Northwest Laboratory, Laboratory facilities development, 1980- . (Stottlemyre and Jackson in Tsang (Ed) 1980b, Minor 1980)

This facility is designed to permit simulation of anticipated ATES reservoir conditions such as temperatures, localised stresses, fluid flow rates, and water qualities. Operational features include alternating flow directions and thermal and mechanical cycling. It is planned to use this facility for fundamental studies, routine site-specific testing for input to reservoir design and operational criteria and environmental studies.

2.16 Pacific Northwest Laboratory, Laboratory experiments on the effect of temperature on injectivity. 1980- . (Stottlemyre, Krupka and Cooley in Tsang (Ed) 1980b, Minor, 1980)

Investigation is being carried out into the causes of laboratory observations of reduction of permeability in sands and sandstones with increased temperature. Several researchers have observed a 50% to 100% decrease in silica sand and sandstone permeability to water when the temperature is increased from 20°C to less than 200°C. Similar changes are not observed when dry nitrogen, mineral oil or dry alcohol is used as the working fluid. Equipment is currently being developed to permit simultaneous measurement of fluid temperatures, pressures, viscosities, and chemistry as well as the stress and deformation of the porous material. Potential causes for this effect being investigated include: (1) densification (porosity decrease) due to temperature-induced increases in compressibility, (2) particulate plugging due to temperature-enhanced dispersion of pre-existing fine particles or physicochemical weakening of the silica dominated sediments and/or (3) unidentified viscosity perturbations due to dissolved or suspended silica.

2.17 Seasonal Thermal Energy Storage Program of Pacific Northwest Laboratory, USA. 1980. (L Scott in Tsang (Ed), 1980a)

Two current projects of the Seasonal Thermal Energy Storage Program (STES) are described. The objective of the first is to assess groundwater reinjection experience in air conditioning applications. The contract for the study has been placed with Midwest Research Institute (MRI). Real and potential problems with reinjection operations will be identified and the study will be completed in September 1980.

The objective of the second project is to qualitatively describe the ATES potential of major aquifers throughout the US. The contract for this study has been placed with Century West Engineering Corporation. The study is due to be completed by October 1980.

2.18 Aquifer Thermal Energy Storage demonstration program, Pacific Northwest Laboratory, USA. 1980- . (K Fox in Tsang (Ed), 1980a)

Four projects are being considered. A demonstration at the University of Minnesota will use the Minneapolis Campus Southeast Cogeneration Plant. An investigation into the use of stored winter chilled water for summer air conditioning systems at the campus of the State University of New York has been proposed. The third demonstration involves aquifer storage of waste heat from a diesel generator power plant and its subsequent use for district heating in the town of Bethel, Alaska. Details of the fourth project are not yet available.

All the projects discussed above can be described as being relatively small-scale with injection temperatures generally within the range specified for this report (30^{o}-120^{o}C). Most were aimed at obtaining pressure and temperature data for the general understanding of heat and fluid flow in the aquifer and for the validation of numerical models. For the reasons discussed in Section 1 it would appear that full scale projects utilising such relatively low temperatures of injection may require heat pumps to upgrade the recycled heat. There is a need to extend the storage temperature in experimental work to investigate how higher temperatures will affect geochemical aspects.

Four much larger scale projects have been reported; a brief resume of each follows.

2.19 J F Kennedy ATES project, USA. 1978-80 (Singer, 1978, Hibshman, 1979, Minor 1980)

This experiment involved the study of the storage of cold water in confined aquifers for seasonal use in chilled water air-conditioning systems. It was intended that aquifer water, withdrawn during off-peak hours in the winter, should be cooled by cold winter air and storing it in the aquifer at 2 to 3°C. During the air conditioning season the cool water would be withdrawn to supply the chilled water for airport air conditioning at 7°C. Initial studies showed the system was not feasible. It is reported that the results cannot be applied to the chilled water storage concept in general, however, for a number of reasons, including the requirement that all construction would have to be done at a busy airport in the nation's highest cost labour market.

2.20 Minneapolis-St Paul ATES project, USA. 1978- . (Meyer, 1978)

Perhaps the largest proposed ATES project in the USA to date, this proposal is currently under evaluation. The objectives are to evaluate the technical and economic feasibility of incorporating thermal energy storage components into a proposed district heating project for the twin cities of Minneapolis and St Paul. It will utilise the results of a continuing study of large-scale cogeneration and district heating for the Twin Cities. By comparing the capital requirements and fuel consumption of a specific cogeneration/district heating system which does not include ATES to those of a system with ATES, serving identical heat loads, the study will provide a measure of the value of annual cycle ATES. No quantitative results are yet available but it is noted that injection temperatures would need to be greater than 100°C. Economic analysis of district heating involving ATES from power and heat cogeneration plants as opposed to heat-only boilers indicate significant savings due to reduced capital investments, fixed charges, and fuel consumption in central plants.

2.21 CEA and Elf-Aquitaine, France. (Winn, 1977)

This is another theoretical study carried out jointly by the Commissariat à l'Energie Atomique and the oil company Elf-Aquitaine. The study estimates that the cost of a storage facility should be less than £1.2/m^3 for a viable system. A diagram of a rather grandiose scheme is reproduced and some details of a suitable aquifer are put forward together with estimates of energy recovery at 50-70%. The study envisages a confined aquifer at 200-600 m below ground, exhibiting intergranular flow, storing water at a temperature difference of about

100°C. Projected figures for a scheme using a 40 m thick aquifer, 600 m below ground, with maximum inflow or outflow rates equivalent to 230 MW, indicate that after one or two year's service a storage efficiency of 70-80% could be achieved. One of the major constraints imposed on the concept is a groundwater flow velocity of no more than a few metres/year whilst for engineering and aquifer protection reasons the authors envisage a heat exchanger system so that the aquifer water is part of a closed system.

2.22 China Features, China. 1963-1980 (T Sang in Tsang (Ed), 1980b)

The June 1980 copy of the ATES Newsletter (Tsang (Ed), 1980) carried the first reports to appear in the West of ATES experiments in China which commenced as long ago as 1963. The experiments involve storage of much larger quantities of water than are presently used in experiments in either the USA or Europe. The Chinese experiments involve the storage of both winter cooled water and water warmed by industrial surplus heat or solar energy in the summer.

Following the injection of treated industrial waste water and surface waters in the Shanghai area into aquifers in order to control subsidence and replenish underground water, it was noted that the temperature of the injected water changed very little. It was therefore decided to pump winter cooled water underground to be used in summer and so in 1965, 127 Shanghai factories were involved in such an experiment. The following summer 48 of the city's factories injected water to be used in winter. Both experiments are reported to have been successful. Currently in Shanghai the following maximum volumes of water are involved:

Winter injection of cold water	14.98 MCM
Summer withdrawal of cold water	11.67 MCM
Summer injection of heated water	4.89 MCM
Winter withdrawal of warm water	3.31 MCM

The report quotes details of operation of an ATES scheme utilising winter cooled water at one factory for use in the summer for cooling. It is estimated that the capital construction investment at the factory is 30% of the purchase cost of refrigerating plant and the electricity consumption is 5 to 30% of that involved in the use of other technologies. Thus, it is estimated that this one factory saved a total of more than half a million yuan (approximately US$ 312,000) from 1970-1978. Similarly, textile mills in Shanghai have saved a total of over 400 million kilowatt-hours of electricity.

3. MATHEMATICAL MODELLING CONSIDERATIONS

3.1 Introduction

An understanding of the hydrothermal processes involved in ATES is necessary to allow construction of realistic models. Such simulations will enable extrapolations and predictions to be made and can reduce the number of expensive field experiments necessary in a practical study. Extrapolation of the hydrochemical processes from field experiments to the different temperatures and pressures of full scale projects will not always be possible. However analytical investigations should enable prediction of hydrogeochemical reactions under differing conditions and so the combination of experimental, hydrogeochemical, and modelling (both numerical and analytical) approaches to the investigation of ATES will be important. This section considers some of the hydrothermal processes involved in ATES and the problems of modelling the systems.

3.2 Convection

The spatial fluid density variation resulting from a thermal anomaly in an aquifer will result in convective transport. The inclusion of convective terms in the flow equations complicate the theoretical situation to a point where analytic solutions are almost impossible. Associated difficulties arise in numerical computation and special care must be taken in choosing time steps. It would therefore be of great value to know whether convection is likely to be significant in any given situation. The Krefeld experiment (Werner and Kley, 1977) was successfully modelled without convection, and there was no evidence of thermal convection in the aquifer used in the Auburn experiment (Molz et al., 1979). However, the Neuchatel experiments (Mathey, 1976) indicate significant convective disturbances.

Mathey (op cit) reports that the conditions for the appearance of natural convection in porous media were defined by Nield (1968) and studied experimentally by Katto and Masouka (1967) and Combarnous (1970).

Natural convection occurs when the Rayleigh number, which characterises the regime of natural convection, reaches a critical value (Nield, op cit). In the absence of solute effects this value is $4\pi^2$ (Horton and Rogers, 1945). It would appear that as yet there has been no published theoretical or experimental study considering the case of a thermal disturbance of a cylindrical type such as could result from hot water injection into an aquifer through a borehole. In the absence of such studies some consideration will be given to the onset of convection in two dimensions.

The equation given by Combarnous (op cit) shows that the Rayleigh number is directly proportional to the permeability, the temperature difference and thickness of aquifer over which the temperature difference occurs. Thus if it is required to model a field experiment and it is desired that the convection component can be ignored then a low vertical permeability, a low temperature gradient and a thin aquifer would be ideal. However, it is evident that other constraints are also important to field experiments, e.g. the higher the injection temperature the higher will be the recovery temperature for fixed storage periods and the thicker the aquifer the greater the storage capacity. It is also desirable that the formation should have a relatively high horizontal permeability to permit efficient injection and withdrawal of heated water. Thus, in order to decrease the likelihood of convection occurring - which is desirable both from modelling and experimental considerations - it would appear that an aquifer with low vertical permeability in relation to horizontal permeability is desirable.

Using linear perturbation analysis Nield considered the problem of onset of convection. His results indicate that in a confined aquifer with the temperature at an injection well constant and the temperature of the overburden and the aquifer water also constant then the critical Rayleigh number $R_{ac} = 39.48$ in the absence of solute effects. This confirms Horton and Rogers (op cit) original determination $R_{ac} = 4\pi^2$.

3.3 Thermohaline convection

Nield (op cit) also discusses effects in thermohaline convection arising from the fact that heat diffuses more rapidly than does a dissolved substance. Whereas a stratified layer of a single component fluid is stable if the density decreases upwards, a similar layer of a fluid consisting of more than two components, which can diffuse relative to each other (as in groundwater), may be dynamically unstable. If a particle of such a solution is displaced vertically, it loses any excess heat more rapidly than any excess solute. The resulting buoyancy force may act either to increase the displacement of the particle, and thus cause monotonic instability, or to reverse the direction of the displacement and so cause overstability (oscillatory instability), according to whether the solute gradient is destabilising and the temperature gradient is stabilising or vice versa.

3.4 Hydrodynamic dispersion

Tyvand (1977) considered the additional effect of hydrodynamic dispersion, caused by a uniform basic flow, on the onset of convection in isotropic media. He considered the porous layer to be homogeneous and bounded by two infinite perfectly heat-conducting impermeable horizontal planes kept at constant temperatures. Isotropy with respect to permeability and thermal diffusivity is assumed in the horizontal but not the vertical plane and so his work is directly relevant to groundwater flow through sediments where horizontal and vertical permeabilities may differ.

Tyvand (op cit) showed that the dispersion caused by a uniform basic flow delays the onset of thermal convection in an anisotropic porous medium with horizontal isotropy. The stabilising effect was shown to be stronger the higher the Peclet number (i.e. the ratio of the convective flow to the diffusive flow, see Mathey, 1977). For Darcian flows the Peclet number will always be small and accordingly dispersion effects will be very small. For convection driven by a solute gradient, however, which may be the case if the injected water differs chemically from the native groundwater, dispersion effects will be much more significant even at low Reynolds numbers. This is due to the much smaller molecular diffusivities and thereby much larger Peclet numbers involved. In summary therefore the onset of convection is independent of longitudinal dispersion while dispersion in lateral directions has stabilising effects.

3.5 Breakthrough

In a full scale ATES scheme connected to a heat source (e.g. industrial waste heat, power station cooling water etc) a doublet system of wells is a logical operational arrangement. This procedure maintains the aquifer pressure, prevents subsidence and ensures an indefinite supply of water. The doublet would operate by water being withdrawn from one well, heated - either directly in a power or industrial production process or indirectly by a heat exchanger- and then reinjected into the aquifer for storage via the other branch of the doublet. When thermal energy is required, water would be withdrawn from the hot branch of the doublet and the heat extracted, through the heat exchanger for use in the heat supply system, before being reinjected via the original branch of the doublet. As a result a zone of injected water is created around each injection well at a different temperature from that of the native water. These zones will grow with time and may result in breakthrough where either hot water is withdrawn at the cold branch or cold at the hot branch. If breakthrough occurs, the water temperature is no longer constant at the production wells and the efficiency of the whole operation is reduced; either the stored hot water available decreases in temperature or the water abstracted for cooling purposes becomes hotter thus reducing the efficiency of the production plant.

Gringarten and Sauty (1975) developed a mathematical model for investigating the non-steady state temperature behaviour of production wells during the reinjection of heat depleted water into aquifers with uniform regional flow. Results were presented in terms of dimensionless parameters helpful for the design of such systems. Further work was reported by Lippman and Tsang (1980) who made use of Gringarten and Sauty's model. They investigated breakthrough time for typical aquifer conditions with a simple doublet and typical recharge/withdrawal rates relating to current power station design. Breakthrough time was shown to be proportional to the square of the distance between wells in the doublet and so increasing the distance of separation would significantly increase breakthrough times. Lippman and Tsang (op cit) suggest that in actual field tests a much larger number of wells could be used. These wells could be arranged in patterns similar to those used in tertiary oil recovery operations. The analysis of the behaviour of such configurations would of course be more complex than the case of a simple doublet system.

These models appear to be adequate for the investigation of breakthrough under varying conditions.

3.6 Boundary conditions

In order to model simultaneous mass and heat flow in an aquifer, problems arise both in choosing sensible model boundaries and in specifying the conditions there. The main problem concerns the thermal boundaries - which clearly do not coincide with the aquifer/aquitard interfaces.

One approach to this problem would be to fix the thermal boundaries (somewhat arbitrarily) at such a distance from the region of interest that, for the period to be modelled, they could reasonably be considered to be either constant temperature or constant heat-flux boundaries. An extension of this idea would be to couple a numerical model of the aquifer to analytical models of heat flow above and below the aquifer; this technique could also allow the boundaries to be effectively at infinity.

Preliminary analytic modelling should help to decide the importance of the correct choice of boundary conditions and thus help in choosing a reasonable solution to the problem.

3.7 Unconfined aquifers

If the water surface is not confined, i.e. it is at atmospheric pressure, hot water will tend to spread out over the native cold water, due to convection/buoyancy effects, in a thin layer. This increased surface will significantly increase cooling rates. If the injected water is above boiling point a portion of the water will flash to steam and start to rise thus causing rapid cooling and increasing the difficulty of recovery. For these main reasons little work has been carried out into modelling of heat storage in unconfined aquifers. It is likely that the increased number of degrees of freedom in an aquifer with a free water surface as opposed to confined conditions would result in complexities which could not satisfactorily be modelled.

3.8 Analytical models

Several analytical solutions of the heat and mass flow equation are referred to in Ariahara et al., (1976) - the introduction of which provides a survey of work on hot-fluid injection for oil recovery - Werstein et al., (1977) Widmyer et al., (1977) and Rae and Robinson (1979), where they are compared with experiments and numerical solutions. The most cited work is by Lauwerier (1955) who assumes a constant injection rate and temperature, zero thermal conductivitiy in the flow direction and infinite conductivity perpendicular to the flow.

An injection well/extraction well doublet is a situation encountered in geothermal work where the cooled reservoir water has to be reinjected. Gringarten and Sauty (1975) provide a semi-analytic solution of the problem of periodic variations of the injection temperature - resulting in a delayed periodic variation of the extraction temperature. Despite the different boundary conditions it should be possible to adapt this solution to the heat storage situation.

Meyer et al., 1977) report the result of an analytical modelling project which examined separately seven principal effects of hot water injection into and withdrawal from a well. These effects were:

Heat exchange of the porous aquifer matrix with injected hot fluid.
Longitudinal heat conduction through the interface of hot and cold water.
One-dimensional radial flow involving fluids with large viscosity differences.
Two-dimensional radial horizontal flow in a stratified aquifer with fluids of different densities.
Upper and lower bounds on buoyancy near a tilted interface, with viscosity and density differences.
Heat loss into upper and lower confining layers.
Combined effects during injection and withdrawal cycles.

The model enabled the authors to develop scaling rules for sensitivity analysis and design of less-than-full-scale field tests by use of dimensional analysis. One important scale effect is intuitively obvious but worthy of note. For the same temperature conditions, heat loss rates will be higher for small-scale tests than for larger tests or demonstrations; the rate of heat loss being governed by the ratio of surface area, through which heat escapes, to the enclosed volume where the heat is contained. To extrapolate results of small-scale tests to a larger test or demonstration therefore requires scaling of time. Scaling factors were reported for time, areas, volumes, amount of energy stored and peak energy withdrawal rates.

3.9 Numerical models

A number of numerical models for simultaneous heat and fluid flow have been reported. Tsang (1979) provides a brief summary of current projects and Table 1 is amended from his Table 3.

In his report, Tsang (op cit) makes specific reference to only three of the listed projects as many of the models are under development and their details have yet to be reported. The three projects are a) Lund University, Sweden; b) BRGM, France, and c) Lawrence Berkeley Laboratory, USA.

a) Lund University. A two-dimensional finite difference model has been specifically developed to study the storage of hot water in long narrow glacial deposits known as eskers (Claesson, et al., 1978, and Hellstrom, 1978). Also semi-analytic methods have been used to examine several related topics in ATES such as buoyancy tilting of a vertical thermal front, entropy analysis of numerical dispersion, effects of temperature-dependent viscosity in a two-well extraction/injection system, and other basic problems.

b) BRGM. A number of numerical models have been developed (Gringarten et al., 1977; Noyer, 1977) for the study of fluid and heat flow. These include a two-dimensional steady-flow semi-analytical model, a layered two-dimensional finite difference model and a program to calculate dispersion effects. Some of these models were used in analysis of the Bonnaud experiment described in Section 2.3.

RESEARCH INSTITUTE	COMMENTS
Technical University of Denmark, Denmark and Risø	1-D and 2-D Finite Element Models under development Use of compensation wells for countering regional flow investigated
Lund University, Sweden	2-D doublet semi-analytic model 2-D finite difference program developed to study storage in eskers
University of Neuchatel, Switzerland	2-D and 3-D Finite Element models under development
Ecole des Mines de Paris, France	3-D Finite Element Model under development
Bureau des Recherches Géologiques et Minières (BRGM) France	Layered 2-D Finite Difference Models Modelled Bonnaud experiment Dispersion modelling studies
University of Yamagata, Japan	Finite Difference Method using a complex potential function
United States Geological Survey, USA	Intercomp model - Finite Difference scheme, used to model (Auburn 1976) experiment
Lawrence Berkeley Laboratory, USA	3-D Integrated Finite Difference Model for conduction, convection and consolidation Extensive generic studies on ATES Modelling Auburn (1978) experiment
University of Houston, USA	Model under development to study steam injection into permeable earth strata (two-phase program)
Royal Institute of Technology, Switzerland	Finite element hydrogeological models in combination with analytical and numerical heat flow models
Institut für Wasserbau und Wasserwirtschaft	Finite element model to solve problem of heat flow in porous media

TABLE 1. ATES numerical modelling (modified from Tsang 1979)

c) Lawrence Berkeley Laboratory. During the past 6 years a number of numerical models have been developed. They include the model "CCC" (conduction, convection and compaction) which has been chosen for ATES studies at Berkeley. This program employs the integrated finite difference method and is fully three-dimensional incorporating the effects of complex geometry, temperature-dependent fluid properties, gravity and land subsidence/uplift. It has been used to model the Auburn experiments described in Section 2.4.

An example of the use of the model "CCC" is given in Tsang et al., (1978) as part of a study on the physical feasibility of using underground aquifers as a storage system for hot water solar energy collections. The "CCC" model and another less sophisticated, 2-D, model were used to investigate four cases: a) daily storage; b) seasonal storage with semi-annual cycles; c) seasonal storage with annual cycles, and d) a two-well (doublet) system. The hydrodynamic and thermal behaviour of the storage system were analysed and illustrated.

The Hydrogeology Unit of the IGS possesses a copy of the program "CCC". The following comments relate to a preliminary assessment of the model - a guide (Lippman and Mangold, 1977) to preparing data and the output from a trial run is also available.

1) Boundary nodes are (i) constant head and/or mass flux nodes, (ii) constant pressure and/or temperature nodes. The effects of using non-coincident thermal and flow boundaries might need clarification.

2) Specification of consolidated parameters may prove difficult. Lippman et al., (1977) were able to assume a constant specific storage.

3) The program was written specifically for DCD 7600 machine and requires modification if it is to be used on other computers.

4) The information available is limited with regard to the detailed workings of the program, which is sparsely commented. It would not therefore be easy to implement any major changes.

3.10 Conclusion

There is an extensive literature concerned with the topic of modelling the injection and extraction of hot fluids into and out of aquifers. In deciding on a modelling approach to a specific project it will be important to obtain an indication as to the importance of convection. If convection should appear not to be an important factor then analytical solutions should be considered. Indeed, initial work should include simple analytical modelling using simplifying assumptions in order that some estimate of the importance of depth of burial, aquifer thickness, injection temperature etc. can be made. The work of Gringarten and Sauty (1975) would appear to be particularly relevant. It is also important that boundary conditions are correctly defined. For more general problems, including convection, the "CCC" model appears to be adequate.

4. CONSIDERATIONS FOR ESTABLISHING AN AQUIFER THERMAL ENERGY STORAGE PROJECT

4.1 Introduction

This section discusses the parameters which need to be considered in relation to field experiments in ATES. To give an indication of energy rates involved,the following simple calculation is included: assuming the native groundwater in the target aquifer to be at 15°C and the injected water at 50°C then a recharge rate of 1 mgd (approximately 1500 m^3/day) would represent an energy storage rate of 8 MW. Consideration of the parameters, important for the efficient operation of ATES in aquifers, will be based on literature previously quoted; it is unfortunate that most of the literature reporting experimental and theoretical work does not provide specific reference to preferred conditions for ATES, however, the work at Berkeley (see Section 2.14), is directly concerned with characterisation of parameters for ATES.

4.2 Aquifer parameters

The published results of experiments carried out in shallow phreatic aquifers (e.g. Section 2.1 and 2.2) indicate some of the practical problems involved in using this type of aquifer. It would appear that confined aquifers offer potentially higher efficiencies as storage media due to the presence of the upper confining layer. The upper confining layer protects the stored thermal energy from infiltration of cooler surface water and/or precipitation. It also restricts vertical movement of the buoyant thermal anomaly and, if the aquifer vertical conductivity is sufficiently low, convection is minimised within the aquifer itself. This report considers the possibilities of using a water source at a temperature between 30° and 120°C and if temperatures greater than 100°C are to be used then confined aquifers with sufficient hydrostatic pressure to prevent flashing to steam must be found. Thus, the remainder of this report will be concerned with confined aquifers only.

4.2.1 Aquifer depth

The constraints on aquifer depth would appear to be fairly broad. The aquifer should obviously not be too deep to make drilling, injection and recovery costs uneconomic. As mentioned above, if injection of water at temperatures greater than 100°C is being considered then it is necessary for pressures within the aquifer to be high enough to prevent the water flashing to steam. Mathey (1977) considers that ATES is an economically and technically realistic solution for the optimisation of the product/consumption ratio of thermal energy, without the help of the thermal pumps at depths of less than 1000 m.

4.2.2 Groundwater flow

It is evidently desirable that the groundwater flow in the proposed recharge/abstraction area is low in order to prevent the introduced thermal anomaly being either diluted or transported away from the recovery wells during the storage period. However, it is possible to control the regional groundwater regime by the use of a linked system of abstraction and recharging wells (Whitehead and Langhetee, 1978; Molz and Bell, 1977).

4.2.3 Porosity

Molz et al., (1978) stated that if the product of the head gradient and conductivity divided by porosity is relatively large, the heated water will be convected away from the production well before it can be removed. This statement emphasizes the interrelationship of the parameters being discussed separately in this section and indicates the difficulty of defining limits for individual parameters in isolation. However, Werner and Kley (1977) report that essential conditions for ATES include an available pore volume of about 20%. Meyer and Todd (1973), in their theoretical considerations, calculated that heat recovery with an efficiency of the order of 96% was possible, using injection temperatures of the order of 99°C into a 100 ft thick formation at a depth of 500 ft and having a porosity of 25%, over a storage period of 90 days. The Auburn University experiment was carried out in a formation with estimated porosity of 25%. Therefore as an approximate guide a target formation should have a minimum porosity of 20%. It is evident that in two target aquifers with differing porosities, all other conditions being equal, the injected thermal anomaly will occupy less bulk volume in the aquifer having the higher porosity.

4.2.4 Permeability

The significant physical difference between confined and phreatic ATES is the presence of the upper confining layer to the potential storage formation. The impermeability of this upper layer prevents any upward movement of the injected water and also shields the target aquifer from hydraulic disturbance from above (e.g. percolating recharge water). In the previous sections which discuss the onset of convection the importance of a relatively high horizontal permeability and low vertical permeability was discussed. It was stated that as the Rayleigh number increases free thermal (and even thermohaline) convection becomes more likely. As shown by Molz et al., (1979), since the Rayleigh number is proportional to the hydraulic conductivity, it will be larger in the vertical dimension for a sandy gravel than it would for, say, a medium sand-silt-clay. Thus for the same temperature regime, appreciable thermal convection could occur in one medium and not in another.

Qvale, (Claesson et al., 1980) reports that 2D model research into buoyancy effects has shown that high values of aquifer permeability ($k > 50$ Darcies) combined with aquifer thicknesses larger than 20 m give rise to highly undesirable convection currents at injection temperatures in the interval 80-100°C. However stable flow conditions were found at lower values of aquifer permeability ($k < 15$ darcies and thickness = 20 m).

Some researchers have reported an apparent degradation of permeability with moderate increases in fluid temperature - 50-100% decrease having been reported in silica sand and sandstone permeability to water when the temperature was increased from 20°C to less than 200°C (Minor, 1980, Stottlemyre et al., in Tsang (Ed), 1980b). The degradation is time-dependent and, in experimental studies (Stottlemyre et al., (op cit)), had not achieved steady state at the end of 6-hour flow tests. These experimental studies are systematically investigating potential causes which include:

(1) densification (porosity decrease) due to thermo-mechanical alteration, (2) particulate plugging due to temperature-enhanced dispersion of pre-existing fine particles or spalling of chemically (hydrolytically) weakened sand grains, and (3) anomalous fluid viscosities due to temperature induced silica leaching.

Whilst the existence of fissure permeability will not necessarily render an aquifer unsuitable for ATES it will make analysis and simulation more complicated. It is therefore preferable that the groundwater flow mechanism should be intergranular in preliminary studies.

4.2.5 Transmissivity

This parameter is proportional to horizontal permeability and it is important that the target aquifer should be capable of high yields (and therefore have high transmissivitiy) in order to achieve efficient recharge/abstraction. Although transmissivities are generally highest in aquifers having high secondary permeability the necessity to avoid significant fissuring is over-riding.

4.2.6 Storage coefficient

It is evident that in two target aquifers with differing storage coefficients, all other conditions being equal, the radius of influence of the cone of impression will be least in the aquifer having the higher storage coefficient.

4.3 Geochemical considerations

In order to achieve compatibility between injected and formation water it is obviously desirable that the two should be as chemically similar as as possible. Ideally, formation water from the target aquifer should be used for injection. However, the abstraction point would need to be sufficiently distant from the recharge point so as to not disturb the local conditions.

The geochemical problems involved in recharge experiments have been briefly discussed by Monkhouse and Phillips (1978). Geochemical considerations will be additionally complicated by the temperature differentials involved in ATES studies and it is important that full study is given to this aspect in any experimental work carried out. The chemistry associated with aquifer stability must also be considered (Swolfs, 1972 and Swolfs and Friedman, 1972).

Assuming particulate matter is absent from the injected fluid (as is generally the case with groundwater), and that any potential effects of micro-organisms can be controlled by the use of an appropriate biocide, physico-chemical interactions between the fluid and the host aquifer remain a major consideration. Modifications of the hydraulic characteristics of the aquifer could arise from:

(a) Solution-precipitation reactions.
(b) Changes in the state of the clay minerals

4.3.1 Solution-precipitation reactions

Dissolution is unlikely to occur to any significant extent, particularly in a sandstone aquifer, and even if it were to do so would probably not degrade the suitability of the aquifer for TES. Precipitation of solid, caused by reaction between the injected and native fluids, is a potentially more serious problem. However, research undertaken by the oil industry on the flooding of reservoirs has shown that the mechanics of displacement prevent mixing of the connate and injection waters to a large extent and so limit the effects of precipitation (Bernard, 1957). Experiments resulting in the production of $BaSO_4$ within sandstone core material have shown that precipitation of even this very insoluble salt has a negligible effect on permeability. The increased temperature of the injected fluid would naturally tend to reduce the possibility of precipitation occurring by increasing the solubilities of the solid phases, in most cases; an important exception would be, of course, anhydrite ($CaSO_4$), the solubility of which decreases with increasing temperature. Until the target aquifer is chosen and the chemical composition of both the formation water and the injected fluid fully characterised, no rigorous prediction of the potential for precipitation can be made.

4.3.2 Changes in the state of the clay minerals

Contact between clay minerals and a fluid of different chemical composition from that with which they were previously in equilibrium may bring about changes in their physico-chemical state by various mechanisms, depending on the types of clay mineral involved and the differences in composition between the connate and injected fluids.

Smectites, e.g. montmorillonites, may be characterised by their tendency to take up large amounts of water under certain conditions, by an osmotic effect, and so physically swell. Because of the presence of cations, e.g. Na^+ or Ca^{++}, between the alumino-silicate layers of the clay, water will tend to diffuse into the lattice by osmosis if the injected fluid is of a lower ionic strength than that with which the mineral was previously in equilibrium; conversely, if the fluid is more concentrated the clay will shrink. The exact type of cation is relevant, in that sodium montmorillonite would swell proportionately more than calcium montmorillonite, because of the weaker binding forces between the layers resulting from the lower charge density associated with the monovalent ion.

Exposure of all types of clay mineral present within the host aquifer to a change in composition of the interstitial fluid may have an additional and potentially more serious effect than would the simple swelling of smectites. If the change in composition is in the direction of a decrease in ionic strength, e.g. by the injection of a more dilute fluid, the clay particles will tend to deflocculate and disperse. Such movement could markedly affect the permeability of the aquifer by the blocking of pore necks by the clay particles. Dispersion of deflocculated clays - rather than simple swelling is regarded as a major mechanism whereby the permeability of oil-bearing formations is impaired on flooding. Again, because of the influence of charge density, clay particles having monovalent cations on their external surfaces tend to be bound less strongly, and thus to deflocculate more easily, than those having divalent ions. Jones

(1964) reports that the addition of calcium or magnesium to the injected fluid can substantially reduce dispersion and blocking.

Predictions based on the known behaviour of pure clay minerals should be assessed cautiously, since the presence, in reality, of hydrated iron oxides on the surfaces of clays in an aquifer, will tend to inhibit deflocculation. It should also be noted that limited information (C.Neal personal communication) suggests that increasing the temperature within a formation may tend to encourage swelling of clay material.

4.4 Biological considerations

Iron bacteria commonly cause clogging of recharge wells since in the course of their metabolism they produce large quantities of slime (ferric hydrate). Marshall, et al., (1968) note that once iron bacteria have become established they are difficult to eradicate. Aeration during pre-treatment reduces the iron content of the water but as Monkhouse and Phillips (op cit) point out, air dissolved in, or carried with, the recharge water can be transported through the face of a recharge well and into the aquifer itself and may thus result in reduction of hydraulic conductivity. Therefore care must be taken in the injection process to avoid air entrainment (cf Monkhouse and Phillips, op cit). The general problem of the growth of bacteria and algae in warm water obviously needs consideration.

4.5 Distance from supply wells

It is desirable that experimental studies should not affect domestic, agricultural or industrial supplies. Quantitative derogation of existing supplies may result if the source water for the experiment is abstracted from wells too close to existing supply wells. Qualitative derogation, on the other hand, will depend on the geochemical relationship between aquifer, formation water and injected water over the temperature range involved and the extent to which the thermal anomaly disperses within the target aquifer.

Injection of heated water into an aquifer can be considered, in a simplified manner, as causing three different (but obviously related) physical effects: a) transmission of increased potential through the aquifer over a considerable distance from the injection well; b) displacement of native groundwater from around the well by hotter water but for a lesser radius of influence than a); c) heating of the aquifer matrix within much of the zone of displacement of native groundwater adjacent to the well. As stated previously, this is a simplified consideration of the process of hot water injection into an aquifer and such effects as heat transfer between injected and native water at the interface, mixing resulting from hydrodynamic dispersion at the interface, heat transfer through the upper and lower confining layers and movement of native groundwater under a pre-existing gradient are ignored. It is also assumed that heat exchange between the aquifer and injected water is instantaneous. Under such conditions the radii of influence of effects a), b) and c) can be calculated by the use of simple formulae.

a) Radius of influence of increased potential or the cone of impression.

The extent of the zone of influence of injection as shown by increasing potential is given by a formula resulting from Jacob's equation (Kruseman and De Ridder, 1970).

$$r_e = 1.5\sqrt{\frac{Tt}{S}}$$

r_e = radius of influence
T = Transmissivity
t = time since start of injection
S = storage coeffient

b) Radius of influence of displacement zone

Injected hot water will have different physical properties than those of natural groundwater in that both its density and viscosity will be less than the cold water being displaced, causing the hot water to over-ride the cold water and to displace it from the top of the aquifer downward in a cone shape. If the broadening with time of the apex of the cone at the base of the aquifer is ignored (Meyer et al., 1972) a simple formula involving the volume of a cone and aquifer porosity can be used to give an overestimate of the radius at the top of the aquifer of the displacement zones as follows:

$$R_w = \sqrt{\frac{3Q}{\pi b \alpha}}$$

where R_w = radius of influence of upper surface of displacement zone

Q = injected volume

b = aquifer thickness

α = porosity

c) Heating of aquifer matrix

During subsequent injection-storage-abstraction cycles the quantity of heat loss to the aquifer matrix will decrease as the ambient temperature of the matrix in the zone of displacement rises. For a cone shaped anomaly, as discussed above, the radius of influence of the upper surface of the heat anomaly is given by the following formula if conduction effects away from the cone are ignored and local thermal equilibrium between water and matrix is assumed - thus the whole of the anomaly is at injection temperature:

$$R_h = \sqrt{\frac{3\ Q\ S_w}{\pi b S_a}}$$

where R_h = radius of influence of upper surface of heated zone

Q = injected volume of water

b = aquifer thickness

S_w = volumetric specific heat of water

S_a = volumetric specific heat of saturated aquifer

Comparison of the equation for R_h with the equation for R_w given in b) above shows that R_h will be less than R_w as S_w/S_a is generally greater than $\frac{1}{\alpha}$.

See Appendix A for more detailed discussion of the heat anomaly.

Thus it can be seen that the pressure, water and heat interfaces will be at differing distances from the recharge well. As hot water moves through the matrix, heat is lost into the matrix material. If the matrix material has not yet been warmed, it is at the temperature of the native groundwater. Recharged water moving through the aquifer will cool rapidly and approach the matrix temperature. After recharge has proceeded for some time, temperature along a path radial from the well will at first be very nearly the same as the injected water, dropping only slowly until the heat interface is reached. At the heat interface, the temperature of water and matrix will drop abruptly and approach asymptotically the native temperature. At a further distance from the recharge well the water interface will be encountered and further still the radius of influence of the cone of impression (or increased potential resulting from recharge) will be encountered.

In connection with the siting of injection wells in relation to existing supply wells (equation in a) above) it is important to avoid natural groundwater gradients which would result in the transfer of injected water away from the recharge well thus decreasing potential recovery and possibly affecting temperature of existing supplies.

Permission from water authorities for experimental injection of warm water is more likely to be forthcoming if target aquifers can be proposed in which the formation water is not suitable for supply - e.g. in areas of high salinity.

4.6 Other considerations

In selecting suitable target aquifers for experimental ATES studies there are obviously considerations other than the physical and geochemical parameters of the aquifer to be considered. Some of the principal considerations follow.

4.6.1 Clogging of recharge wells

The efficiency of a recharge well will tend to decrease with time due to clogging of one, or a combination, of the screen, the gravel pack and the aquifer itself (Monkhouse and Phillips, 1978; Edworthy and Downing, 1979). Clogging can result from single causes such as micro-organisms, geochemical incompatibility of the waters, and suspended solids in the injected water or a combination of these. Treatment of the water prior to injection, such as aeration (with subsequent de-aeration), settling, sand filtration, micro-filtration and chlorination, can substantially reduce clogging effects.

Clogging was a major technical problem encountered in the Auburn University experiment (Molz et al., 1978 and 1979). In two different experiments two separate problems were encountered. In the initial experiment clogging was due chiefly to the relatively large suspended solids concentration in the supply water. In the second experiment it was concluded that the observed decrease in hydraulic conductivity was due to clay particle dispersion, migration, and subsequent blocking of the relatively small pores connecting larger pores. This resulted from swelling and dispersal of the clays, initially in equilibrium with the formation water having a high ionic concentration, coming into contact with water having a relatively low concentration of ions.

Thus, careful consideration must be given to, and monitoring during any experiment must be carried out on, the effects of borehole, screen, pack and formation clogging.

4.6.2 Fluid viscosity

Injected hot water will have markedly different physical properties to those of natural groundwater. Not only will the hot water be as much as 10% less dense than the cold groundwater but its viscosity can be about 1/5 that of the cold water being displaced.

As mentioned in 4.6. the injected water displaces the cold native water in the form of an inverted cone; an initially vertical interface tilts gradually with time as the less dense fluid over-rides the denser fluid. A survey of literature from petroleum research (Meyer et al., 1972) reports that the interface could be treated as a plane-radial (i.e. expanding cylinder) surface for viscosity ratios of less than about 10 and that the segregation increased as a function of the viscosity ratios of the two fluids.

The viscosity ratio of two fluids in a porous medium directly affects the relative permeability of each. The effect of local variation in fluid viscosity and flow resistance on mixing and stratification at the thermal front can cause significant decrease in the energy recovery (Fabris and Gringarten, 1976 and 1977; Sauty et al., 1978).

4.6.3 Land uplift and subsidence

The decrease in pressure resulting from abstraction from a confined aquifer can sometimes result in quite marked subsidence of the topographic surface. Generally when such subsidence occurs it develops slowly and is distributed over wide areas. Such subsidence results from a combination of elastic compression of the water, elastic compression of the aquifer matrix material and non-elastic compaction of the aquifer structure. If abstraction of the groundwater results only in elastic compression of the groundwater and aquifer matrix (as a result of the increased pressure differential between aquifer and geostatic pressures) then reinjection of water can normally restore the original situation. However, if compaction of the aquifer results then aquifer storage may be permanently decreased and recovery of the former topographic surface will not normally be possible.

With regard to recharge wells elastic expansion of both water and aquifer matrix due to increased pressure can occur but non-elastic expansion is limited and uplift in recharge wells is not generally a major problem. However, both subsidence and uplift are extreme effects and if a target aquifer is to be used where such effects are likely then a doublet configuration (source water being abstracted from target aquifer at sufficient distance from the recharge well to prevent breakthrough) should minimise the possibility of effects as pressure within the aquifer is maintained.

4.6.4 The prediction of thermal pollution

Tsang (1979) states that proper accounting of the heat left in the aquifer at each storage-recovery cycle should be made. The rate of dissipation of the heat into the surroundings has to be investigated to ensure minimal effects on the environment.

4.6.5 Corrosion

Ordinary water-well pumps, submersible motors, and other well equipment are not generally rated for operation above about 70°C. Special well equipment will be required, increasing in cost with increasing temperature. Corrosion of materials is a potential problem. It is likely that some of the technology developed for geothermal resource exploitation will be directly relevant to ATES. Ideally techniques for the control of corrosion should be investigated as part of any field experiment.

5. SUITABLE AQUIFERS FOR ATES STUDIES IN THE UNITED KINGDOM

5.1 Introduction

One of the objectives of this report is to identify aquifers within the United Kingdom suitable for ATES experiments. It must be emphasized that, for a full scale ATES scheme to be economically viable, it is necessary that heat source, storage aquifer and demand centre are all located in close proximity because of the problems involved in heat transport. However, for experimental studies the constraint relating to demand source can be ignored. In Section 4 several requirements were discussed relating to hydrological and geochemical properties of aquifer and waters involved. However, there are other considerations that may prove more important in site selection for an initial experiment.

It is evident that an aquifer affording high yields is desirable in order to facilitate injection and abstraction of heated water. However, it is unlikely that water authorities would permit thermal pollution of aquifers close to established or potential supply locations.

Attention is therefore focussed on sites in target aquifers at 'safe' distances from existing supply wells (see 4.5) or saline aquifers (greater than 500 ppm total dissolved solids being undesirable for drinking water and many industrial uses) which inevitably have less information available about them.

Thus it will almost certainly be necessary to carry out a certain amount of hydrogeological investigation at potential ATES experimental areas in order to determine the local hydrogeological conditions. In some areas, supply aquifers become too saline to be of value for supply (e.g. down-dip and below confining beds) and where such areas are proposed a certain amount of extrapolation of aquifer parameters from areas of supply may be possible.

Another important consideration for the initial study concerns the source of the recharge water to be used.

It has already been suggested (Section 3.1) that extrapolation from small scale experiments can be made with regard to the hydraulics of the problem by use of modelling techniques. Extrapolation with regard to geochemical considerations from lower to higher temperatures ranges is difficult and will depend on hydrogeochemical investigation. Whilst these preceding statements apparently imply that if the temperature range is defined then there is no lower limit to the scale of the experiment, it should be realised that the study has to be of sufficient size to give an indication of the technical problems that may be encountered in a full scale ATES scheme. This report necessarily assumes a suitable source of heated injection water. However, the practical difficulties of providing such a source should be borne in mind and consideration given to the possibilities of using waste water from either existing industrial processes or power stations.

5.2 UK aquifer summary

Monkhouse and Richards (1979) have summarised aquifers in the United Kingdom - see Table 2. As stated earlier, whilst the existence of fissure permeability will not necessarily render an aquifer unsuitable for ATES it will make analysis and simulation more complicated. Therefore it is desirable that in preliminary studies the flow mechanism in the target aquifer should be intergranular rather than fissure, whilst in later studies or in production conditions certain fissured aquifers may prove suitable. It is also desirable that the target aquifer should be high yielding. With these considerations in mind inspection of Table 2 suggests the following aquifers as being of possible value for an ATES project: Thanet Beds (Eocene), Lower Greensand (Lower Cretaceous), Sherwood Sandstone (Permo-Trias), Coal Measures (Upper Carboniferous) and Millstone Grit (Lower Carboniferous). On further broad consideration the Coal Measures can be dismissed because of known aquifer complexity, the very high throughflows in many areas, land subsidence and mining problems. The Millstone Grit is also dismissed as fissure flow is dominant. Thus consideration is given to the remaining aquifers where they are confined at some distance from established and potential supplies. Table 3 gives details of laboratory values of vertical and horizontal permeabilities and porosities of those aquifers potentially suitable for ATES.

Era	System	Subsystem	Aquifer Names	Flow Type	Import-ance	Normal Yield (m^3/day)	Max Yield (m^3/day)	50% Probable Yield (m^3/day)	10% Probable Yield (m^3/day)	Comments
Cainozoic	Quarternary	Holocene	Superficial deposits	I	*					
		Pleistocene	Upper & Mid. Pleistocene	I	*					
			Crag	I	**	400-900	22C0			dominantly sandy, sometimes shaley snads and maybe ferruginous
	Tertiary	Pliocène	Coralline Crag	I	**					
		Oligocene								
		Eocene	Bagshot Beds	I	*	80-400				
			Blackheath & Oldhaven Beds	I	*	80-400				
			Woolwich & Reading Beds	I	*	850+				
			Thanet Beds	I	**	Up to 1300				Yield drops as clay increases
Mesozoic	Cretaceous	Upper Cretacious	Chalk & U. Greensand	F	****			3200	8000	
		Lower Cretacious	Lower Greensand	I	***			110	4700	
			Hastings Beds	I	**	400-900	4380	860	3000	
	Jurassic	Upper Jurassic	Portland & Purbeck Beds (Spilsby Sandstone)	F (I)	* (***)	400-900		(860)	(2500)	
			Corallian	F	**	850	4300			
		Middle Jurassic	Great & Inferior Oolitic Lst	F	***			2600 480	10600 4200	Middle Jurassic alone Upper & Middle Jurassic combined
		Lower Jurassic (Lias)	Bridport & Yeovil Sands	I	**	80-400				
			Marlstone Rock	F	*	<200				
	Triassic		Sherwood Sandstones	I & F	****	500 300	10000 700 1000	220	9000	--- Midlands --- Cheshire & Vale of Clwyd --- N of England --- overall
Upper Palaeozoic	Permian		Magnesian Lst.	F	***			3600	8000	
	Carboniferous	Upper Carboniferous	Upper Coal Measures	I&F (M)	**	200-300	5000			
			M & L Coal Measures	I&F (M)	*					
			Millstone Grit	I&F (M)	**	1200-1700	4300			
		Lower Carboniferous	Carb. Lst.	F	**	300-350				
	Devonian	Old Red Sst.	Old Red Sst.	I&F or F	*	<100				

Key:

Importance		
	*	Aquifer of minor importance only
	**	Aquifer providing useful local supplies
	***	Aquifer of importance locally, often providing public supplies
	****	Aquifer of major importance

Figures of normal yield, max yield, 50% probable yield and 10% probable yield taken from Monkhouse and Richards report - as was bulk of table.

Flow type		
	I	intergranular flow is predominant
	F	fissure flow is predominant
	I&F	fissure and intergranular
	I&F(M)	multilayered sequence

TABLE 2. List of Aquifers in the United Kingdom

(Modified from Monkhouse and Richards, 1979)

TABLE 3. Horizontal and vertical permeability and porosity values for selected aquifers as measured in the Laboratory.

FORMATION	LOCATION	LABORATORY TEST RESULTS					REFERENCE
		HORIZ. PERM. MEAN Kh (m/d)	HORIZ. PERM. RANGE (m/d)	VERT. PERM. MEAN Kv (m/d)	MEAN POROSITY (%)	POROSITY RANGE (%)	
Thanet Sands	Witham	.23	.07 - .29	3.82×10^{-2}	-	-	Aquifer Properties Lab. IGS Unpubl. Results
Lower Greensand		0.99	18 - 4.23	3.24	32	8-41	- " -
Bunter Sandstone	Sherwood Forest Notts.	4 ,	2.10×10^{-2} -10.0	3.	29	14-34	Williams <u>et al.</u>, 1972
Bunter Pebble Beds	Cannock Chase Staffs	9	-	-	-	26-33	Lovelock 1972
Bunter Sandstone	Fylde Lancs	0.5	10^{-1} - 10	0.2	-	-	Brereton and Skinner, 1974

5.3 The Thanet Beds

Thanet Beds reach a maximum thickness of the order of 30 m in East Kent near the mouth of the Thames Estuary - where the formation is dominantly sandy - but diminish westwards with increasing clay content. Perrin (1971) reports that smectite is the dominant clay mineral with subordinate mica. Due to the presence of the underlying Chalk, which normally provides a better yield, few boreholes are currently constructed in this aquifer, although such boreholes can yield up to 1300 m^3/day. Its transgressive base is marked by a bed of unworn, green coated flints set in a matrix of dark clay and glauconitic sand called the Bullhead Bed. The Thanet Beds are overlain by the Woolwich and Reading Beds - a variable group of sands and clays of lower yield.

It would appear unlikely that the Bullhead Bed could be relied upon to be consistently thick or impermeable enough to provide adequate separation from the Chalk; bearing in mind also the unsuitable clay mineralogy (Smectite being liable to swelling, see 4.3.2) Thanet Beds appear unsuitable for ATES studies.

5.4 The Lower Greensand

The Lower Greensand crops out around the margins of the Weald, in the Isle of Wight, and to the north of London in Bedfordshire and Cambridgeshire. Around the Weald, two aquifers are present, the Folkestone Beds above and the Hythe Beds below, separated by the relatively impervious Sandgate Beds. In the Isle of Wight and Dorset and in the outcrops north of London, the Lower Greensand is not divided into separate aquifers, being sandy throughout. Where the sandy facies are encountered north of London, up to 2100 m^3/day may be obtained from a single borehole (Monkhouse and Richards, op.cit.).

Perrin (1971) reports that in east England the Lower Greensand contains kaolinite and mica while carrying variable amounts of goethite and amorphous iron oxides with amorphous material locally forming a substantial part of the clay fraction. In Berkshire smectite takes the place of kaolinite and in the Isle of Wight there appears to be a reversion to the kaolinite-mica assemblage.

In the Leighton Buzzard-Newmarket area the Lower Greensand is overlain conformably by the Gault Clay and rests unconformably upon the Oxford, Kimmeridge or Ampthill clays depending on the area. The following description of the Lower Greensand is based on the report by Monkhouse (1974).

That part of the Lower Greensand which was deposited first comprises fine-to-coarse-grained, crossbedded sands, poorly consolidated apart from a few ferruginous bands, and with varying amounts of glauconite. Upwards, the Lower Greensand acquires a greater degree of ferruginous cementation, the uppermost beds being sufficiently indurated to receive the local name of "sand rock". Silty and clayey laminae and lenses are common (Worssan and Taylor, 1969). Where the formation as a whole extends beyond the original depressions in the surface on which deposition occurred, the thickness is much reduced and the lithology tends to be almost wholly "sand rock". Confined conditions prevail throughout the aquifer beneath the Gault cover (unconfined at outcrop) except for a few restricted areas close to outcrop. Groundwater levels have not been depressed regionally below the base of the Gault by groundwater development although this may occur locally in the immediate vicinity of pumping wells. Figure 1 shows the groundwater contour map. The form of the piezometric surface at distances of 20-25 km from the outcrop is uncertain as, due to increased salinity in the Lower Greensand aquifer, water in these areas is obtained from the Chalk and there are few, if any, abstraction wells penetrating the Lower Greensand. Salinity generally increases down-dip as shown by Figures 2 and 3. Figure 4 shows the thickness of the Lower Greensand in the area.

Monkhouse (op cit) reports only two aquifer tests (as opposed to specific capacity tests) in the Lower Greensand, both carried out in the "sand rock" part of the formation. T values of 149 m^2/day and 244 m^2/day and associated S values of 9.94×10^{-4} and 8.94×10^{-7} were obtained at Kingston and a T of 70 m^2/day and S of 5.7×10^{-4} obtained at Cambridge.

Monkhouse (op cit), using specific capacity data, estimated that the Transmissivity of the aquifer generally decreases down-dip. No evaluation of vertical and horizontal permeabilities is available.

In conclusion, it would appear that the Lower Greensand down-dip of Newmarket, Cambridge and Baldock may be suitable for experimental ATES studies although little information is available on the hydraulic parameters in this area. It is also noted that the aquifer is relatively thin (approximately 10 m) in this area and will tend to be almost wholly "sand rock" lithology which contains a relatively high ferruginous cement.

5.5 The Permo-Triassic Sandstones

Recent work (Warrington et al., 1980) has resulted in proposals for a revised nomenclature for the British Triassic stratigraphy. This report will generally employ the new nomenclature but, where necessary, the pre-1980 nomenclature will also be given. Figure 5 indicates the outcrop areas of the Permo-Trias in the United Kingdom. The Sherwood Sandstone Group is now defined as including the former "Bunter Series" and "Keuper Sandstone". In parts of northern England, the Permian strata underlying the Trias are also sandstones and, in the absence of palaenotological evidence, the classification of formations around the Permian-Triassic boundary remain an arbitrary matter - it is thus convenient to consider the Permo-Trias as one unit. The flow mechanism is a combination of fissure and intergranular flow, the bulk mechanism being chiefly intergranular with local flow, close to boreholes, depending to varying extent on fissures.

Generally the Permo-Triassic Sandstones comprise considerable thicknesses of friable, red sandstones of continental origin disposed in deep, often fault-controlled basins. Thus with regard to ATES this formation lends itself to relatively large scale operation. For this reason relatively large volumes of heated source water will be required for optimal operation of either experimental or production ATES. As the Permo-Triassic Sandstone constitutes the second most important supply aquifer in the United Kingdom it would seem likely that Water Authorities would prefer initial ATES studies to be confined to saline areas of the Permo-Triassic which are unsuitable for supply. This report, therefore, considers only two regions of Permo-Triassic Sandstone, the Cheshire Basin and the Nottinghamshire area, both of which offer saline parts of the aquifer and relatively high industrialisation (i.e. potential supplies of waste hot water). This is not to say, however, that other areas of the Permo-Triassic sandstones are not suitable as target aquifers for ATES and they should not be excluded from further consideration depending on local conditions.

The clay mineral content of the Sherwood Sandstone is quite low and heterogeneously distributed, so that it is likely that the swelling of smectites *in situ* would have a negligible effect on permeability. However, defloculation and dispersion of clay mineral particles in general, arising from the injection of a more dilute fluid, could degrade the aquifer's suitability for ATES.

5.5.1 The Permo-Triassic of Cheshire

In the Cheshire basin the Sherwood Sandstone is believed to be underlain by the impermeable Manchester Marl, and overlain by the Mercia Mudstone - see Figure 6. Groundwater contours for 1965 (Figure 7) indicate the gradients involved in areas of abstraction but also show that little is known of the groundwater regime under confined conditions beneath the Mercia Mudstone. The lack of knowledge in this area is due to urbanisation, but it is also believed that down-dip, below the Mudstone, the groundwater becomes increasingly saline (Monkhouse, R A, pers. comm.). This general lack of information from the confined area makes assessment of its potential for ATES experimental studies difficult. It seems probable that the thickness of both the Mercia Mudstone and the Sherwood Sandstone in this area renders it unsuitable. The Mercia Mudstone in Cheshire being up to 1200 m thick (including 600 m of salt beds) while the Sherwood Sandstone is up to 900 m thick. However significant marl bands within the Sherwood Sandstone may result in locally discrete thinner aquifers which may offer some potential to ATES studies.

5.5.2 The Permo-Triassic of Nottinghamshire

The Sherwood Sandstone in this area is over and underlain by impermeable strata and dips eastwards ranging in thickness from 300 m in the north to nil about 8 miles south of Nottingham, (Land, 1966), see Figures 8-12. Recharge is mainly by precipitation but there is some recharge from the rivers Trent and Leen. Generally high permeabilities result in low groundwater gradients (see Figure 13), and east of the outcrop the water is confined. Total dissolved solids generally vary between 150 and 350 mg/l but reach 400-500 mg/l at Nottingham. Between 12 and 17 miles east of the outcrop the normal groundwater of the Sherwood Sandstone gives place to a saline water with high sulphates and chlorides.

Study of the aquifer properties of Permo-Triassic sandstones based on laboratory analyses of samples from the whole of the United Kingdom were carried out by Lovelock (1972; 1977). The following summary is based on the results of his work from the area of South Derbyshire and Nottinghamshire. The sequence of the Permo-Triassic sandstones with their upper and lower confining beds in this area is as follows:

Former Nomenclature	Revised Nomenclature	Approximate Thickness (m)
Keuper Marl	Mercia Mudstone	150-280
Waterstones		15-35
Bunter Sandstone/Pebble Beds }	Sherwood Sandstone	30-300
Lower Mottled Sandstone		0-60
Upper Permian Marl	Upper Permian Marl	0-60

Both the Lower Mottled Sandstone and the Waterstones are considered hydrogeologically insignificant. Thus of chief interest in the sequence are the Bunter Sandstone/Pebble Beds. The pebble content decreases markedly towards the north until, in the Doncaster area, it is more appropriate to refer to this unit as Bunter Sandstone rather than Pebble Beds. Drilling has shown that the formation outcrop is deeply weathered to depths of between 50 and 100 m. Sampling in this poorly consolidated material was difficult but intergranular permeability was estimated at 2.6-32 m/day with a porosity of 35-40%. For detail of lithological and hydraulic parameter variation through the sequence reference should be made to Lovelock (op. cit.). In summary, laboratory determinations of permeabilities show values ranging from 0.32-6.43 m/day and porosities ranging from 20-34% through the sequence. Probability analysis of the porosity and permeability of the Sherwood Sandstone shows that there is a 50% probability of a sample having a porosity of 30% and vertical and horizontal permeability values of 3.28 and 3.00 m/day respectively.

Lovelock (op. cit.) used the term 'intergranular' transmissivility to describe the intergranular component (as measured by laboratory test) of total transmissivity (as measured by aquifer tests). Comparison of the two transmissivities at 15 widely differing sites in the Permo-Trias showed significant differences, indicating that groundwater movement by fissure flow is important close to pumped boreholes. It remains to be seen what effect these vertical fissures will have on the onset of convection. Thus, with regard to the permeability and porosity requirements for an ATES experimental project discussed in Section 4 the Sherwood Sandstone would seem acceptable.

5.6 Selection of aquifer

The previous paragraphs indicate that the Lower Greensand aquifer in the Cambridge areas and the Permo-Triassic Sandstones of the Midlands are apparently suitable for ATES experimental studies. In summary the aquifer characteristics appear to be of the order indicated by discussion in Section 4 and both afford saline areas at reasonable depths which are not used for supply purposes, see Table 4. However, differences in thickness, depth and local industry suggest that the scale of experiments in the two aquifers would be somewhat different.

TABLE 4. Comparison of aquifer potential for ATES experimental studies. Figures given in the table are very approximate and obviously values will vary considerably from location to location.

Aquifer	Thickness (m)	Approximate Depth to top of Aquifer (m)	Total dissolved solids (mg/l)	Yield (m^3/day)	Approximate Natural Flow Velocity (m/day)
Lower Greensand Cambridge area	10-50	60	Up to 1000 at outcrop W of Cambridge and down-dip to E	Up to 2000	(Based on field determination of K = 30 m/day) 5×10^{-5}
Permo-Triassic Notts. area	30-300	240	Potable up to 13 miles east of outcrop. >3000 17 miles E of outcrop.	Up to 10 000	(Based on field determination of K = 13 m/day) 2×10^{-5}

As mentioned earlier, this report necessarily assumes availability of a suitable source of water for the experiment. However practical problems involved in the provision of such a source may prove to be a significant factor in the location and design of a preliminary experiment. A consideration of the location of power stations (as potential suppliers of source water for ATES experiments) may be helpful. Figure 14 shows the distribution of the power stations programmed for commissioning between 1961 and 1970. The high concentration along the Trent Valley - a total of 18 in operation in 1971 - as opposed to none planned for commission between 1961 and 1970 in the Cambridge area - suggests that, when the thickness of aquifer is also considered, the Permo-Triassic Sandstones of the Midlands would be suitable for a relatively large scale preliminary UK ATES study. However, the problems involved in recharging heated Trent River water with a high total dissolved solids content may outweigh the convenience of a local readily available supply. The apparent lack of suitable readily available source water and the thinness of the aquifer suggest that the Lower Greensand aquifer of the Cambridge area would be more suited to a relatively small scale experiment where injection water would be heated on site - the available heating capacity probably constituting the limiting factor with regard to injection rates and temperatures.

6. NOTES ON EXPERIMENTAL APPROACH

6.1 Introduction

The purpose of this section is to present some notes on experimental procedure, practice and equipment.

6.2 Recharge Well

Monkhouse and Phillips (1978) have produced a detailed description of the design, construction and maintenance of recharge wells. Experience in design and operation of recharge wells has been described by several authors (Harpaz, 1970; Marshall et al., 1968; Sniegocki, 1963; Sniegocki and Brown, 1970; Sternau, 1967; Edworthy, 1978; Edworthy and Downing, 1979).

The recharge well may be used solely for recharge or it can be constructed to serve as an abstraction well also, in which case it must be equippped with a recharge main or mains to inject water into the well and also a pump and rising main to withdraw water from the well. Even if the well is not to be used for abstraction, pumping will at some time be necessary for cleaning. Study of available literature would seem to indicate that a dual purpose well is the most favoured design in ATES studies to date and it would seem that the possible capital savings through use of a single dual purpose well will be significant. A dual well configuration (one for recharge and one for abstraction) would be advisable in situations where there is a significant groundwater gradient in the target aquifer; the abstraction well would then be placed downgradient of the recharge well to intercept the injected water.

Monkhouse and Phillips (op cit) list the following as needing consideration in the design of a recharge well.

(i) The equipment factor: i.e. all the necessary pipework, pumps etc that are to be installed in the well. The minimum diameter of the well will largely be controlled by this factor.

(ii) The length of open well: this will depend largely upon the thickness of the aquifer and upon the calculated recharge, see later notes.

(iii) The cleaning factor: the mechanism by which the well will be restored to the original recharge capacity after clogging.

(iv) The construction factor: i.e. the various features such as lining tube diameters, screen types, filter packs, grouting verticality, development techniques, etc.

(v) The maximum rate of recharge: Appendix B, Monkhouse and Phillips (op cit) provides a worked example of determining the dimensions of a recharge well for a particular recharge quantity.

With reference to note (ii) above, the length and diameter of the well open to the aquifer will depend upon:-

(a) the thickness of the saturated aquifer;

(b) the concentration of clogging matter contained in the recharge well;

(c) the head available under which water can be recharged;

(d) the velocity at which water passes through the screen,

and (e) the pumping water level expected when the well is pumped.

Again, reference should be made to Monkhouse and Phillips (op cit) for further details. Figure 14 shows the design of a dual purpose well used in a recharge experiment in the unconfined Permo-Triassic aquifer at Clipstone Forest, Nottinghamshire (Edworthy, 1978).

6.3 Operation of the dual purpose well

It is possible either to recharge at a constant rate, allowing the pressure to rise as clogging takes place, or to recharge at a reducing rate while maintaining a constant head. There is little to choose between the methods on theoretical grounds but care must be taken not to allow the pressure to rise high enough to cause rupture of the confining beds. This problem was encountered in the first field experiment carried out by Auburn University (Molz et al., 1978).

Smith and Hanor (1975) recommend the injection pressure should not be allowed to increase about 75% of natural geostatic pressure to avoid this problem; it is possible that high temperature water will weaken aquitard materials or increase their permeability thus exacerbating the problem.

In order to relieve pressure build up it will be necessary to clean the well periodically during and after recharge. In practice the borehole should be cleaned when the permeability has fallen by 50% - as shown by a 50% decrease in recharge capacity.

Recharge water with a high natural concentration of suspended solids must be filtered and/or settled. The cost of treatment should be balanced against the necessary frequency of cleaning up the borehole to arrive at an optimum level of treatment within the constraints of the costs and objectives of the proposed experiment. The clogging effect of micro-organisms and the need for treatment of the water (see Section 4.3) should also be considered. Clogging as a result of air entrainment is likely to prove less of a problem in confined than in unconfined aquifers but it should be borne in mind. The use of high temperature injection water will enhance corrosion problems (see 4.6.6) and when equipiing the borehole attention must be paid to the specifications relating to range of operating temperatures.

6.4 Observation wells

The construction of several observation wells will be necessary to monitor hydraulic and thermal conditions within the aquifer before, during and after the injection/recovery cycle. Assuming isotropic conditions a cruciform arrangement of observation wells centred on the recharge well will give adequate control. However, it is generally advisable to locate wells on at least three differing radial directions from the well in order to be able to define principal permeability axes in the more natural anisotropic condition. The design and construction of the observation bores is not critical - the majority should be open only in the target aquifer but it may prove valuable to monitor events in adjacent aquifers and aquitards although hydraulic and thermal connection between aquifers must be avoided. Thermistors should be positioned in the wells (both observation wells and the injection well) at differing depths to monitor the movement of the thermal anomaly and provision should also be made to monitor heads in the boreholes. The means of overcoming the technical problems of achieving adequate instrumentation of all boreholes will require significant research. The material used for screens and casing in the observation bores (if necessary) is unimportant but should be strong enough to support the walls of the bore under the temperatures and pressures which will be involved. Ideally they should have the same thermal capacity as the aquifer material but this is probably not too critical, but it is important that the borehole walls have a low conductivity value to prevent conduction in a vertical direction. In the Auburn University experiment it was realised that the temperature recorded by thermistors in some of the observation bores was the result of dynamic equilibrium between formation water moving horizontally through the well screen and thermal convection occurring in the well bore. Convection was controlled by back-filling each observation well within the thermal radius of influence with a clean medium sand. It should be noted that it is necessary for some of the observation bores to be positioned beyond the estimated zone of influence of the thermal anomaly in order to help define boundary conditions for later modelling.

6.5 Source water

The water for the experiment (i.e. prior to heating) may be obtained from an outside source (e.g. mains supply, surface reservoir, power station, industrial process, or another aquifer) or from the target aquifer itself. If it is obtained from the target aquifer another well will be required, separate to and at some distance from the dual purpose well, forming a doublet system. For the system to operate properly, source and recharge wells must be far enough apart to prevent breakthrough and thus recirculation of the injected heated water out through the source well. The breakthrough effect in doublet wells has been analysed by Gringarten and Sauty (1975), Lippmann and Tsang (1980) and others. The separation required between wells will depend upon aquifer parameters, the maximum injection volume and rate, and the water temperatures. The doublet configuration will avoid land subsidence (all water withdrawn is immediately returned to the aquifer during storage injection) and minimise clogging, which often occurs when non-native waer is injected into an aquifer (Meyer, 1978). It also permits the use of a heat exchanger to avoid circulating mineralised groundwater through hot-water transmission or distribution pipelines. Water suitably treated for sending through pipelines passes through one side of the heat exchanger, picking up heat or delivering it for storage. Only the well-water side of the heat exchanger is exposed to possible corrosive or scaling effects. Conversely, the groundwater and aquifer are protected against possible pollution from the chemicals used to treat the pipeline water.

The major disadvantage of the doublet system is the additional cost of drilling the source production borehole. In order to avoid this a source separate from the target aquifer must be considered.

6.6 Site and Laboratory investigation

Additional to the actual construction of the recharge/abstraction and observation bores and the operation of the recharge/abstraction cycles a certain amount of other work both on site and in the laboratory must be carried out. With regard to site work accurate surveying of the ground surface and verticality tests of selected boreholes should be carried out before, during and after the experiment in order to assess any movement resulting from the recharge/abstraction process. It is also important that accurate lithological, drilling and geophysical logs are made at the majority (if not all) of the boreholes. Cores should be drilled at several key sites in order to enable laboratory testing of samples from various horizons. Following construction of the main recharge/abstraction well and sufficient observation bores, pump-tests should be carried out to determine aquifer and well parameters.

Laboratory tests should be carried out on core samples - at horizons as directed by the site hydrogeologist - to determine porosity and both vertical and horizontal permeabilites (Lovelock, 1972) and also the thermal characteristics of the sample. Molz et al., (1978) recommend the [illegible] source method [illegible] the thermal capacity of saturated or unsaturated media (Van der Held and Van Drunen, 1949; Nix et al., 1969).

Tables 5 and 6 are taken from Hall et al.,(1978) and show the thermal properties of selected rock materials and rocks under certain conditions and are included here as a guide to the range of values that may be encountered.

6.7 Modelling studies

As described in Section 3 a combination of analytical and numerical models will be necessary to investigate ATES in confined aquifers. Initial analytical modelling would be used to define boundary conditions for a numerical model and also investiage the importance of aquifer depth and thickness, injection temperature etc. For more general problems the "CCC" model could be used.

Table 5. Thermal properties of selected rock materials and rocks under certain conditions. (after Hall *et al*., 1978)

		Thermal Conductivity (Joules/cm./sec./$^{\circ}$C)	Volumetric Specific Heat (Joules/cc./$^{\circ}$C)
Rocks in the saturated zone	Estimated average porosity %		
Plateau gravels	25	1.05×10^{-2}	2.60
Chalk	30	1.05×10^{-2}	3.01
Triassic Sands Sandstone	25	1.05×10^{-2}	2.60
Lower Greensand	25	1.05×10^{-2}	2.60
Carboniferous Limestone	3	1.51×10^{-2}	2.50
Rocks in the unsaturated zone	Estimated specific retention %		
Plateau gravels	2	0.33×10^{-2}	1.80
Chalk	29	1.21×10^{-2}	3.01
Triassic Sandstone	10	0.59×10^{-2}	2.00
Lower Greensand	10	0.59×10^{-2}	2.00
Carboniferous Limestone	0.5	1.26×10^{-2}	2.5

Sources: Ingersoll *et al*., (1954), Baver *et al*., (1972).

Table 6. Values of thermal conductivity of natural materials.
(after Ingersoll et al., 1954)

Material	Thermal conductivity (Joules/cm./sec./°C)
Limestone	2.01×10^{-2}
Marble	2.30×10^{-2}
Granite	2.72×10^{-2}
Dry quartz sand	0.26×10^{-2}
Dry soils	$1.7\text{-}3.4 \times 10^{-2}$
Wet soils	$1.3\text{-}3.4 \times 10^{-2}$

7. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT IN ATES

7.1 Introduction

The previous sections in this report have reported on ATES literature and have considered the practicalities of ATES field experiments in aquifers in the United Kingdom. The purpose of this section is to indicate the needs for research and development in the field of ATES in relation to the United Kingdom.

7.2 Field experiments

7.2.1 The need for experimental work

As reported in Section 2, a considerable amount of experimental ATES work has been carried out in the United States, China and, to a lesser extent, France, West Germany, Switzerland, Japan, Denmark and Sweden. To date, the only published work carried out in the UK relating to ATES is that by the Institute of Geological Sciences into the storage of low grade heat in unsaturated Chalk (Day et al., 1980). In view of the apparent feasibility of ATES as reported in the literature there is a definite need for further investigations to be carried out within the institutional and economic conditions in this country.

7.2.2 The scope of an experiment

It is not intended that this report should include detailed description and costings of a field experiment but it will be useful to give an indication of the necessary scope and aims of any future experiment. An initial experiment would have three main objectives: 1) To investigate the feasibility of ATES by determination of the percentage of energy recovery possible in the aquifer(s) under study. 2) To provide parameters to permit construction, development and calibration of numerical models. 3) To provide field experience (even if only on a small scale) of the practical problems involved with ATES systems.

The scale of an initial experiment will probably be determined by the available rate of supply of source water at a suitable temperature and/or the thickness and depth of the aquifer at the selected site. For example, an experiment situated in the Trent valley utilising the Permo-Triassic Sandstone as target aquifer, which may be able to utilise waste water from one of the many power stations in the area, would be on a much larger scale than an experiment in, say, the Lower Greensand of the Cambridge area. Using this thinner target aquifer coupled with the probable need to heat water specifically for any study would substantially restrict the size of the experiment. The major considerations involved in ATES experimental work have been given in Section 4.

The basic experimental configuration should consist of a central, dual purpose, recharge/abstraction bore, open only in the target aquifer, (unless existing groundwater gradients necessitate the use of a doublet system of wells to permit interception of the heated water downgradient). The central well should be surrounded by a number of observation bores at differing radial directions and distances from it, instrumented to monitor temperatures at different depths (generally within the aquifer but with some control points in the aquicludes) and potentiometric heads. Similar instrumentation is required in the central bore.

Drilling should commence with one or more of the observation holes, to identify any problems (actual or potential) before construction of the central well. In order to determine the detailed nature of the aquifer locally and its particular physical and chemical properties the central bore should ideally be cored through the whole aquifer thickness. The core samples will then be used to provide specimens of interstitial waters for chemical analysis and also discrete samples for analysis of the aquifer's physical properties (vertical and horizontal permeabilities, bulk density, porosity, thermal capacity and conductivity). Following coring of the central well it will be necessary to ream it to sufficient diameter for the final design specification.

The final diameter of the central dual purpose well will depend upon the hardware to be used in it. For example Edworthy (1978) reports that the recharge well used at the Clipstone site contained separate pump inlet and recharge outlet both connected to individual rising mains which were contained within the main well screen/casing which was set in a gravel pack. Additionally the gravel pack was penetrated by two 75 mm diameter pipes to enable backwashing of the well to alleviate clogging. The final reamed diameter of the bore in this case was 920 mm. To reduce drilling costs a smaller diameter well may be used with one dual purpose main only and recharge could either be performed with the pump in position but not operating (some form of by-pass valve may be desirable) or alternatively the pump could be installed following completion of injection and during the storage cycle.

It is likely that the screen and casing will need to be installed to ensure stability of the borehole in poorly consolidated sections during development and under experimental conditions of recharge, abstraction and cleaning. If possible all bores should be inspected by down-hole TV camera prior to the setting of screen and casing and, following completion and development, all bores should be logged by geophysical methods.

Prior to the ATES experiment, aquifer testing should be carried out to determine the hydraulic parameters of the aquifer. In order to investigate borehole efficiency and to decide on a suitable rate for the subsequent constant rate test a multi-rate "step-test" should be carried out. This should be followed by a series of packer tests carried out at discrete intervals over the open area of the central dual-purpose well. Following recovery after the final packer test a constant rate test should be carried out followed by a recovery test of similar duration. Collection of water samples for chemical analysis at each interval during the packer tests and intermittently during the constant rate test should also be carried out. It is evident that the preceding recommendations may be limited by budget considerations.

The main ATES experiment will consist of recharging source water at a known temperature into the aquifer via the central borehole for a fixed period and abstracting the water following a storage period of similar duration. Temperatures and hydraulic heads within the main and observation boreholes will need to be regularly monitored throughout the experiment. The temperature and recharge rate of the source water must also be accurately monitored.

7.3 Modelling studies

Analytical and numerical modelling studies should be closely related to field experiments. Initial modelling should be used to guide experimental procedures and the overall objective of a modelling study should be to provide a verified numerical model of the field situation to enable extrapolation of experimental results to a full scale operation.

Existing computer models (see Section 3) should prove valuable to the progress of future ATES research in this country. Plans should be made to acquire the most relevant at an early stage in order that they may be fully assessed and a detailed programme, with regard to model use and development, can be formulated.

7.4 Legal and institutional framework

It is evident that abstraction of groundwater requires licensing by the relevant Water Authority which will also need to be informed of any intended artificial recharge to groundwater. It is also possible that recharging of water at a higher temperature than the native groundwater may require the permission of the Waste Disposal Authority as designated by the Control of Pollution Action 1974 - although it is not clear in the wording of this Act whether thermal pollution is covered by it. If it is deemed to be pollution it should be noted that IGS is a "prescribed person" under the relevant regulations who must be consulted prior to issue or refusal of a license by the Waste Disposal Authority. It is necessary that the legal and institutional framework relating to ATES be investigated at an early stage of any future research and development programme.

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APPENDIX A

Extent of the thermal anomaly

Before any heat injection experiment is undertaken, an estimate of the extent of the thermal anomaly to be produced would be required. If the flow is essentially intergranular, a reasonable assumption is that after several injection/storage/abstraction cycles the water and matrix would be in local thermal equilibrium and can be characterised by a single temperature at every point. The heat transport equation will then be:

$$\frac{\partial \theta}{\partial t} + \frac{\underline{q}}{S_a} \cdot \nabla\theta = K\nabla^2\theta \qquad \text{(A1)}$$

where θ is the temperature

t is the time

$\underline{q}$ is the specific discharge (usually given by Darcy's law)

S_a is the volumetric specific heat of the saturated matrix

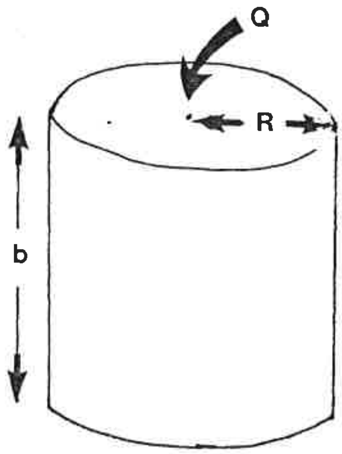
and K is the thermal diffusivity of the saturated matrix.

For prediction of the of the extent of the anomaly (ignoring convection), equation (A1) should be solved numerically in conjunction with the groundwater flow equation. However, some useful estimates of the extent of the thermal anomaly can be made by ignoring the conduction term, $K\nabla^2\Theta$, which analytical solutions show will be small provided:

$$\frac{4Kt}{R^2} << 1 \qquad \text{(A2)}$$

where R is a length characterising the size of the anomaly. With this assumption, the whole of the anomaly will be at the injection temperature with a sharp temperature interface at its boundary. There are three simple cases where the position of the interface after a given time is easily calculated.

(a) For cylindrical flow from a line source in a confined aquifer:



Q = volumetric flow rate

t = time of injection

R = radius of influence

b = aquifer thickness

S_a = volumetric specific heat of saturated aquifer

S_w = volumetric specific heat of water

T_I = injection temperature of water

T_A = pre-injection temperature of aquifer

T_W = pre-heating temperature of water

The heat energy required to heat injection water -

$$Qt\ (T_I - T_W)\ S_w \tag{A3}$$

The heat energy available to aquifer (i.e. w.r.t initial aquifer temperature) =

$$Qt\ (T_I - T_A)\ S_w \tag{A4}$$

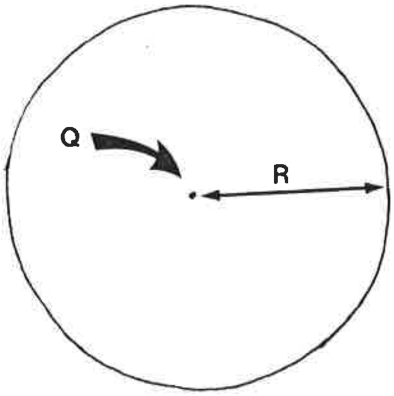
The heat transferred to the aquifer resulting from injection =

$$\pi\ R^2 b\ (T_I - T_A)\ S_a \tag{A5}$$

Equating (A4) and (A5) gives

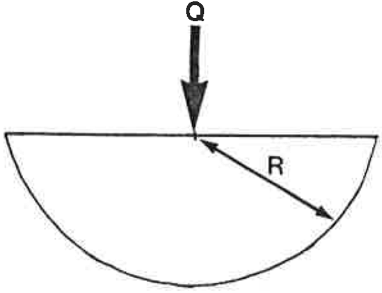
$$R = \left(\frac{Qt\ S_w}{\pi b\ S_v} \right)^{\frac{1}{2}} \tag{A6}$$

(b) For radial flow from an injection point remote from any confining boundary-forming a spherical anomaly:



$$R = \left(\frac{3Qt\ S_w}{4\pi\ S_v} \right)^{1/3} \qquad \text{(A7)}$$

(c) For radial flow from an injection point just below a confining layer:



$$R = \left(\frac{3Qt\ S_w}{2\pi\ S_v} \right)^{1/3} \qquad \text{(A8)}$$

As the anomaly grows, the rate of movement of the interface becomes slower and thermal conduction becomes important - see equation (A2)

As discussed in Section 4.5(b) the lower density of the injected water will cause it to override the colder native water and to displace it from the top of the aquifer downward in a wedge shape. The cone shape as approximated in 4.5(b) will have an upper radius of influence given by the following formula

$$R = \left(\frac{3Q\ S_w}{\pi b\ S_a} \right)^{\frac{1}{2}} \qquad \text{(A9)}$$

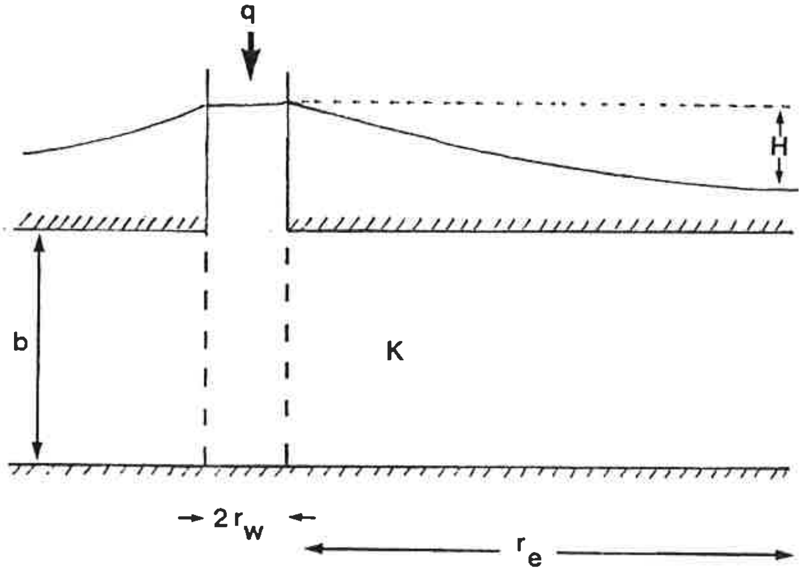
APPENDIX B

Hot water injection flow rates

The following formulæ give the relationship between rates of injection and the dimensions of the water anomaly for differing injection conditions. The following symbols are used:

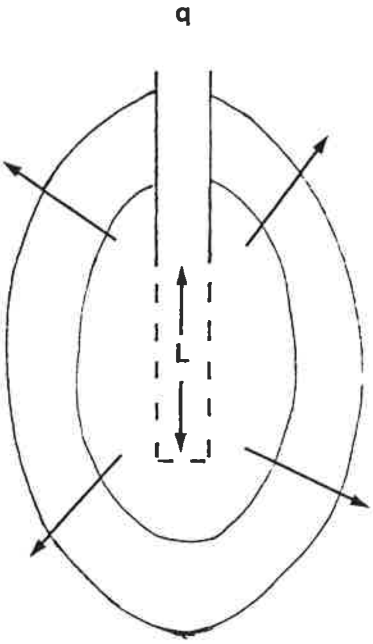
q	rate of injection
L	open length of well
K	aquifer permeability
H	injection head above initial water level
r_e	radius of influence of anomaly
r_w	radius of well

(1) Fully penetrating well



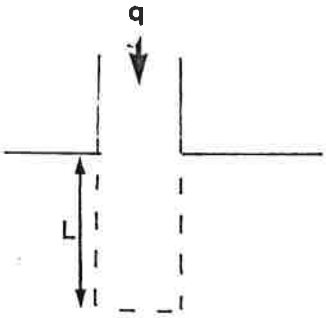
$$q = \frac{2\pi\ b\ KH}{\ln\ {}^{r_e}/{}_{r_w}} \qquad \text{(B1)}$$

(2) Partially penetrating well remote from confining layers:



$$q = \frac{2\pi\ L\ KH}{b\ (L/r_w)} \qquad \text{(B2)}$$

(3) Partially penetrating well below confining layer



$$q = \frac{2\ L\ KH}{\ln(2L/r_w)} \qquad \text{(B3)}$$

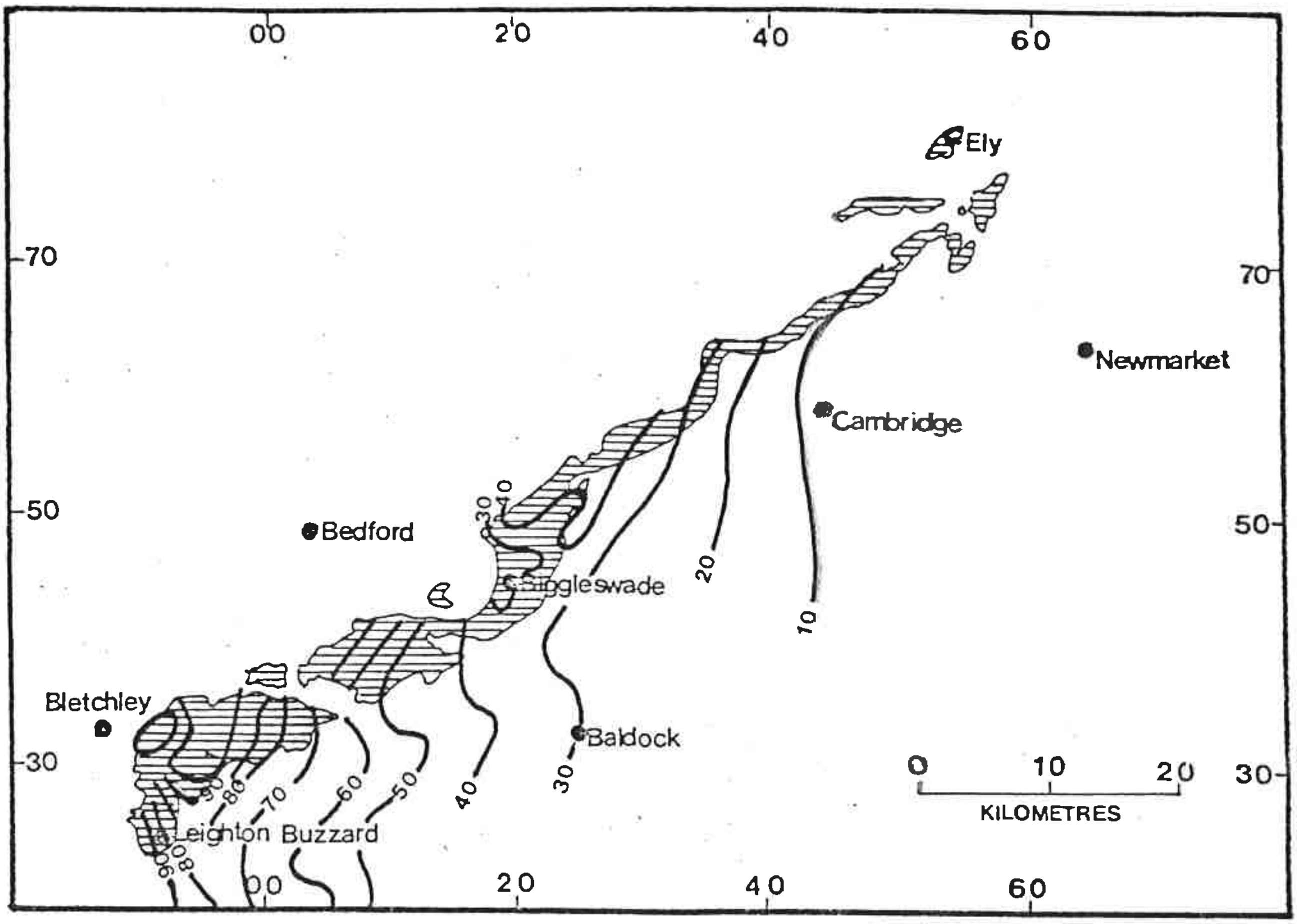


FIGURE 1. Groundwater levels in metres (AOD) in the Lower Greensand of the Cambridge-Bedford region (after Monkhouse 1974)

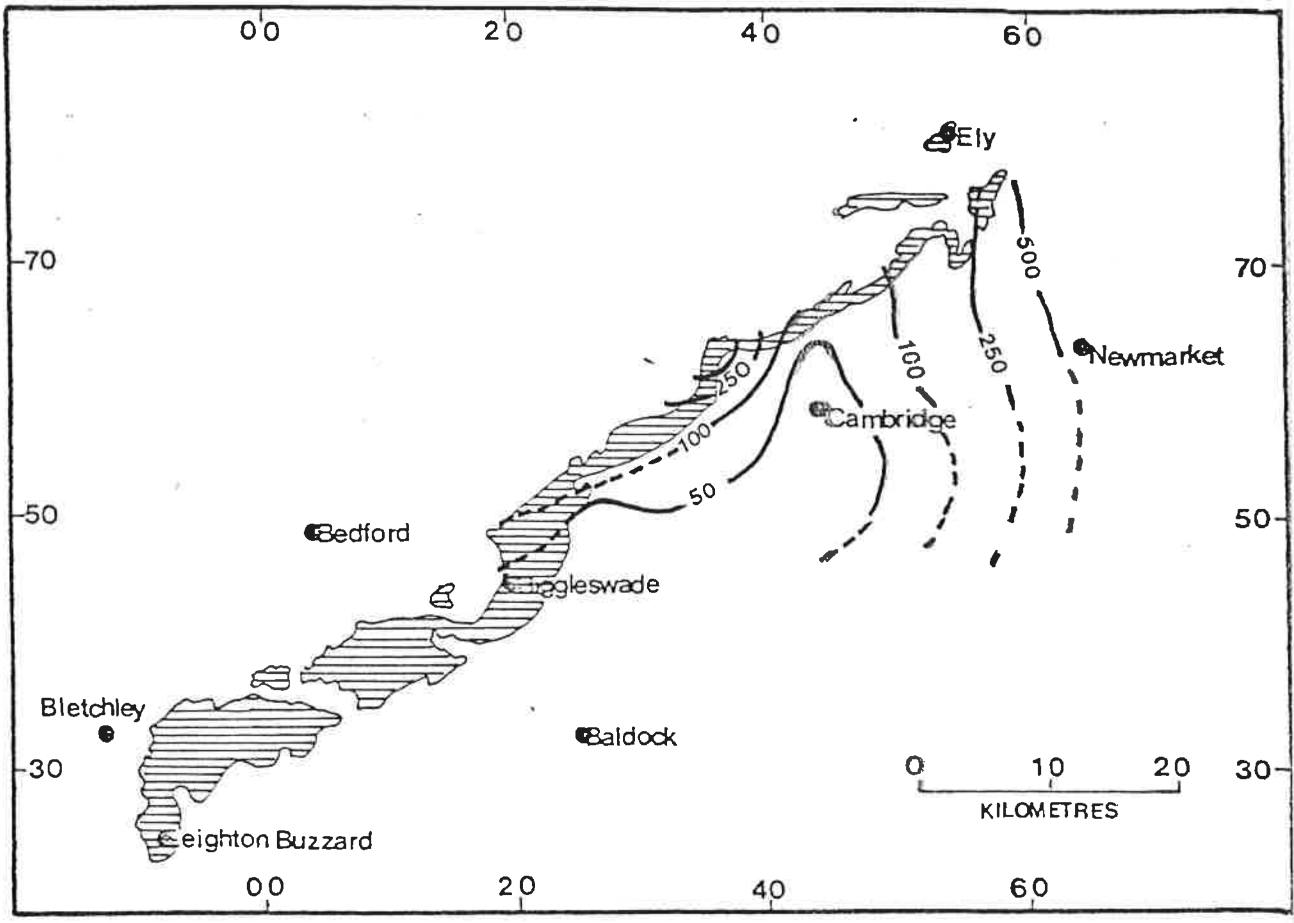


FIGURE 2. Isochlors in the Lower Greensand - mg/l (after Monkhouse 1974)

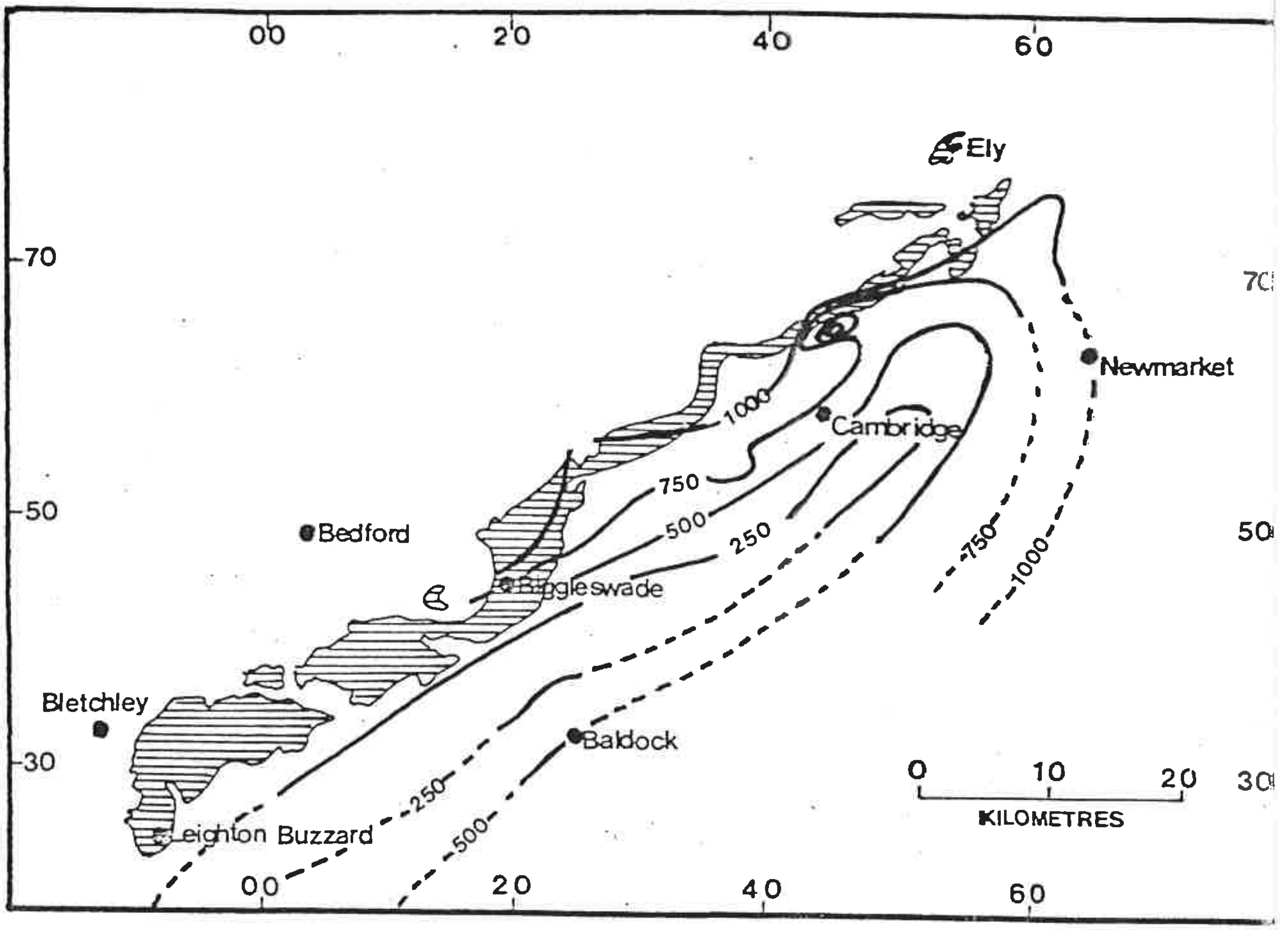


FIGURE 3. Total ionic concentration of groundwater in the Lower Greensand - mg/l (after Monkhouse 1974)

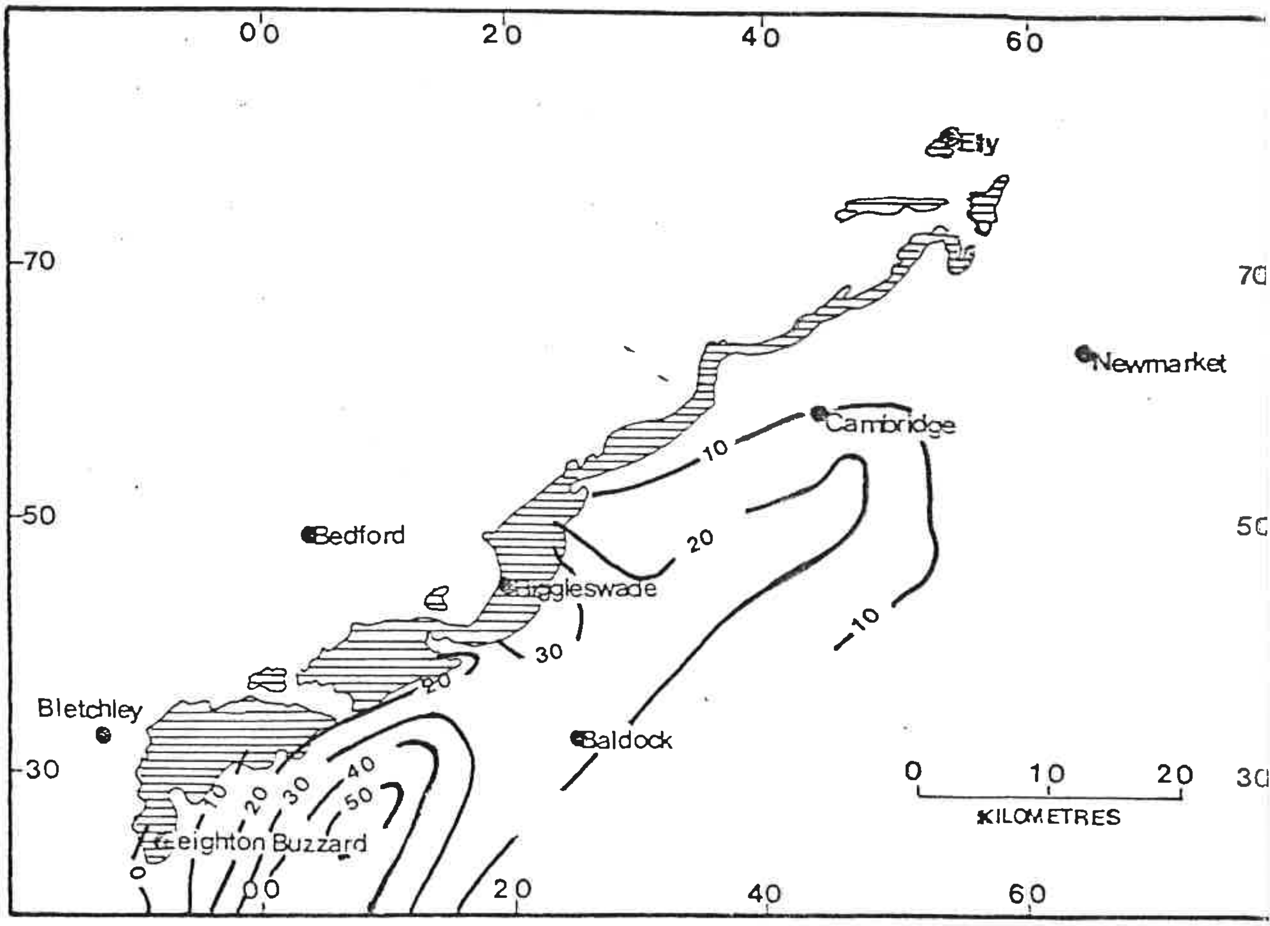


FIGURE 4. Variation in thickness of the Lower Greendsand - metres (after Monkhouse 1974)

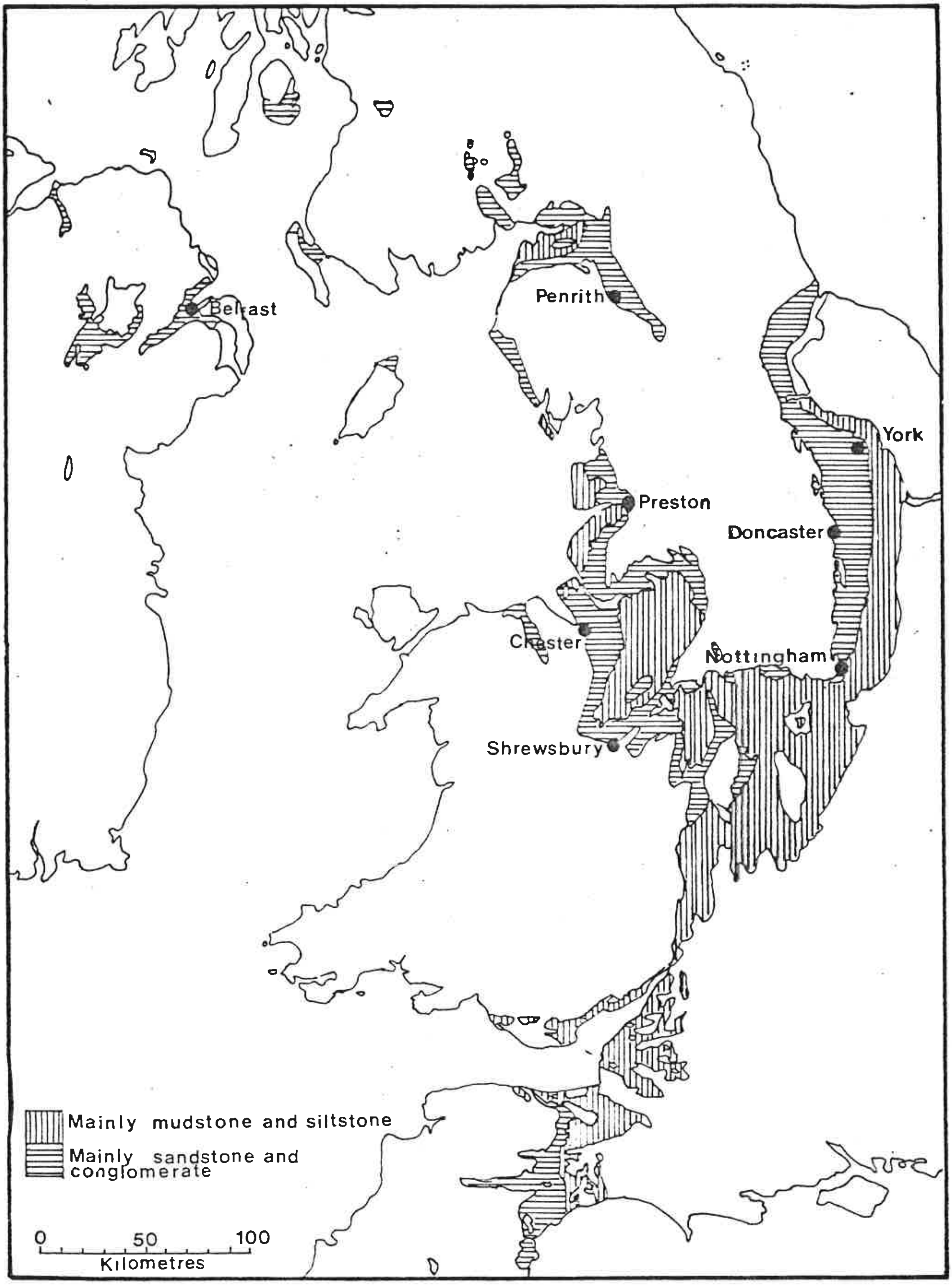


FIGURE 5. Map showing distribution of Permo-Triassic sandstones in the United Kingdom. (after Lovelock 1977)

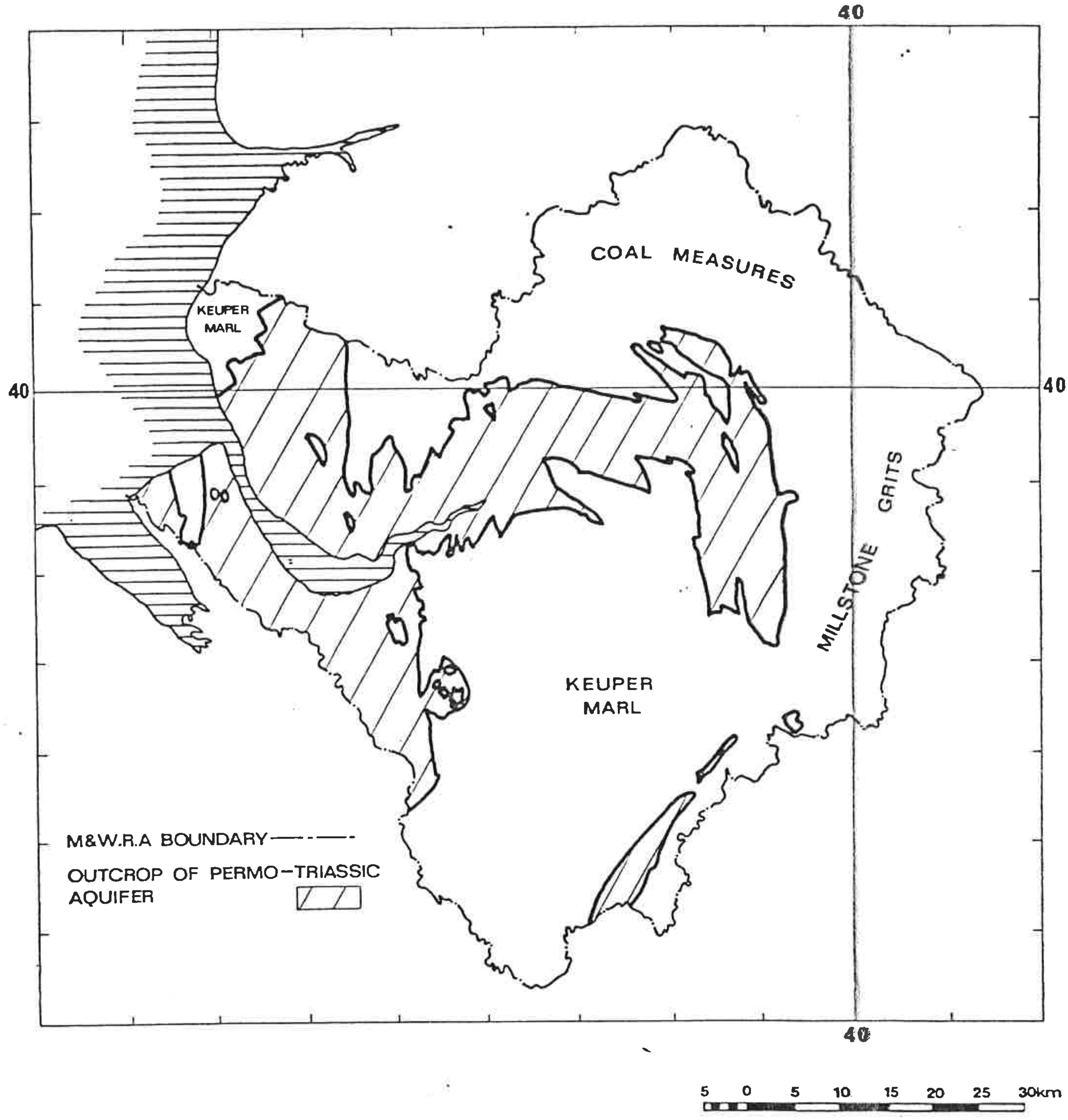
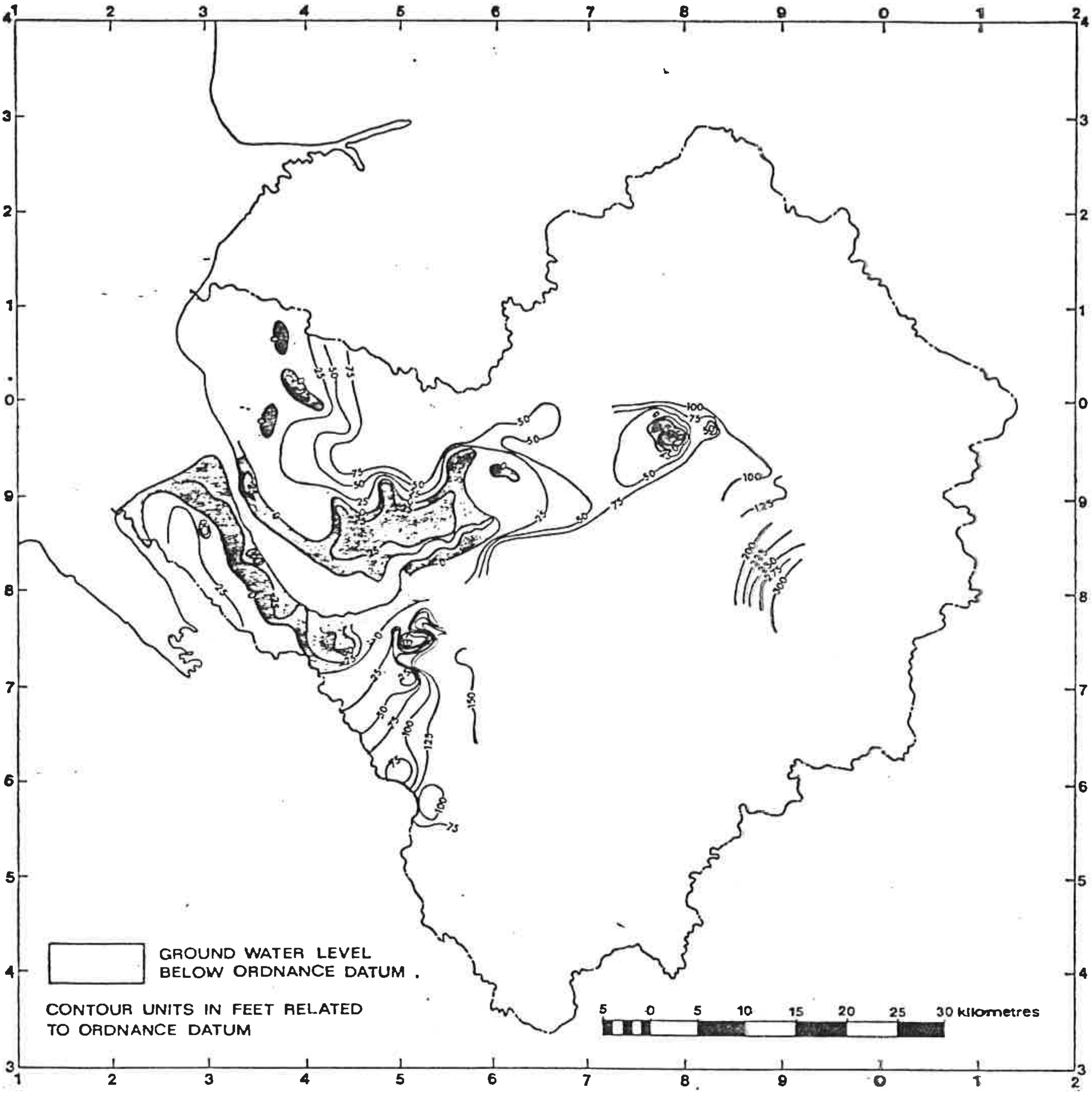


FIGURE 6. Outline solid geology of the Mersey and Weaver River Authority area (Anon- 1969)

FIGURE 7

GROUND WATER CONTOURS FOR THE PERMO-TRIASSIC AQUIFER IN 1965

(Anon, 1969)



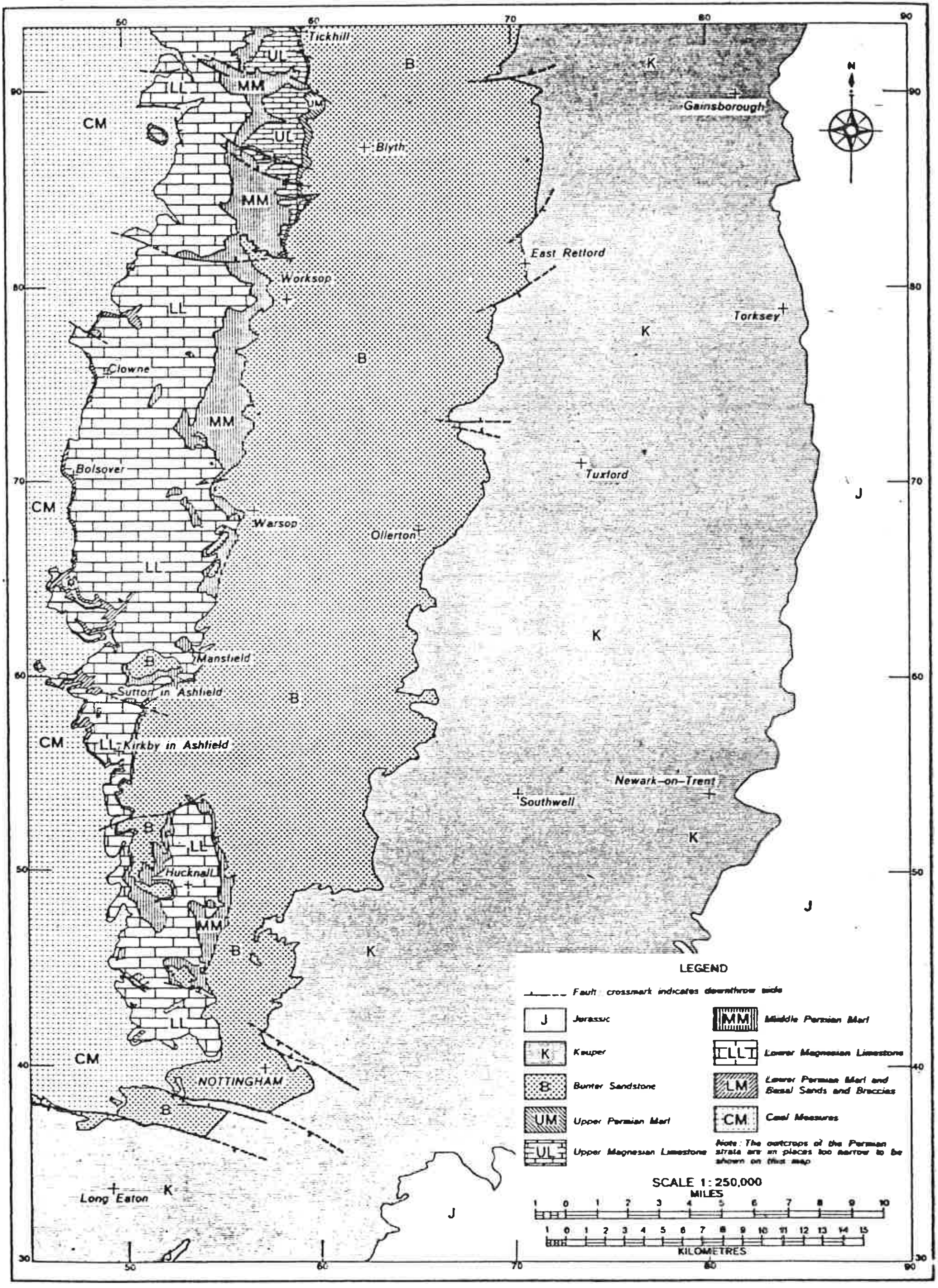
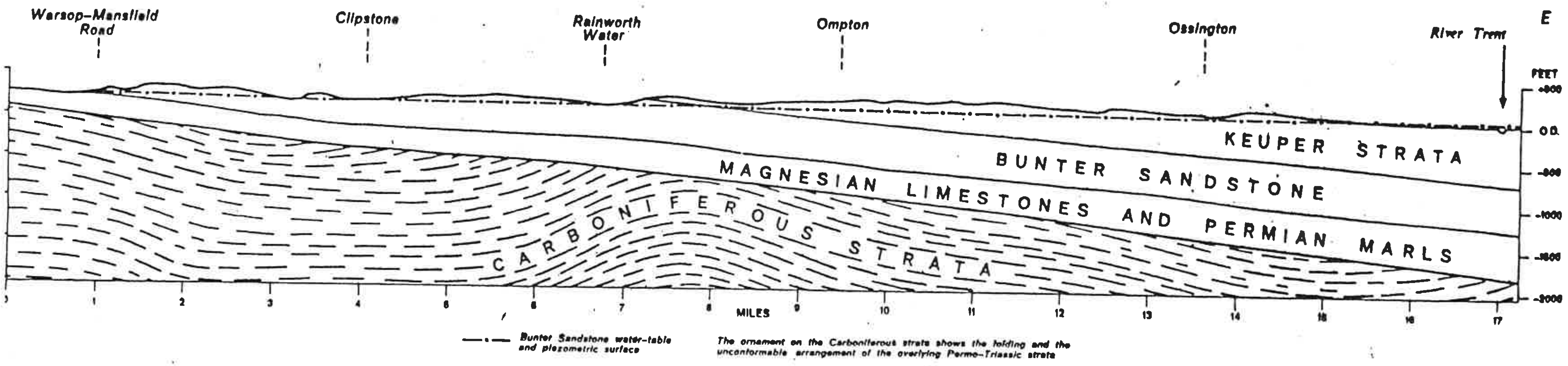


Fig.8 OUTLINE GEOLOGICAL MAP (SOLID) (Land, 1966)



The ornament on the Carboniferous strata shows the folding and the unconformable arrangement of the overlying Permo-Triassic strata

Fig. 9 GEOLOGICAL CROSS-SECTION (Land, 1966)

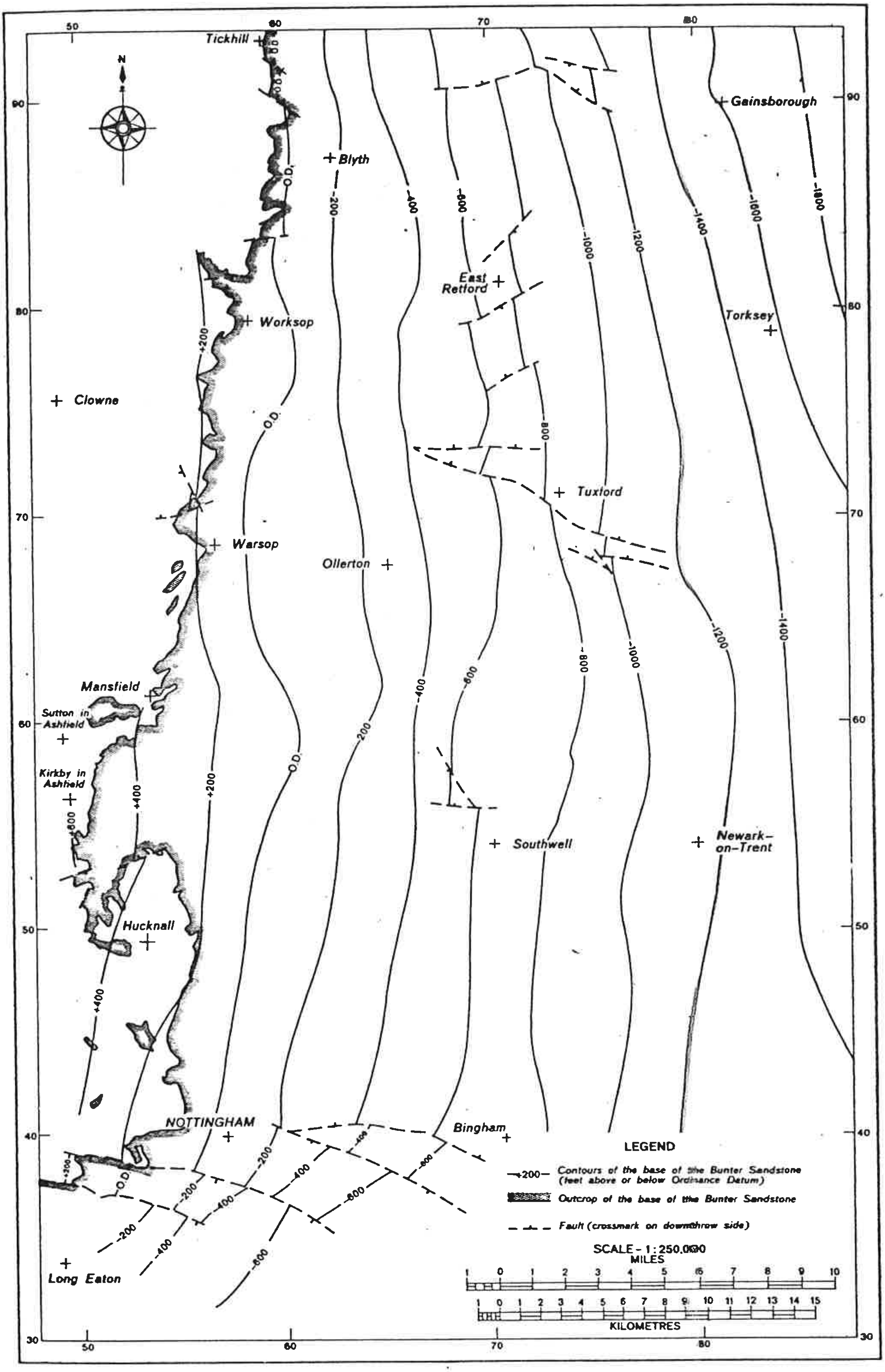


Fig.10 CONTOURS OF THE BASE OF THE BUNTER SANDSTONE (Land, 1966)

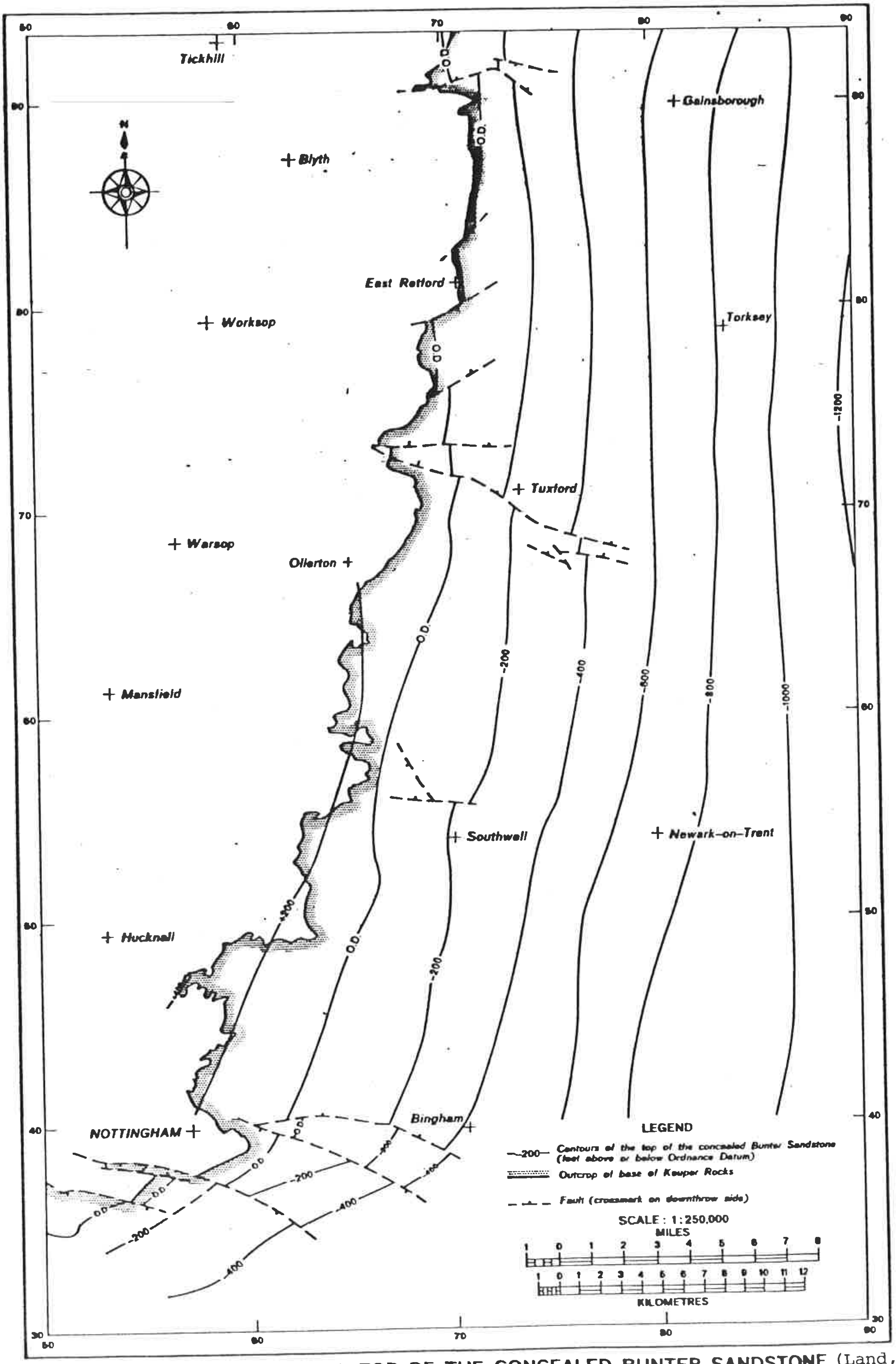


Fig. 31 CONTOURS OF THE TOP OF THE CONCEALED BUNTER SANDSTONE (Land, 1966)

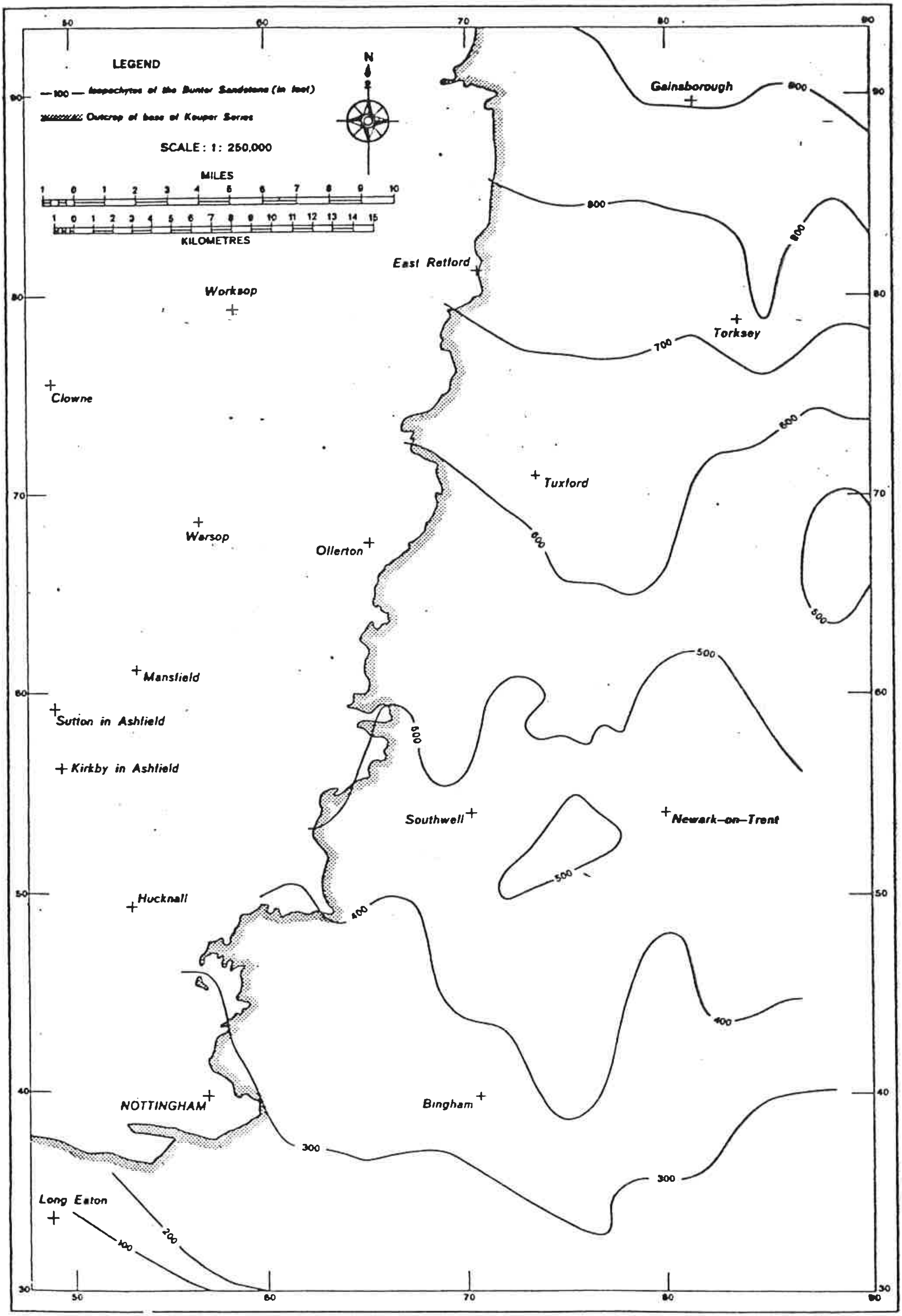


Fig.12 THICKNESS OF BUNTER SANDSTONE BENEATH KEUPER STRATA (Land, 1966)

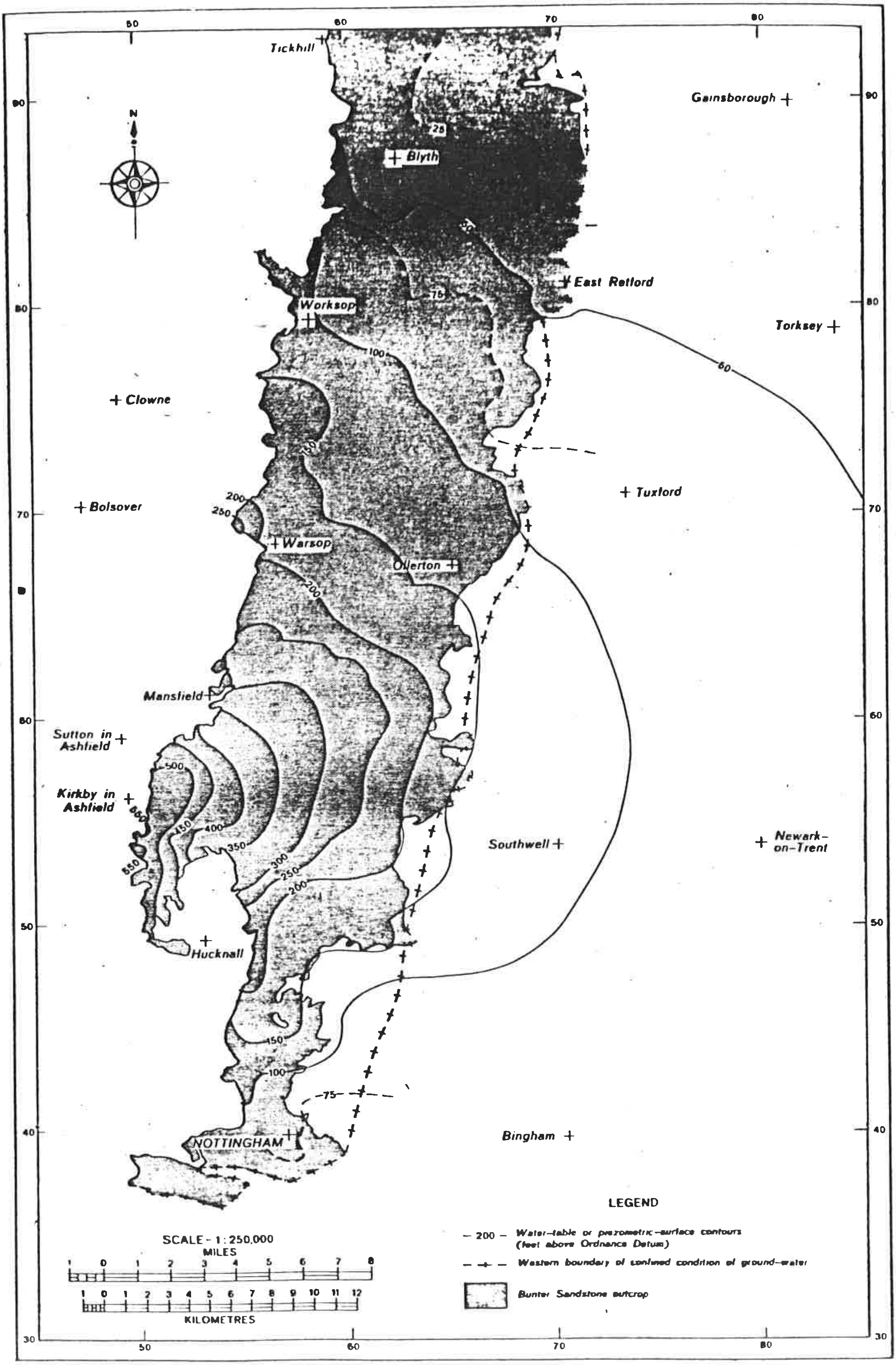


Fig.13 GROUND-WATER LEVELS (Land, 1966)

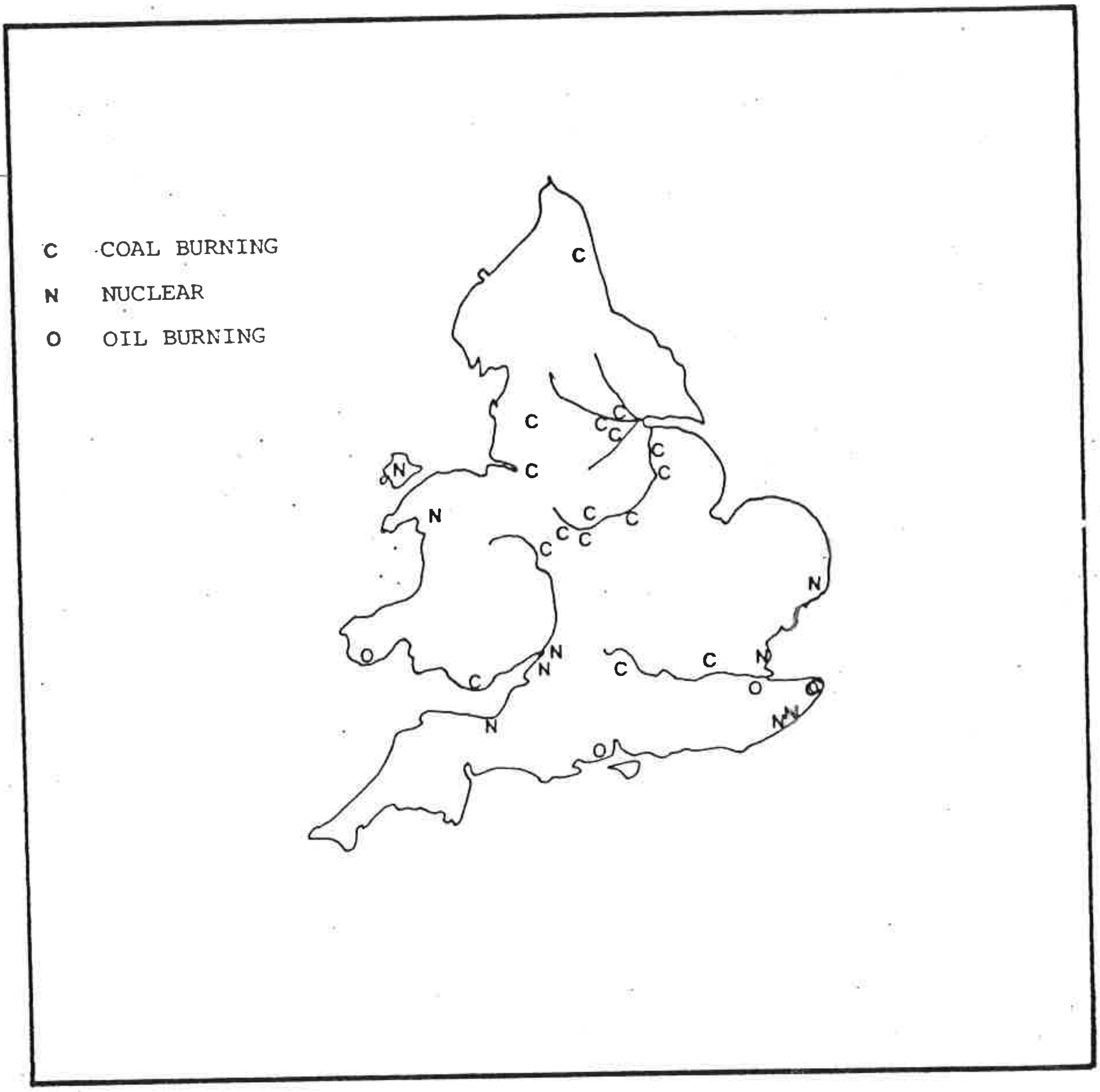


FIGURE 14 Power stations programmed for commissioning between 1961 and 1970. (after Pipe --)

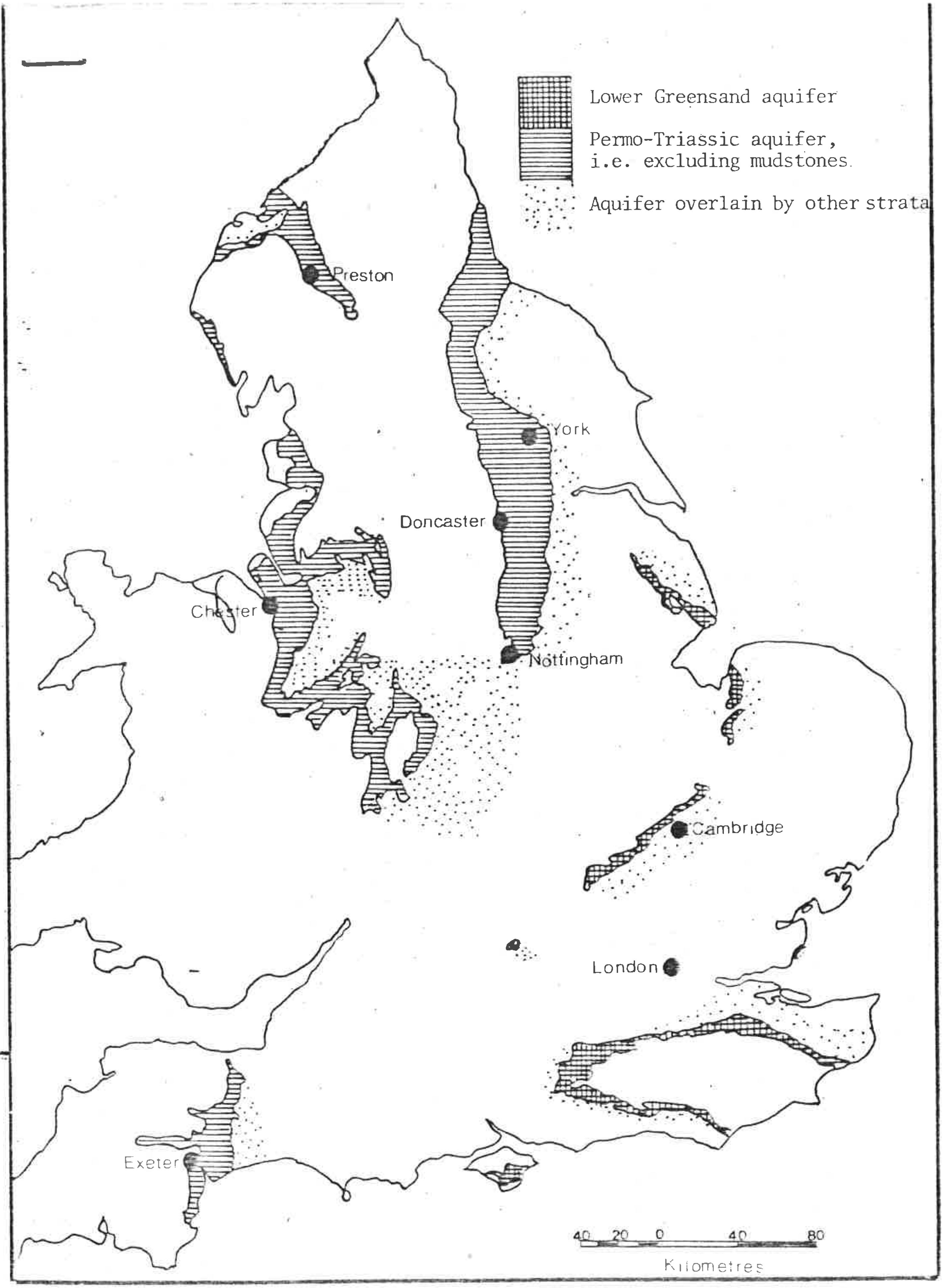


FIGURE 15. Distribution of aquifers with potential for ATES in England and Wales. This map shows only the Lower Greensand and Permo-Triassic aquifers but other aquifers should not be precluded from local consideration. The dotted shading indicates areas where the aquifers are overlain by other strata but still have potential for water supply. It is possible that major ATES programmes would involve confined aquifers at greater depths and distances from outcrop.