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MUSGRAVE PROCLAIMED WELLS AREA GROUNDWATER ASSESSMENT

by

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GROUNDWATER AND ENGINEERING

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Executive Summary

The Musgrave Proclaimed Wells Area (PWA) contains a number of small groundwater lenses of potable quality surrounded by brackish to saline groundwater. A potable groundwater lens is defined as groundwater with a salinity of less than 1000 mgl^{-1} contained within the Quaternary Limestone sequence. Only one lens, Polda is currently used, the other lenses have been reserved by the Minister for Environment and Natural Resources for any future augmentation of the current reticulated water supply for Eyre Peninsula. A re-appraisal of groundwater resources of County Musgrave was required due to the potential competing use of the water for processing a kaolin deposit at Poochera. The mine processing would require approximately 300 ML/year water with a salinity of less than 6000 mgl^{-1}. This study builds upon previous work done by MESA and EWS to obtain a greater understanding of groundwater resources in the region. A number of techniques have been used in the investigation including drilling, groundwater monitoring, geophysics, isotope geochemistry and the development of a spatial database.

Potable groundwater resources occur along the western coastal margin of Eyre Peninsula due to slightly elevated rainfall and a suitable host rock (Quaternary Limestone) to receive recharge. This has resulted in higher recharge rates and significant lower salinity groundwater than would normally be associated with similar semi - arid environments. Groundwater is contained mainly within two hydrostratigraphic units, an upper Quaternary Limestone aquifer and a lower sand aquifer. The Quaternary Limestone aquifer contains the potable groundwater lenses and has the hydraulic characteristics of an unconfined to semi-confined aquifer. The yield of the limestone varies from 5 up to 50 LS^{-1} . The Tertiary sand aquifer is confined in those areas where it underlies the saturated Quaternary Limestone, elsewhere it is unconfined. The yield from the sand is considerably less than the limestone with a range of 1 to 10 LS^{-1}. Other minor occurrence of groundwater occur within weathered bedrock or fine grained sands of the Jurassic sequence. However groundwater in these types of rock generally have low yields and high salinities and are not of major economic importance.

The groundwater systems of County Musgrave are recharge controlled. The origin of the groundwater is dominantly via infiltration of 'recent' rainfall. There is a strong correlation between groundwater levels and rainfall indicating a positive relationship between rainfall and recharge events. The monitoring data indicates that a recharge event will only occur if monthly rainfall exceeds at least 60 mm. The intensity of rainfall is as important as the amount of rainfall for a recharge event to occur. For example some rainfall events well in excess of 60 mm will not result in recharge to the groundwater system as the rain occurred over a longer period of time.

As the groundwater system is strongly linked to rainfall, inferences can be drawn about past groundwater levels by knowing the rainfall distribution history. The rainfall statistics (cumulative monthly deviation from the mean) strongly mirrors the observed hydrograph data. Years of below average precipitation (low cumulative monthly deviation from the mean) correspond to lower water levels in the lenses while conversely years of above average rainfall correspond to high water levels in the lenses and high cumulative deviation from the mean rainfall statistics. By examining the rainfall statistics prior to monitoring we can draw inference about past groundwater levels in the lenses. Groundwater levels were most likely at a peak around the early 1920s and 1950s while the lenses were at lows in the early 1900s and around 1930s.

The groundwater systems of County Musgrave have been under stress from 1973 to 1994. This has caused a regional decline of the water table between 1 and 5 metres throughout a large portion of the study area. This is reflected by a reduction of 10 % in the areal extent of the saturated Quaternary Limestone. This reduction in size of the groundwater lenses is not due to over pumping from the Polda trench. The decline in water levels occurs in all groundwater lenses whether there is a large pumping centre or not. The decline is a result of subtle (reduced) changes in precipitation which has resulted in reduced recharge rates and consequent declining groundwater levels. Therefore in periods of below average recharge (declining groundwater levels) the groundwater systems will continue discharging at a rate greater than recharge. Management of these resources must consider appropriate risk management practices.

Major ions, stable isotopes (δ^{2}H, δ^{18}O) and radiocarbon (^{14}C) were analysed throughout the region. The data suggests that local recharge dominates the water budget and that regional throughflow is minimal to nonexistent. Groundwater salinity is derived from a marine aerosol component and concentrated by varying rates of evapotranspiration (ET) in the unsaturated zone prior to recharge with only a minor component of dissolved salt added by water /rock interactions. Radiocarbon data indicates that the majority of groundwater in the Quaternary limestone aquifer was recharged within the last 30 years. Confined groundwaters can vary in age from less than 30 years to in excess of 18 000 years old.

The Transient Electromagnetic (TEM) method was used in this investigation to assist in understanding subsurface properties. It was useful in mapping the hydraulic basement of the groundwater resources. However the method could not differentiated different hydrostratigraphic units or fresh and saline groundwater.

The groundwater assessment (safe annual yield) from each lens was determined in the traditional manner by determining the average recharge rate to each groundwater lens and multiplying this by the area of the lens. Recharge was calculated using the chloride mass balance method, well hydrographs and Darcian approach. The chloride mass balance gave the best results.

However there are some management problems associated with this approach as average annual recharge rates to the lenses can still result in a net discharge from the system. The concept of an annual sustainable yield in these types of environments is therefore not appropriate because annual recharge varies significantly. Rather an minimum recharge value needs to be determined and appropriate risk management practices adopted so that the resources can be maintained. It is recommended that for an interim period the permissible extracted yield be 40% of the estimated volume of water added by recharge.

INTRODUCTION

The area near Elliston on the Eyre Peninsula of South Australia has a number of shallow, low salinity groundwater lenses. Exploration in the 1960s outlined the `basins' and first order `safe yields' were estimated. The lenses are protected by legislation (Proclaimed Wells Area) and have been set aside for future development in the region. Potential use of the low salinity groundwater as processing water for a large kaolin deposit necessitated a revaluation of the resource to ensure sustainable development. In this report a potable groundwater lens is defined as groundwater with a salinity of less than 1000 mg/l contained within the Quaternary Limestone.

In the 1992/93 financial year money became available under the government's South Australian Exploration Initiative (SAEI). An extensive kaolin deposit in the vicinity of Poochera (about 100 km to the north of Elliston) sought water for mineral processing. As groundwater of the required quantity and quality is not available in the vicinity of the deposit, the groundwater resources of the Musgrave proclaimed Wells Area (Musgrave PWA) were suggested as a potential source.

Previous Work

The "Polda Basin" was first defined in 1911 by R L Jack who prepared a Departmental report on the groundwater of the "Polda Water Area" in 1928. Gibson (1958) and Shepherd (1960) undertook work on Elliston town water supply as a result of which a number of wells were drilled in the Pleistocene aeolianite.

Pumping from the Polda Trench commenced in December 1962 was followed by extensive groundwater exploration in the area. Initially, work was concentrated about the trench itself to monitor the effects of pumping both on water level and salinity as it was recognised that excessive abstraction could cause the migration of more saline groundwater both laterally and vertically. Work expanded and culminated in the production of about nineteen progress reports which are cited in Barnett (1980).

Extensive drilling was carried out in the 1960's (607 holes) to a cumulative depth of 11.15 km. All successful holes were completed as observation wells and have been variously monitored for water level. Limited geological mapping, resistivity surveys (Hussin, 1967 & McPharlin 1967), establishment of meteorological stations, pumping tests for aquifer parameters (Shepherd, 1954, Bleys, 1965 & Painter 1970) were undertaken and documented in a concise report by Painter (1972). Attempts were made at estimated "safe yields" for the six freshwater "lenses" which were delineated by the 1000 mg L^{-1} isohaline contour. Darcian flow and an estimation of recharge from rainfall were used in calculations. The investigation was only partially successful in qualifying the available groundwater resource.

Aquifer characteristics have been obtained irregularly from subsequent two water supply development (Williams, 1973) and by a re-assessment of the Talia Basin (Bowering and Shepherd, 1975). This report documents work undertaken since 1983 and include work done on many of the 1972 recommendations.

Yandell (1976) produced a report on future development of water supplies on Eyre Peninsula within which both surface and groundwater resources were discussed. Previously published lens "safe yield" (Painter, 1972 and Bowering & Shepherd, op. cit) were accepted uncritically, i.e. first order estimations were used in the assessment.

In summary, most quantitative work has centred around the Polda Trench as it is the major abstraction point within the Musgrave PWA (330-2500 ML/yr). First order assessments have been made of the available resources from the six low salinity (less than 1000 mgL^{-1}) lenses. Some recommendations for improving the data base have been implemented.

Evans (1993) made a thorough study of the Polda Lens which was aimed at quantifying its sustainable yield and improving operational performance of the pumping system.

Aims and Objectives

The primary aim of this project were to obtain a greater understanding of the groundwater resources in the region to assist in long term management of these resources The specific objectives were to:

•develop a conceptual understanding of groundwater resources in the region

•review the historical groundwater response to climatic variations and extraction.

•develop a better greater understanding of the hydraulics and recharge mechanisms to the system.

•reassess the sustainable yield of the potable groundwater lenses.

Description of Study Area

The study area (Figure 1) comprises the Musgrave Proclaimed Wells Area with the major town Elliston. The location of wells used in this study is shown in Figure 2. In general, the area is flat to undulating with the land surface gradually rising to the east (Figure 3). The coastal area varies from mobile sand dunes up to 30 m high to steep or sub-vertical cliffs rising 30 to 120 m above sea level. Ephemeral lakes and swamps occur in a broad depression which runs sub parallel to the coast and from 2 to 8 km inland. These salt lakes represent the final discharge for many of the groundwater lenses. East of the depression the land surface rises to elevation ranging from 45 to 75 m above sea level. Mt. Wedge is a prominent topographic feature rising some 240 m above sea level and 210 m above the surrounding county.

Surface runoff is almost non existent being confined to minor ephemeral creeks in the upland areas. Any creeks developed soon disappear on the gentler slopes. Drainage is local into internal closed depressions eg Poelpena Swamp (Figure 5).

The climate is semi arid with hot, dry summers and cool winters. Mean monthly rainfall figures for stations within the area vary from 350 mm/a at Talia to 450 mm/a at Sheringa. The Rainfall isohyets and evaporation data are shown in Figure 4.

Landcover (Figure 5) in the region includes Mallee (Eucalyptus), open plains and swamps. The Mallee zones overlie thin red soils and calcrete where the vegetation can vary from lightly dispersed vegetated county to dense scrub. The Mallee area has previously been considered to restrict any recharge to groundwater.

The undulating plains country is characterised by calcrete flats with numerous sinkholes and contains the major zones of potable groundwater. Native sheoaks and red gums are typically found in the plains country.

Swampy areas occur in local depressions of the limestone and act as discharge zones for the groundwater systems. Discharge is likely to occur via transpiration through red gums and by direct evaporation from the water table.

INVESTIGATION PROGRAMS

MESA has undergone a number of investigation programs in County Musgrave since the 1970’s. This section discusses the techniques used while the results of the work is embodied within the text.

Drilling Program

A number of drilling programs have been conducted since the last regional assessment in the 1960's. A total of approximately 60 wells have been drilled or rehabilitated since that time. The total number of wells drilled in the region are shown in Figure 2. The entire observation network drilled in the 1960s (~600 wells) has been reinterpreted which has resulted in slight variations in the distribution of hydrostratigraphic units from the previous interpretation.

Subsequent drilling programs have provided additional information on the distribution of lithology and water quality profiles throughout the region. A number of wells drilled in the 1960's were open to both the Quaternary limestone and Tertiary sand. This has resulted in many instances in recording a composite water level from two hydrostratigraphic units. As a result a number of wells were rehabilitated and finished as dual completion wells. Another suite of wells were drilled to provide well control points for the geophysical surveys.

Groundwater level and quality monitoring

Groundwater level monitoring commenced with the large scale drilling program in the 1960's and has continued on a monthly basis till the early 1980's. Since that time the network was rationalised to include only a number of selected observation wells in each Hundred. This has enabled long term water level trends to be determined. Unfortunately rationalisation of the network did not allow piezometric surfaces and the areal extent of the low salinity lenses to be mapped. As a result monitoring of the full network has recommenced in July 1993 in order to achieve these objectives.

A number of wells are now inadequate for monitoring purposes due to collapse or lack of access. Further upgrading and rationalisation of the network will need to be considered in the future.

Groundwater quality monitoring commenced throughout the entire study area in 1992. There is a lack of data at this stage to assess any meaningful results.

Geophysics

Geophysical surveys were conducted in Kappawanta and Sheringa A and B lenses. The aim of the surveys were to distinguish different hydrostratigraphic units, map zones of fresh groundwater and delineate basement.

Geochemical Sampling

Water samples were collected from a number of selected wells from 1993 to 1995. The samples were analysed for oxygen-18 ($\delta^{18}O$), deuterium ($\delta^{2}H$), radiocarbon (^{14}C) and major ions. The aim of the program was to obtain information on recharge mechanisms under differing land use, groundwater flow process and potential interconnection between the unconfined and confined aquifers.

GEOHYDROLOGY

Geological Setting

The study area contains crystalline basement gneisses, volcanics and granites of the Gawler Craton. The Gawler Craton has essentially been tectonically stable since 1450 ma. (Parker et al 1985).
A significant feature incised within basement is the Polda Trough which is a narrow east-west intracratonic graben that extends about 200 km off shore from Elliston. The trough contains Permian and Jurassic sediments of sand, clay and lignite.

Overlying the Polda Basin and crystalline basement is a thin veneer of Tertiary and Pleistocene sediments that form the major low salinity aquifers in the region and the focus of this study. Post Tertiary sequences are referred to in geological terms as part of the Eucla Basin. A number of cross sections (Figures 6,7,8 & 9) have been drawn which show the relationship of the various hydrostratigraphic units.

TABLE 1 SUMMARY OF HYDROSTRATIGRAPHY

Age	Unit Lithology	Occurrence	Hydrogeology
Pleistocene	**Bridgewater Formation**: calcareous sands limestone, calcrete at surface, karstic.	Widespread veneer over entire region, increases in thickness towards coast.	**Quaternary Limestone Unconfined Aquifer** generally low salinity, karstic with variable permeability. Contains lithologies of the Bridgewater Formation. Often has semi-confining characteristics. Semi continuous. Thickness 2-10 m.
Tertiary	**Unnamed clay -** red to grey sand gravel in part.	Widespread through region	**Tertiary Confining Bed.** Thin but continuous. Thickness 1-5 m.
Tertiary	**Poelpena Formation**: clayey sand near top grading to fine grained sand, minor carbonaceous and lignite horizons.	Widespread; can form palaeochannel sands.	**Tertiary Sand Aquifer -** salinity varies from fresh to saline. Can be unconfined or confined - porous medium flow. Thickness 5-30 m.
Jurassic	**Polda Formation**: contains carbonaceous clay at top of sequence followed by sand, silts and clays.	Only occurs in Polda Trough.	Confined Aquifer - generally very saline with low permeability's.
Permian	**Coolardie Formation**: predominantly claystone.	Only occurs on eastern margin of Polda Trough.	Only of minor importance.
Pre Cambrian	**Basement**: both weathered and crystalline gneisses, metasediments and granites.	Throughout the region.	**Basement -** contains both weathered and crystalline basement (undifferentiated) weathered basement can contain brackish water with low yields.

Hydrostratigraphic Units

The hydrogeological units were separated on the basis of similar lithological and hydraulic characteristics with the nomenclature being consistent with that used by Smith (1983) and Evans (1993) (Table 1).

Basement

The basement has been defined as Pre-Permian lithology's and consists of metasediments, gneisses, schists and granites. For the purpose of this report, weathered basement and hard crystalline basement have not been differentiated. Groundwater can occur within weathered basement, however the salinity is often very high and yields are low. The crystalline basement is considered to act as hydraulic basement. The structural contour top of basement (Figure 10) were derived from three sources of data. Water wells drilled which have been surveyed for elevation data, mining company data where elevation data has been estimated from topographic maps and geophysical data from the TEM surveys which have surveyed elevation data.

There is a distinct basement high which has its apex in the Hundred of Kappawanta from which basement slopes radially. A depression in the basement occurs towards the north of the Kappawanta High coincident with the Polda trough. Minor ridge and valley topography is also evident towards the south in the Sheringa lenses. The basement deepens rapidly from the southern portion of the Kappawanta High to the Sheringa lenses in the Hundreds of Way and Pearce. A distinct basement ridge occurs along the Way - Pearce Hundred line boundary which partially separates the two Sheringa groundwater lenses. The basement deepens rapidly from the southern portion of the Kappawanta lens to the Sheringa lenses in the hundreds of Way and Pearce.. West of the study area basement crops out near Mt Wedge

Jurassic

The Jurassic sequence occurs in the Polda Trough and consists of sands, silts, carbonaceous clays and lignite. Aquifers within the sequence have low permeability's with high salinities ranging from 30 000-50 000 mg/L. Recent drilling has indicated that thin low salinity Jurassic aquifers maybe present within the Sheringa B lens, although the age has not been confirmed by palynological evidence.

A significant lignite deposit occurs approximately 60 km east of Polda (Eberhard and Waterhouse, 1979). In this area, the hydraulic head is 12 m higher than the overlying Tertiary aquifer indicating a potential for upward leakage. Recharge to this portion of the Jurassic system must therefore occur further to the east. The transmissivity of the sequence is very low (between 0.6 and 45 m^3 day^{-1} $m^{-1)}$ and storage coefficient in the range of 10^{-4} to 10^{-6} indicating confined characteristics.

The aquifer is not considered to have any potential for development due to its low permeability and saline water.

Tertiary Sands Aquifer

The Tertiary sands aquifer contains an interbedded sequence of unconsolidated sands silts and clays. The sequence often is clayey at the top grading to fine sand at the base, where it sits unconformably on weathered or crystalline basement. In certain localities such as the Polda Trough the sequence can increase in thickness and contain a series of interbedded confining beds and aquifers.

The Tertiary sand aquifer is distributed throughout the entire area of investigation and can be either unconfined aquifer or confined. It is confined in those areas where it is overlain either by a saturated confining bed or a saturated Quaternary limestone. The aquifer is unconfined where it is overlain by a clay horizon or an unsaturated confining bed or unsaturated Quaternary Limestone. Cross - Sections A-A^1 to D-D^1 (Figures 6 to

9) illustrates the varying nature of this aquifer. In those areas described as unconfined, there is however some confining (pressure) effect as there is a rise of up to 2 metres between the water cut (defined during drilling) and the final standing water level. The aquifer in these areas is best described as semi - confined. The transmissivity of the aquifer varies from 20 to 270 $m^3 d^{-1} m^{-1}$ while the storage coefficient varies from 1×10^{-3} to 1×10^{-4} indicating compression of the aquifer matrix and water (Dowie and Love 1996). Groundwater velocity in the sand is predicted to vary from 0.2 to 0.8 myr^{-1} on the basis of known hydraulic parameters.

There is only a small head difference (< 1 metre) between the Tertiary Sand aquifer and the overlying Quaternary limestone aquifer. This suggests that there is minimal interaquifer leakage between the two systems under the current day hydraulic regime. Present day recharge to the system must occur where the Tertiary sand aquifer is unconfined.

Tertiary Aquitard

A grey to red clay horizon separates the Bridgewater formation from the underlying Tertiary Sand Aquifer. The clay is sticky to stiff with coarse sand to gravel and can grade to sandy clay at the base. The clay varies in thickness from 1 to 5 metres.

The structural contour plan of the aquitard (Figure 11) has similar features to the structural contour of top of basement and the topographic surface. These are; high zones near Mt Wedge and Kappawanta and trough development in Polda and in the Sheringa region to the south. A three dimensional representation of the top of the Tertiary aquitard is presented in Figure 12 . The plan shows depressions in the aquitard surface which correspond to the fresh water lenses. This may be a useful indicator as to how the shape of the lens may change if we superimposed the water table surface on top of the three dimensional plan.

The clay aquitard was previously interpreted to be discontinuous throughout the region. However, reinterpretation of driller's and geological logs has indicated that the aquitard is almost continuous throughout the entire region. This agrees with the interpretation of Evans in the Polda lens (1993).

Quaternary Limestone Aquifer

The Quaternary Limestone Aquifer contains lithologies of the Bridgewater Formation, consists of calcareous sands, broken shell fragments and limestone. The sequence often has calcrete at the surface and can be indurated to unconsolidated throughout. It forms a thin veneer widespread throughout western Eyre Peninsula but only becomes saturated within the fresh water lenses towards the coast.

The low salinity groundwater lenses occur within the Quaternary Limestone sequence and the directly underlying Tertiary sands As discussed by Smith (1983) the occurrence of low salinity groundwater does not correlate with groundwater basins they should be referred to as **groundwater lenses** as this more accurately describes the morphology of these groundwater systems.

The groundwater lenses are coincident with skeletal soil cover or outcropping Bridgewater Formation and correspond to elevated rainfall zones on the western side of the Peninsula. The potable groundwater lenses are defined by the 1000 mg/l isohaline contour (Fig 1).

Although described elsewhere as an unconfined aquifer it is best referred to as a semi-confined aquifer. This is apparent as there is a rise of up to 2 metres between the water cut and the final standing water level. The confining character is likely to be the result of indurated calcrete horizons which act as thin low permeability horizons. The aquifer has the hydraulic characteristics of a dual porosity medium with both karstic and porous medium flow. Karstic flow occurs through solution enlarged fractures in the indurated limestone while porous medium flow occurs in the unconsolidated sediments. The velocity of groundwater in the aquifer can vary from 2 to 8 myr^{-1}. The transmissivity of the aquifer varies from 800 to 3500 $m^3d^{-1}m^{-1}$ which corresponds to a hydraulic conductivity of between 160 - 700 m day^{-1} for a thickness of 5 metres. The specific yield varies from 3 x 10^{-5} to 6 x 10^{-2} also indicating some confining character (Painter 1972).

GROUNDWATER LEVEL AND SALINITY MONITORING

Piezometric Surface

Groundwater levels have been monitored in the Musgrave Proclaimed wells area since the mid 1960's. The current monthly network monitors 135 wells on a monthly basis. The aim of the monitoring program was to obtain long term trends in groundwater levels as well as establishing a regional piezometric surface. The whole network (up to 600 wells) has been monitored twice a year since 1993, in order to obtain a regional potentiometric surface as well as to map the extent of the quaternary limestone aquifer.

Water table contours are presented for the 1960's (Figure 13 adopted from Painter 1972) and July 1993 (Figure 14). Results represent monitoring data from both the Quaternary limestone aquifer and the Tertiary sand aquifer. Due to the nature of the drilling program in the 1960's, wells were not necessarily completed in individual aquifers. As a result, where the completion was in two aquifers, a composite water level is recorded. However considering the relative small head difference (less than 1 metres) between the two aquifers and the regional nature of the assessment Figures 13 and 14 are considered to give a reasonable representation of the piezometric surface.

Both piezometric surfaces for 1960 and 1993 show similar characteristics. There is mounding of the potentiometric surface coincident with the structural high in Kappawanta. Groundwater moves radially from this apex with the majority of flow towards the west and south west ie towards the sea. There is a slight differences between the two piezeometric surfaces in that the 60 metre contour on the groundwater mound at Kappawanta in 1960's is no longer present in 1993 and the area enclosed by the 50 metre equipotential is reduced in size.

Water Levels Trends

Hydrographs for selected wells are shown in Figures 15, 17 and 18. Well locations are shown on Figure 1. .

The hydrographs show a seasonal variability with peaks corresponding to winter recharge periods and troughs corresponding to lower rainfall periods in summer. There is no correlation to any pumping centres. A number of hydrographs show a similar overall trend to the cumulative deviation from the mean rainfall statistics for Polda for example SQR 8 and WAY 54 (Figure 15). High water tables in 1974-75 and 1983 -84 correspond to high rainfall statistics while low levels of the groundwater lenses in 1978 -79 and 1993 -94 correspond to low cumulative rainfall statistics.

These graphs show there is a strong correlation between cyclic rainfall patterns and trends in groundwater levels. Increases in the cumulative deviation represent years of above average rainfall while conversely decreases represent years of below average rainfall. The method is non-quantitative but is useful for defining rainfall trend and correlates well with piezometric data. From this past water levels in the lenses can be inferred by observing the long term cumulative rainfall statistics for Lake Hamilton and Sheringa. These stations were chosen as they have a near complete long term record (Figure 16). The groundwater lenses most likely had high water levels in the early 1920s and mid 1950s with a minor high in the early 1980s. Groundwater levels were at a low in the mid 1880s early 1900s early 1930s and mid 1960s and early 1990s (nb the trough in the early 1990s is inferred from the Polda rainfall statistics and hydrographs on Figure 15. At the present groundwater levels may be in a new rising cycle since the trough in the early 1990s.

Hydrographs (KPW 18, KPW 34, HUD 27, WAY 15 Figure 17) indicate that there has been a regional decline of the water table of between 1 and 5 metres in the 1980's throughout the study area. A slight recovery of the hydrographs occur between 1990 and 1991 and then a gradual decline since then. The regional decline is independent of land use or pumping stress. The decline does, however correspond to below average rainfall and below average recharge throughout the 1980's. The average yearly rainfall at Polda in the 1970's was 422 mm/a and only 381 mm/a in the 1980's. This demonstrates the stress induced upon these fragile groundwater resources by small but extended periods of below average rainfall. The decline in water levels in a number of observation wells indicates that the groundwater systems are discharging at a greater rate than they are recharging. Discharge from the system may occur via downward leakage or transpiration via vegetation or discharge to Lake Hamilton in the case of the Sheringa lenses.. No attempt has been made to quantify this discharge.

Many of the well hydrographs show that there is a minimum monthly rainfall required to result in a recharge event. A recharge event can be observed by an increase in the well hydrograph. Hydrograph TAA 29 (Figure 18) requires a rainfall event of at least 65 mm to result in a recharge event. This is evident by the 65 mm and 68 mm events in 1980 and 1982 which just raise the water level in the well. Rainfall events below this magnitude do not correspond to increases in groundwater level and storage. Monthly rainfall events greater than 65 mm in 1985 have only a minimal effect on the water table, this is related to the intensity of the rainfall events. KPW 38 (Figure 18) requires a rainfall event at least in excess of 60 mm to cause a rise in the watertable as seen by the event in 1980. However rainfall events in 1985 (60 and 93 mm) did not cause the water level to rise indicating that the intensity of a rainfall event is as important as the amount of the event.

Extent of saturated Quaternary Limestone

The areal extent of the saturated limestone for 1973 and 1994 are shown in Figures 19 and 20 There is a net decrease of 10% in the extent of the saturated limestone from 1973 to 1994. The reason for the reduction in the saturated thickness is interpreted to be due to a reduction in recharge to the system. During this period of time discharge from the system was greater than recharge and the groundwater system was not in hydraulic equilibrium. This does not necessarily equate to a reduction of 10% of the volume of the groundwater resource. The volume reduction is less than this due to thinning of the saturated thickness towards the lens boundaries. The reduction has resulted in a number of the groundwater lenses now being partially discontinuous. For example, Kappawanta is no longer continuous with Bramfield or the Sheringa lenses. Sheringa A and B lenses are known to be separated partially by a basement ridge. The reduction in the extent of the saturated Quaternary Limestone has resulted in a loss of brackish and saline water. The total areal extent of the freshwater lenses has not been reduced, however their has been a reduction in volume do to a reduction in thickness of the aquifer. The reduction to date has occurred in groundwater with a salinity greater than 1000 mg/l.

Salinity monitoring

Groundwater salinity has been monitored since 1990. To date there has been no trends observed in the data. However the monitoring record is considered too short for any long term trends to be detected. The salinity depth profiles (Figures 22, 23, 24, 26) .show that the groundwater systems can be stratified with different zones of salinity. Any large scale extraction from the system should consider this stratification to prevent any upconing of more saline water . One generality that can be observed is that when the quaternary limestone is saturated it usually has a slightly lower salinity than the underlying sand aquifer.

HYDROCHEMISTRY AND ENVIRONMENTAL ISOTOPES

Stable Isotope, radiocarbon and full chemical analysis data are presented in Appendix C. The location of the sampled wells are shown in Figure 1.

Major Ions

Plots of dissolved ions against Chloride (Cl) (Figure 26) reveal positive linear correlations. These reflect concentration or dilution due to variations in the evapotranspiration rate during recharge. The strong correlation of Sodium (Na), Magnesium (Mg) and to a lesser extent Potassium (K) with the sea-water dilution line indicates a marine - aerosol origin. Where sea spray has been transported from the oceanic source deposited via precipitation and concentrated via evapotranspiration with varying residence times in the surface and unsaturated zone. Scatter from the sea-water dilution trend reflects additions or losses to the system due to water/rock interactions.

Stable Isotopes

The stable isotope data for the study area are in the range from -31.3 to - 23.9‰ for δ^2H and - 5.4 to - 3.5‰ for $\delta^{18}O$. Figure 27. The data lie in a continuum between the amount weighted mean of precipitation of Adelaide and Melbourne and plot either on or below the local meteoric water line (LMWL). Those that plot on the line suggest no fractionation during the recharge process while those significantly below the line indicate partial evaporation prior to recharge. As all groundwater are significantly depleted with respect to the stable isotopic composition of sea water (0‰ for δ^2H and $\delta^{18}O$) no connate water is entrapped within the sequence. This applies for all groundwaters even with a salinity in excess of 30 00 mgl^{-1}.

Radiocarbon and $\delta^{13}C$

Radiocarbon (^{14}C) and stable carbon 13 ($\delta^{13}C$) were analysed to determine the relative degree of mixing between the two aquifers as well as zones of preferred recharge to the system. In essence the higher the activity of radiocarbon (in percent modern carbon PMC) then the shorter the time period elapsed since the ^{14}C water was isolated from the atmosphere. Therefore those waters with a high radiocarbon activity indicate zones of preferred recharge.

^{14}C is a radioactive isotope of carbon with a half life of 5570 years, and in ideal situations it can be used to date groundwater up to 30 000 years old. ^{14}C is continuously produced in the atmosphere by cosmic ray bombardment of ^{14}N. The amount of radiocarbon in the atmosphere was substantially increased in the 1950's and 60's due to nuclear weapons testing. Once ^{14}C reaches the groundwater it can be affected by radioactive decay or mixing with different groundwater bodies.

Providing that the initial radiocarbon activity can be determined and that no other process other than radioactive decay is occurring then the ^{14}C residence time (the time period elapsed since the ^{14}C containing water was isolated from the atmosphere) can be determined. If we assume that carbon travels at the same speed of water then indirect water ages can be determined from the ^{14}C residence time.

The radiocarbon data for the entire study varies from 6 to 106 PMC while the corresponding $\delta^{13}C$ data varies from - 10‰ to - 14‰. If the following reaction is considered:

$$H_2O + CO_2 + CaCO_3 \leftrightarrow 2HCO_3 + Ca^{++}$$

and it is assumed that the soil CO_2 to have a $\delta^{13}C$ of - 22 to - 18‰ the resultant $\delta^{13}C$ of the bicarbonate should be in the range of - 9‰ to - 11‰ with a corresponding ^{14}C from the bicarbonate of around 50 PMC. However, many groundwaters have a PMC >60. The data suggests an open system model with the atmosphere where there is an isotopic fractionation of +8‰ between gaseous CO_2 and dissolved bicarbonate. This agrees with to the observed $\delta^{13}C$ and ^{14}C data. Groundwaters are saturated with respect to the major carbonate minerals indicating no dissolution in the phreatic zone. The above suggests that no correction is required to estimating the mean `carbon' age based on chemical data alone.

Following nuclear testing in the early 1960s there was a rapid increase of radiocarbon activity in the atmosphere to in excess of 120 PMC for the southern hemisphere. Data from the Murray Mallee (Leaney and Allison 1986) measured initial ^{14}C in CO_2 from the unsaturated zone between 85 and 95 PMC. If similar values are assumed in this study, groundwaters with an ^{14}C activity >90 PMC can be considered to be post `bomb' and recharged entirely within the last 30 years. The low, <10 PMC groundwaters occur in the confined sand aquifer to the south of the study area near Sheringa where rapid groundwater through flow is restricted by basement highs. In these zones the groundwater residence times can be on excess of 18 000 years.

Transect A-A[1]

Transect A-A[1] (Figures 1 and 28) runs approximately at right angles to the piezometric surface from the east of the Kappawanta lens to Bramfield lens in the west. The two major land-use zones are either cleared or mallee vegetation. The cleared sites tend to correspond to thin skeletal soil or outcropping Bridgewater Formation while the Mallee sites are covered by a thin red/brown soil overlying Bridgewater Formation.

The high PMC valves recorded along transect A-A[1] suggests relatively high recharge throughout the section for both the Quaternary Limestone aquifer or the unconfined sand aquifer. The high radiocarbon valves in combination with $\delta^{13}C$ that have not been significantly enriched suggests rapid recharge to the groundwater system with a relatively short residence time in the unsaturated zone. The lateral variability in radiocarbon data from one well to the next indicates differential amount of local recharge to the system and not recharge from distal lateral sources.

A puzzling feature of the data is that high ^{14}C activities are recorded in the unconfined sequence throughout the transect. This indicates that recharge is independent of landuse whether this be under cleared or mallee sites. As the mallee does not utilise all water in the unsaturated zone there must be some form of macro pore extension from the surface to the water table. However this is in contradiction to the relatively high chlorides below the Mallee sites suggesting low recharge. An explanation to this may be that the radiocarbon data under the Mallee may be an artefact introduced by the deep seated Mallee roots pumping in modern atmospheric CO_2 with an enriched radiocarbon signature.

The chloride ion is a good tracer in groundwater environments due to its conservative properties. As Cl is not effected by any geochemical processes in the system then changes in the Cl concentration must reflect physical changes. These may be as a result of mixing of different water bodies (with different Cl concentrations) or changes in the evapotranspiration rate during recharge. The large lateral variability in Cl concentrations indicates local recharge dominates the water budget and that lateral through flow is minimal. Where the variations in Cl from adjacent wells are a result of mixing different input concentrations of the recharge water due to variations in evapotranspiration.

ASSESSMENT OF GROUNDWATER RESOURCES

Previous assessment of the groundwater resources by Painter 1972, calculated lens yield using Darcian flow techniques and rainfall data. Painter adopted 10 % of winter rainfall as the lens yield for the Quaternary Limestone aquifer and 5 % of the of winter rainfall was considered to be the lens yield for the sand aquifer on this basis. Painter calculated the safe yield for the Quaternary Limestone aquifer to be 15 700 ML/annum and 3700 ML/annum for the Tertiary sand (Table 2). A review of Painters assessment in 1983 (EWS 1983) downgraded the resource to 11 000 ML/annum for the Quaternary

Limestone and 850 ML/annum for the Tertiary sand.

In essence the previous estimates of the safe yield are estimates of the annual recharge to each lens. In this report we have estimated annual recharge by Darcian flow techniques, well hydrographs and the chloride mass balance technique (see Appendix B for details). These techniques have a number of limitations and the lens yields presented here should be considered to be a first order estimate. Future work underway will more accurately determine recharge rates.

There is some uncertainty about the reliability of each method. The well hydrograph method uses annual fluctuations in the well hydrograph to obtain an estimate. The method assumes that the groundwater system "integrates" all recharge events and variation in the hydrograph reflects changes in storage. This method often gives reliable results in shallow unconfined groundwater systems. However due to the semi-confining character of the Quaternary Limestone a rise in the hydrograph represents a change in pressure response (ie release of elastic storage) as well the addition of water. Therefore this method often over estimates the actual recharge value.

The chloride mass balance method calculates recharge from the chloride concentration in both groundwater and precipitation plus the annual precipitation. This method assumes that the chloride is derived from a marine aerosol component and that chloride is not added to the system by dissolution of minerals within the aquifer matrix. However nearby salt lakes in the region within 10-20 kilometres of recharge zones may result in a variation of the net chloride accumulation rate. Also there is a potential for the chloride flux to vary through time. As well chloride has only been measured at one location, Polda, and the spatial distribution throughout the area has not been established. Work underway is measuring chloride at a number of stations in County Musgrave to establish a regional distribution of chloride in rainfall.

The calculation of lens yield using Darcys Law is more suited to groundwater basin analysis and not groundwater lenses. Darcian techniques also have some uncertainty due to the irregular shape of the lenses and radial flow from the groundwater mound at Kappawanta. For example the technique could not determine the annual yield for Sheringa A and Sheringa B due to the shape of these lenses.

The chloride mass balance method gave the most consistent results for estimating lens yield. The Darcy technique where it could be used (Kappawanta and Bramfield) gave results that agreed well with the chloride mass balance technique Table 2. It is recommended that if groundwater resources are to be utilised that the adopted maximum permissible volume be 40% of the yield estimated by the chloride method. This is recommended as an interim measure until a more precise estimation of the minimum recharge value is determined.

As discussed previously groundwater levels in most of the region have declined in the order of between 1 and 5 metres throughout the last 20 years even in areas where there has been no groundwater extraction. This indicates a decline in aquifer storage over this time interval. If we consider the "safe" or "sustainable" yield to be the amount of water that can be withdrawn from the lenses without any long term deleterious effect on the aquifer, then clearly the concept of "sustainable " yield in this type of environment is not applicable.

Because groundwater recharge is controlled by rainfall, years of above average rainfall will result in increased groundwater levels and storage while conversely years of below average rainfall will result in declining groundwater levels and storage. The groundwater systems in the region is currently in **overdraft** where the annual loss from the system is greater than the natural replenishment.

As the groundwater systems are driven by variations in rainfall the size of the groundwater lenses will vary with climatic cycles. The frequency of these cycles is unknown and cannot be predicted with any certainty. Therefore any future use of the resource should consider social/economic factors as well as the risk associated with further overdraft of the resource. The resultant estimates of yield from the groundwater lenses are shown on Table 2. These estimates should only be considered as a interim measure until new risk management policies are developed.

CONCLUSIONS

Local recharge (flow systems) dominate the water budget with minimal lateral throughflow. The majority of groundwater within the potable lenses was recharged within the last 30 years

Groundwater systems are driven by local recharge, however they are currently under stress due to below average rainfall in the last 20 years.

The groundwater systems are not in equilibrium with discharge> recharge

Hydrograph data indicates that there needs to be a monthly rainfall in excess of at least 60 mm to result in a recharge event.

Groundwater is currently in overdraft Management of the resource will need to consider appropriate risk management practices in the future such as moving maximum permissible volumes

RECOMMENDATIONS

Because of the dynamic change in area and volume of these groundwater lenses due to variations in recharge, the magnitude of recharge needs to be determined accurately for future management of the groundwater resources.

Additional work currently in progress will attempt to estimate recharge by measuring chlorofluorocarbons (CFCs) in the groundwater system. CFCs are soluble in water and their concentrations have steadily increased in the atmosphere since the 1940's due to their use in air conditioners, refrigerators and aerosol propellants.

Other work currently underway is measuring chloride in rainfall and in groundwater throughout County Musgrave to obtain a better estimate of the spatial variation of recharge across the landscape

A number of data loggers and rainfall gauges have recently been established in the region. This will provide information on the dominant recharge mechanism and the amount and more importantly the intensity of precipitation required for a recharge event to occur.

Review and upgrading/ rationalisation of the monitoring network is required

TABLE 2 ESTIMATION OF GROUNDWATER YIELD

Lens name	Area km^2	Darcys Yield ML/year	Chloride Yield ML/ year	Maximum permissible volume* ML/year
Polda*	62	*	*	*
Kappawanta	62	2040	1980	800
Sheringa A	43	n/a	1230	500
Sheringa B	62	n/a	1730	700
Bramfield	147	4000	4500	1800
Talia	55	1520	n/a	600

Table 2 County Musgrave groundwater assessment (n/a method not applicable for this lens) For more details on assessment refer to Appendix B based on 40 % of the annual yield. Nb Polda* yield was calculated by Evans 1994 to be between 1350 -2000 ML/year.

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APPENDIX A

Glossary of Technical Terms

Aquifer: A formation, in the saturated zone which is sufficiently permeable to yield significant quantities of water to wells and springs.

Confined Aquifer: An aquifer in which the pressure is significantly greater than atmospheric and is bounded above and below by a confining bed. When a confined aquifer is intersected by a well the pressure is sufficient to cause the water to rise significantly above the supper level of the aquifer. When the pressure is sufficient to cause the water to flow at the surface it is known as artesian.

Confining Bed: A bed of low permeability occurring above and below a confined aquifer and below an unconfined aquifer or perched groundwater.

Hydraulic Conductivity: The rate at which water can move through the interstices of the sediment or rock. It is measured as the flow per unit cross sectional area under unit hydraulic gradient. The units are m^3day/m^2 commonly expressed as m/day.

Hydraulic gradient: Expressed as a ratio or percentage, the hydraulic gradient is the change in static head per unit of distance. Unless specified the distance is in the direction of maximum change in static head.

Recharge: the movement of water from the ground surface through the interstices of the unsaturated zone to the water table.

Permeability: A measure of the ease with which an aquifer can transmit water under a potential gradient. It is a property of the aquifer only and is dependent on the size and shape of the pores but is independent of the nature of the fluid.

Porosity: The ratio, usually expressed as a percentage. of the volume of interstices or voids to the total volume of a sediment or rock forming the aquifer.

Potentiometric Surface: A surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

Safe Yield: The maximum rate at which groundwater can be withdrawn from an aquifer without causing depletion, salinity increase or excessive pumping costs.

Saturated Zone: That part of an unconfined aquifer in which all interstices or voids are filled with water at a pressure greater than atmospheric.

Specific Yield: The ratio of (1) the volume of water which there rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

Static head or Static Level: The height to which water rises in a well which is not being pumped. It is a measure of the head or pressure in that part of a aquifer open to a well at a specified time.

Transmissivity The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is the product of the hydraulic conductivity and the saturated thickness of the aquifer and is expressed in m^3day/m.

Unconfined Aquifer: An aquifer in which the water level does not rise significantly above the level that it is intersected in a well.

Water Table: The surface of water in a well entering an unconfined aquifer. The water table is at the top of the saturated zone where the pressure is atmospheric.

APPENDIX B

Groundwater Assessment

The results for the groundwater assessments are shown in Table B3. The size of the individual lenses was mapped by using salinity and water level monitoring data. The salinity data was taken form the time of drilling, this is a reasonable assumption as salinity monitoring data within the last 5 years has shown that there has been no detectable change. The entire groundwater water level monitoring network (600 wells) was monitored to enable an accurate calculation of the lens sizes. The Bramfield lens has increased in size from 55 km^2 (1970 assessment) to 147 km^2 this assessment. While the actual size of the lens has not increased this reinterpretation of the data suggest more water storage than previously estimated. Part of this new interpretation is that the extent of the western boundary (under Bramfield hill) has been included in this study.

The groundwater assessment for each lens was determined by multiplying the annual recharge by the area of the groundwater lens. The area of the groundwater lens was calculated from salinity data and from the annual monitoring data.

Recharge to the Kappawanta, Bramfield and Sheringa lenses were calculated using the following three methods:

1. **Comparison of change in groundwater level from bore hydrographs.**
2. **Chloride Method**
3. **Darcy's Law Method**

1. Comparison of change in groundwater level from bore hydrographs

$$R = \Delta GWL \times Sy \times A$$

where

R = average annual recharge
ΔGWL = average annual change in groundwater level in hydrograph
Sy = specific yield of aquifer
A = area of recharge

The change in groundwater level (ΔGWL) was determined from well hydrographs by taking the annual change in groundwater level from peak to peak of the hydrograph. The specific yield was assumed to be equal to the effective porosity with values ranging from 0.15 to 0.3. The results of this method do not take into account changes water level due to compression of water or aquifer matrix. Thus the values represent the maximum amount of water potentially available for groundwater recharge. The actual groundwater recharge will be less than this value. The results from this method are considered not to be reliable due to the semi-confining characteristics of the limestone aquifer and therefore do not measure the volume of water added.

2. Chloride mass balance Method

Recharge can be calculated using a mass balance approach between the chloride in groundwater and rainwater, and precipitation in the following way.

$$R = \frac{P \times Clp}{Clg}$$

R = Recharge   Clp = Cl in precipitation
P = Precipitation   Clg = Cl in groundwater

The chloride in groundwater at each bore was measured at the time of drilling. The precipitation values are taken from the nearest weather station data. Chloride in rainwater was estimated from the Hutton and Leslie method normalised to data available from Polda lens where the chloride was measured to be 10 mgl^{-1} in rainfall

A range of recharge values were calculated, for each observation well as well as the average for each potable lenses. For a complete analysis the mean distribution of chloride across the landscape at a number of different stations would need to be determined. Future work will include measuring chloride fallout at a number of stations with varying distances from coast.

Lens	**Kappawanta**	**Bramfield**	**Sheringa A**	**Sheringa B**
Range (mm/a)	20-49	15 -78	30 - 59	16 - 88
Average (mm/a)	31	31	36	28

Table B 1. Results from the chloride mass balance approach to estimate recharge. The table shows the variation in recharge values for each individual lens and the arithmetic mean for each lens. The mean was used in the groundwater assessment determinations.

Observation number	**Lens**	**Bore hydrograph mm/yr**	**Cl method mm/yr**
KPW 38	Kappawanta	92	40.6
KPW 55	Kappawanta	85	37.4
WAY 15	Sheringa A	135	24.2
PER 15	Sheringa B	146	22.1
PER 1	Sheringa B	130	74.7
WAY 10	Sheringa A	102	
HUD 5	Bramfield	112	56.7
TAA 20	Bramfield	131	32.4
WAD 20	Bramfield	151	50.3
WAD 11	Bramfield	130	34.0
WAY 54	Sheringa A	139	38.9

Table B2. Example of individual bore recharge analysis using the bore hydrograph method and the chloride mass balance approach.

3. Darcy's Law Method

Recharge to a defined area may be calculated if the inflow and outflow to the area are known:

Recharge = Outflow - Inflow

The inflow and outflow of groundwater through the defined area can be calculated using Darcys Law

$$Q = WiT$$

where

Q = rate of groundwater flow m^3/day

W = width of flow path (m)

i = hydraulic gradient

T = transmissivity (m^2/day)

Pump tests in the 1960's provided transmissivity data for the various regions (Painter 1972). The width and hydraulic gradient can be measured. This method was unsuitable for the Sheringa lenses and parts of the Kappawanta and Bramfield lenses due to complicated aquifer boundaries and an undulating potentiometric surface. Due to the irregular shape of the groundwater lenses the lenses were divided into a number of segments to complete the Darcian analysis.

Results from Darcian analysis was only possible for the Kappawanta and Bramfield lens due to the irregular shape of the other lens, and are presented in the main body of the text and the table at the end of the appendix.

Summary

An estimated range of recharge, calculated from the chloride method, are provided in table B3. The values obtained from the Darcy method all fall in close proximity of this working range. All the values provided by the well hydrograph method are above this range of values, as this is only an indication of potential recharge and neglects soil moisture changes, surface runoff and surface storage parameters.

PREVIOUS STUDIES				PRESENT STUDY		
LENS NAME	**AREA KM^2**	**LENS YIELD**		**AREA KM^2**	**LENS YIELD ML/YEAR**	
		1970	**1985**		**CHLORIDE**	**DARCY**
POLDA	75	2700	3250			
KAPPAWANTA	47	3100	2250	62	1980	2040
SHERINGA A	41	3600	1400	43	1230	n/a
SHERINGA B	80	1800	1800	62	1730	n/a
BRAMFIELD	55	3600	1400	147	4500	4000
TALIA	23	890	890	55	n/a	1520

Table B3 - Summary of groundwater assessment from previous studies and this study.

APPENDIX C CHEMICAL AND ENVIRONMENTAL ISOTOPE ANALYSIS

The observation number refers to the well number sampled (Figure 1). Field Conductivity is in μS/cm. Major ions are expressed in mg/l. Total dissolved ions (TDS) was determined by summation of the major ions.$\delta^{2}H$ and $\delta^{18}O$ are expressed in per mil (‰) relative to V-SMOW. ^{13}C are expressed in per mil (‰) relative to standard PDB. ^{14}C is expressed n percent modern carbon.

APPENDIX C
Environmental Isotopes and Chemical Data

Obs No. nd	Aquifer Cond EC	Field pH	Temp	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Si	F	Br	TDS	H-2	0-18	C-13	C-14	
BLS 47	U	1944	7.04	21.9	117	48	274	11.3	548.5	45.7	398	0.5	61		1.1	1505	-28.3	-5.07	-13.4	85.7
KPW 69	C	1315	8.39	24.9	31.3	19.8	304	10.5	489.8	251	135		16.6		0.95	1259	-27.2	-4.9		
KPW 68	U	925	7.36	22	84.1	29	93.4	4	317.8	27.8	132	18.9	16.6		0.44	724	-31.3	-5.02	-12.2	71.4
KPW 72	C	1841	7.82	22	41.7	29.4	339	8.9	473.6	117	334	0.6	20		1.93	1366	-26.6	-4.96	-11.8	37
KPW 38	U	828	7.5	22	73.1	23.8	79.9	3.8	260.3	21	118	22.5	17.5		0.39	620	-28.5	-4.8	-11.5	60.9
KPW 34	U	530	7.63	21.6	83 7	31	1.9	9.3	8.5	193	19	9.7	0.25	0.09	365	-30.3	-5.42	-12.7	73.6	
HUD 41	U	2020	6.92	21.8	152	57	227	8.3	419	32	525	0.5	17	0.42	1.2	1439	-30.2	-4.97	-13.6	81.5
HUD 59	C	1457	7.55	24.2	167	23	111	4.4	401.4	22	288	0	13	0.33	0.59	1044	-29.7	-5.3	-13.9	88.7
TAA 2	C	1060	7.37	18.2	123	16.6	89	2.6	313	17	177	13	13	0.43	0.35	779	-28.1	-4.9	-13.8	83.9
WAD 11	U	1070	7.66	22.6	77.9	21.7	134	4.1	240	39.7	191	45.8	9.7		0.95	765	-25.7	-4.19	-11.3	73.1
TAA 60	C	2070	7.15	21.6	93.8	41.6	317	8.8	386.2	130	467	1.1	15.5		1.28	1445	-27.6	-4.73	-13	42.8
TAA 61	U	2070	7.15	21.6	80.4	13.9	77.3	2.1	213.9	46.5	129	13.6	6.6		1.014	585	-25.2	-4.33	-12.6	
WAD 30	U	923	7.67	20.3	85.8	17	92.3	3.4	249	23.2	149	15.9	8		0.48	644	-27.4	-4.77	-13.4	76.4
WAD 31	C	859	8	20.6	73.7	14.1	98.7	3.9	212.9	24.1	162	9	9.5		0.51	608	-27.6	-4.94	-13	71.5
BLS 39		49700	6.83	21.7	810	1452	11000	222	833.9	2972	19654	76	60		54	37058	-26.6	-4.23	-12.7	105.9
SQR 96	C	14770	4.62	22.4	90 230	3382	95	40.7	366	6112	26	27	0.25	6.8	10460	-26.1	-3.47		25.4	
PER 5	U	1064	7.38		65 21	147	4	229	17	215	38	12	0.51	0.23	749	-26	-4.7	-11.8	55	
PER 30		1263	7.51	21.5	68 26	171	4.6	180.9	49	287	38	11	0.51	0.53	837	-27.2	-4.5	-10.2	50.1	
SQR 2	U	1600	7.42	22	57 46	236	13	315	73	365	30	28	5.5	0.65	1177	-24.6	-4.4	-10.7	60	
WAY 54		1380	7.7	20.9	89 31	179	5.4	265.7	40	321	36	15	0.48	0.57	977	-25.8	-4.56	-11.4	64.1	
PER 1		819	7.46	21.5	102	16.6	68	2.2	187	88	113	31	11	0.42	0.22	624	-28.4	-4.7	-10.4	
PER 15		1583	7.7	20.9	78 31	219	5.8	183.6	66	409		10	0.49	0.73	1036	-27.5	-4.63	-10.6		
PER 41	I	12980	7.03		181	272	2605	50	315.9	145	5008		27	0.75	14	8661	-29.3	4.77	-11.8	10
PER 42	D	17110	6.63		194	422	3473	67	301.5	1120	6408		41	0.84	12	12040	-28.4	-5.19	-11.1	6.3
PER 39	T	8300	6.92		101	157	1636	39	297.8	374	2856	53	44	0.5	4.2	5612	-28	-4.53		17.6
PER 40	S	2830	7.19		116	66	444	9.6	329.6	228	800		18	0.5	2.4	2015	-26.5	-4.24	-11.6	52
29161		1503	6.88	21.4	117	42	166	4.4	461.7	50	265	32	23	0.48	0.37	1162	-31.2	-5.53	-12	59.7
KPW 78		752	7.33	21.6	79 15	68	2.2	220.1	17	116	26	13	0.5	0.02	571	-28.3	-5.01	-12.7	59	
PER 44	D	1890	8.23		81 45	265	12	245	62	512	5.6	15	1	1.1	1245	-28.6	-4.75	-11.3	48.5	
KPW 80	U	840	7.81		74 23	86	5.4	252.5	28	139	11	28	0.55	0.31	648	-29.2	-4.78	-13.9		
KPW 79		671	7.33		71 14.4	62	2.6	216.2	15	89	22	13	5.8	0.18	511	-31.2	-5.53	-12	59.7	

Obs No. nd	Aquifer Cond EC	Field pH	Temp	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Si	F	Br	TDS	H-2	0-18	C-13	C-14	
KPW 77		707	7.38		71 15	63	2.7	224.3	15	96	22	13	0.49	0.19	523	-30.9	-4.55	-12.7	68.9	
KPW 74	Q	880			71 26	87	3.6	256.1	20	150	17	17	0.565	0.31	655	-28.1	-5.2	-10.9	55.8	
KPW 75	T	1083	8.03		85 39	108	6.9	372.8	18	182	3.6	24	0.6	0.37	862	-26.2	-4.01	-12.9	60.5	
KPW 76	T	982	7.32		103	27	87	3.5	312.8	17	169	11	32	0.45	0.29	767	-23.9	-4.58	-13.3	78.3
PER 43	Q	1610	7.5		81 31	223	5.7	180.5	67	429	32	10	0.47	0.84	1061	-28.6	-4.75	-10.9	61.7	
HUD 55		1630	8.07		95.8	31.1	182	6.5	401	13.6	281		7.9		1	1020	-28.3	-5.1	-12.9	58.5
PEA 2		809	8.23		41.8	25.7	77.9	7.6	229	6.5	118		31.4		0.592	538.5	-25.9	-4.52	-10.4	52
HUD 24		4090	8.07		1.68	103	523	25.3	524	33.36	999		22.5		3.46	2235	-28	-4.71	-12.6	70.6
BLS 20		3560	8.1		71.2	78.5	569	25.4	436		32.6	864	20.1			3.2 2100	-29.1	-4.87	-12.5	81.9

APPENDIX D

GEOPHYSICAL SURVEYS

Overview

Previous studies over the Polda Lens, combined with knowledge of the electrical properties of the rocks, showed that Transient Electromagnetic (TEM) surveys could contribute to the understanding of groundwater processes. In particular, basement and clays show specific, though not unique, signatures; and indications of the presence and salinity of groundwater can be seen.

The equipment used for this survey was the Geonics Protem system, which has characteristics to allow analysis of near surface (the top 20 metres) resistivities. Readings were taken at 50 metre intervals using a 50 metre transmitter loop, and the data inverted using a MESA in-house one-dimensional package, GRENOCC. This resulted in resistivity-depth sections along each survey line which could then be correlated with drilling results and conclusions drawn on the distribution of water and rock types between the bores.

The resistivity-depth sections resulting from these surveys are probably the simplest distribution of resistivity that could result in the measured data. Such inversions are not unique, however, and the veracity of these interpretations must be checked by drilling before reliance can be placed on the results. Likewise the correlation between the resistivities and geology is not unique, so other evidence, such as drilling, is required before the geological cause of the geophysical parameter can be positively identified.

The section in Figure 1 is presented as an example only. The resistivity zones indicated are interpreted from the TEM data, the boundaries being somewhat arbitrary. The highest resistivities (Zone 1) probably indicated low porosity crystalline rocks such as unweathered basement, while zone 2 may be weathered basement. Zone 3 is intermediate resistivity and could indicate relatively dry porous rock above the water table or low permeability rocks below. Both zones 3 and 4 could indicate low salinity groundwater in porous rocks. The resistivities in zone 5 are too low for anything but saline groundwater, either in a porous rock or in clays.

This section shows favourable conditions for good quality water over the western two-thirds, with care being needed to control the saline wedge at the west end. At the east end groundwater is only likely in fractures in the crystalline basement.

The detailed analysis of the geophysical data will be presented in a separate report. The plans shown here are a summary of results.

Figure 2 gives a general impression of Musgrave County basement contours. It is to be expected that these features, such as the basement high over Kappawanta, will control groundwater flow to some extent. this, however, depends on the thickness and nature of the overlying sediments. Prominent basement lows are evident in all lens areas.

Kappawanta Lens

Figures 3 show gross basement features. It is clear that the basement surface is quite rugged, but since there is always a cover of at least 20 metres of overburden or weathered rock the basement contours may not have much effect on groundwater in the Quaternary and Tertiary aquifers particularly in the unconfined upper aquifer. Basement aquifers are, however, more accessible.

Areas where fresh bedrock is more than 50 metres below surface are generally quite conductive just above basement, indicating clays or fairly saline groundwater. The top 20 metres are still in a resistivity range which correlates which salinities below 2 000 mg/l TDS, however. Areas where resistivities indicate that saline groundwater may come close to within 20 metres of surface are outlined. Extraction of groundwater in these areas could result in problems of saline contamination through doming?

The basement resistivities are quite variable, and could be useful in mapping rock types and fracture zones.

Sheringa `A' Lens

The major features are, again, basement topography and the presence of saline groundwater, as shown in Figures 2 and 54. In this case the central basement high probably does extend above the water table, and therefore will be a controlling influence on groundwater flow in all aquifers. the basement high drops away very steeply to the east and quite gently to the west and south. To the north there is a step at the point where saline water is expected, but basement may still be within 30 metres of surface.

A saline wedge occurs to the south and west of this area, essentially towards the coast. While this generally at least 20 metres below surface the water level may also be this deep, so some interference may be evident. The dangers of saline incursion with extraction of water also exists.

On the east side basement drops away very steeply and there are indications of saline groundwater within 10 metres of surface and 5 metres of the water table. Bore WAY-12 yielded good quality water in the Quaternary aquifer at 6 metres depth, so it seems likely that the higher conductivities are form the underlying clays and saline water in the Tertiary sands.

To the north basement remains fairly shallow, within 30 metres of surface, but there are indications of a saline layer above this. It has similar characteristics to an upper conductive band to the east, and probably indicates conductive clays rather than free saline groundwater. Low salinity groundwater could be present above the clays.

In summary, there is a basement high in the centre of this area over which groundwater is expected to be absent or sporadic at best, other than in basement fractures. To the east and north conductive clays underlie a possible Quaternary groundwater resource, underlain by saline saturated Tertiary sediments to the east and by basement on to the north. To the west and south both Quaternary and Tertiary aquifers are expected to contain low salinity groundwater except near the coast and in the extreme west, where a saline wedge intrudes the Tertiary aquifer and may enter the Quaternary as well.

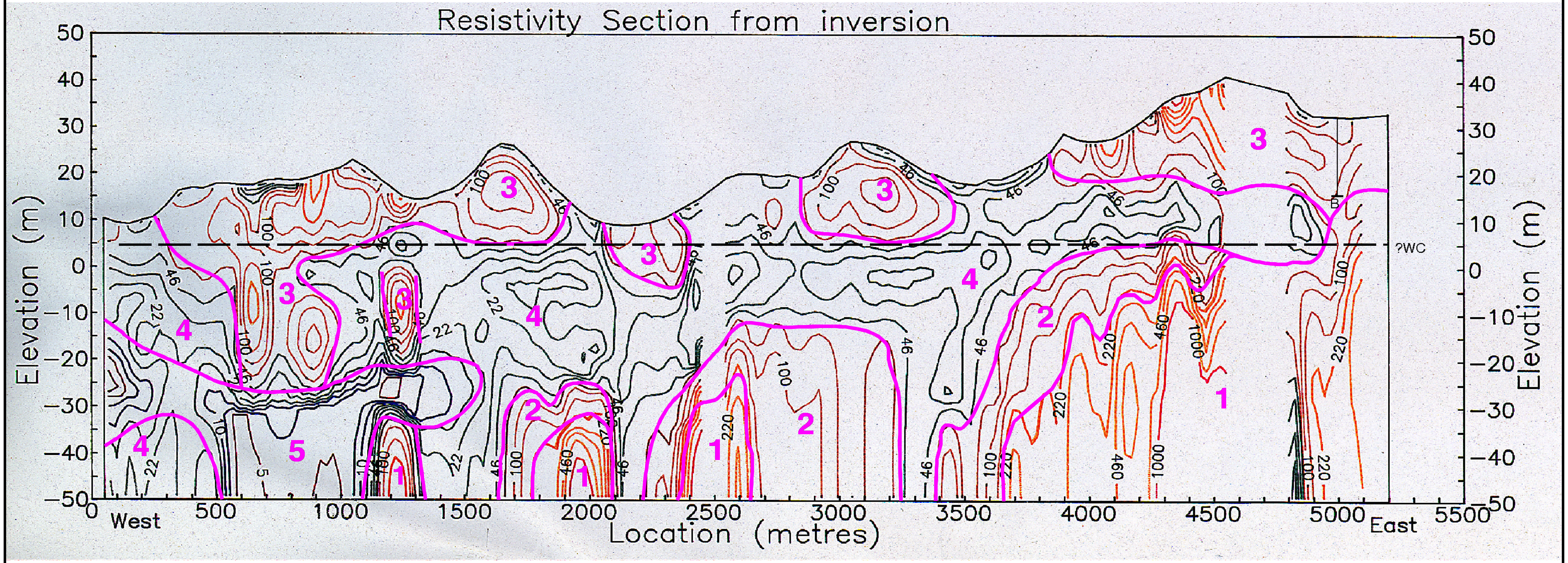
Sheringa `B' Lens

Figure 5 shows the general features of this area. Along the western edge (Line 1) shallow basement verges on topographically higher ground. Impervious basement reaches the water table at about 10 metres AHD in places and may well interrupt the movement of water in both Quaternary and Tertiary aquifers. Basement is also shallow to the east, on Line 2, but only reaches to about 20 metres below the water table in this area. It should not affect groundwater flow. Between these two basement is deep and saline groundwaters are indicated by low resistivities along all of Line 3 and most of Line 4 and the south end of Line 3, where shallowing basement may contain it.

Low salinity groundwater is likely over shallow basement is sufficiently deep. It may be saline at the north end of Line 1. A thin layer (2-10 metres) of fresh water may also be present overlying the saline groundwater underLines 3 and 4. Over the westmost 2 000 metres of Line 4 lower salinities may prevail at a depth of 40-50 metres, possibly under conductive clays.

Summary

In summary the geophysical surveys have been useful in defining the configuration of the basement add more detail



1 Unfractured crystalline basement

2 Fractured or weathered basement

3 Dry material, or containing low salinity groundwater

4 Moist material, groundwater salinity moderate (1000 - 5000mg/L TDS)

5 Clays or saline groundwater (>5000mg/L TDS)

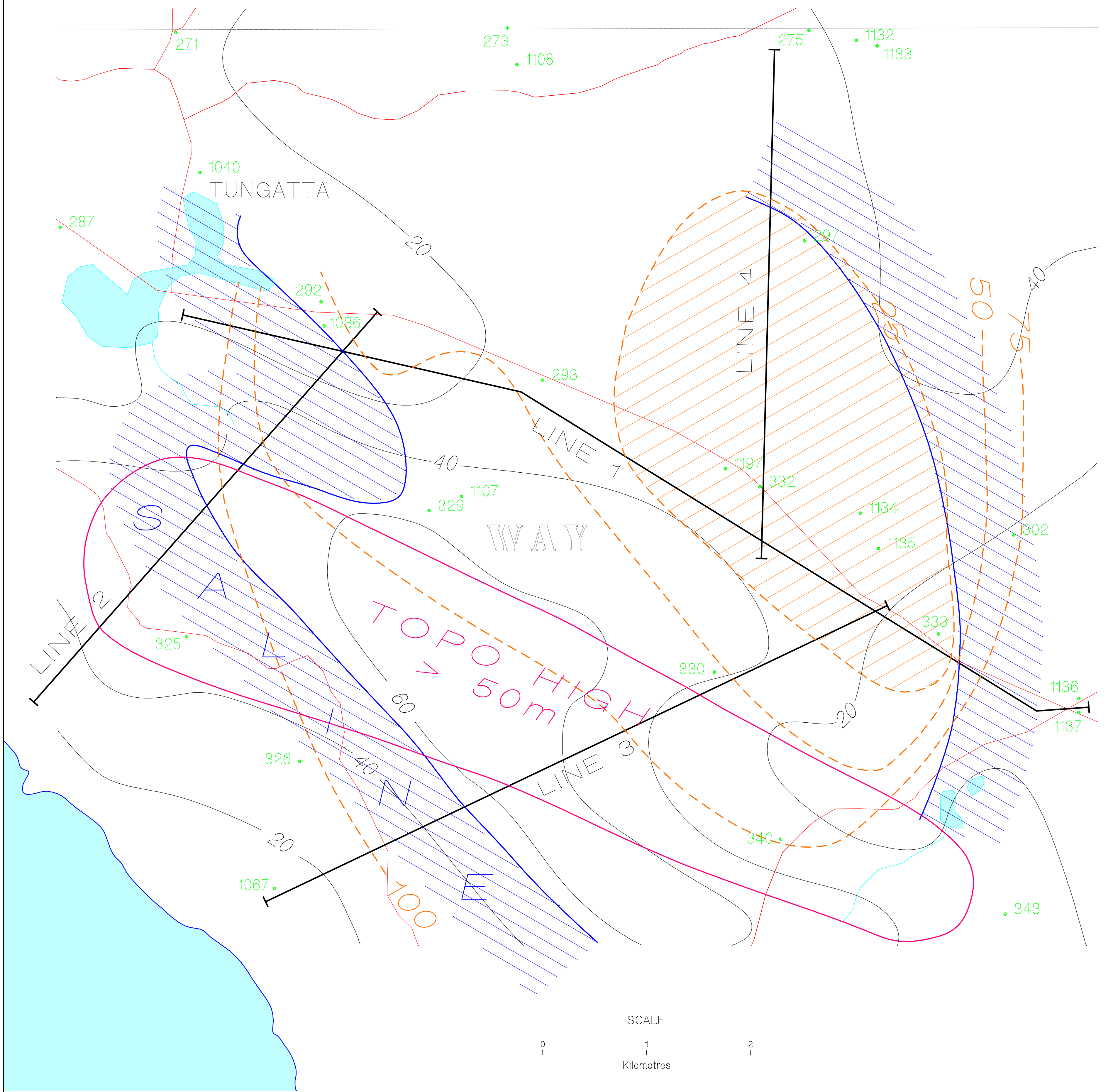
Appendix........D1

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SHERINGA A PROTEM SURVEY TRAVERSE

96-0976 MESA

5900AL.CDR



LEGEND

(orange hatching)	Shallow basement	-40-	Depth to basement (metres)
(blue hatching)	Saline groundwater probably in the Tertiary aquifer	20	Surface elevation (mAHD)
		LINE 1	TEM survey lines
		489	Well with unit number

Appendix.......D2

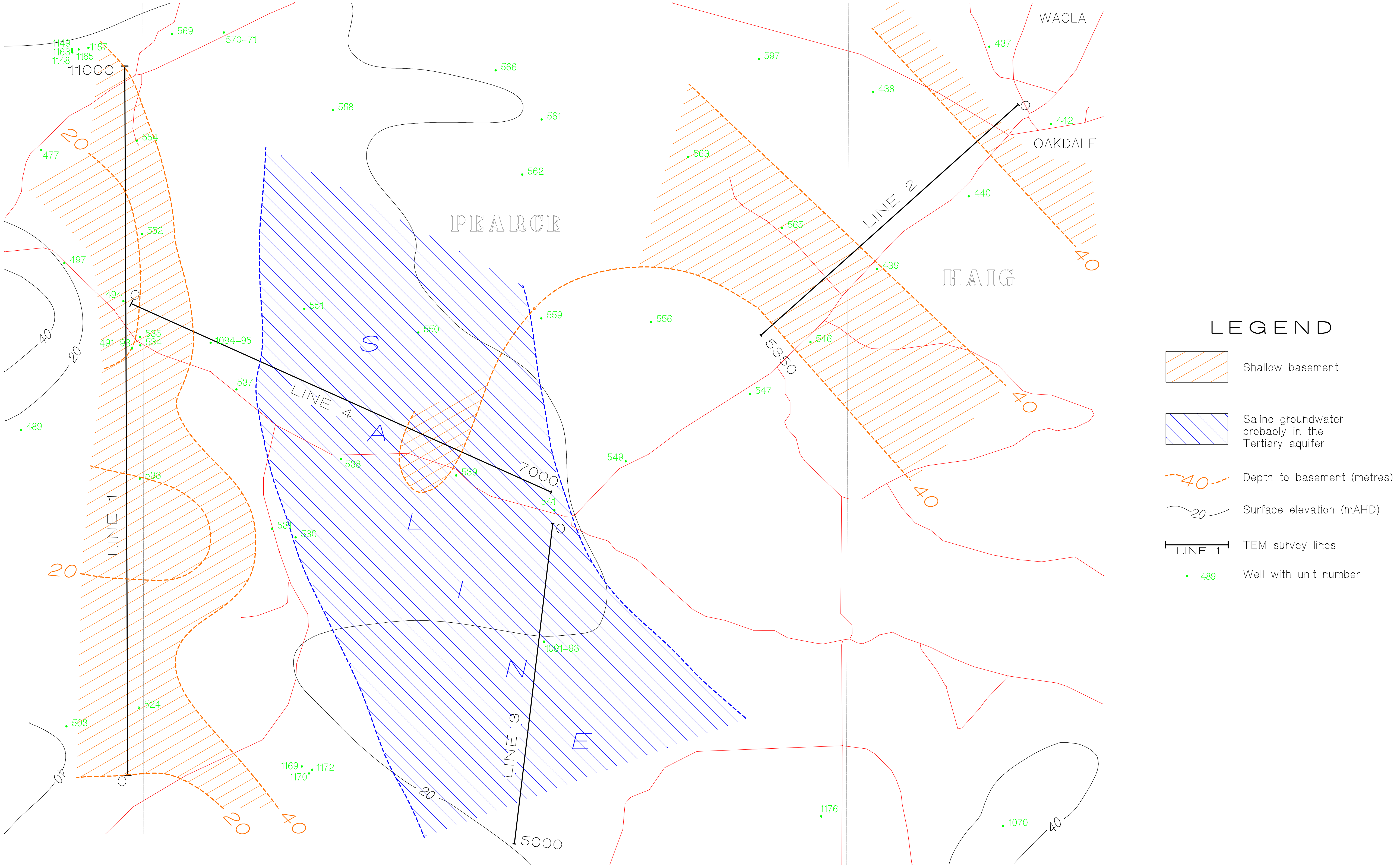
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SHERINGA A LENS BORES, TEM LINES AND INTERPRETED BASEMENT DEPTH

1996–0977

Job No. 5900AL.DTA

MINES and ENERGY RESOURCES SOUTH AUSTRALIA



Appendix.......D3

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

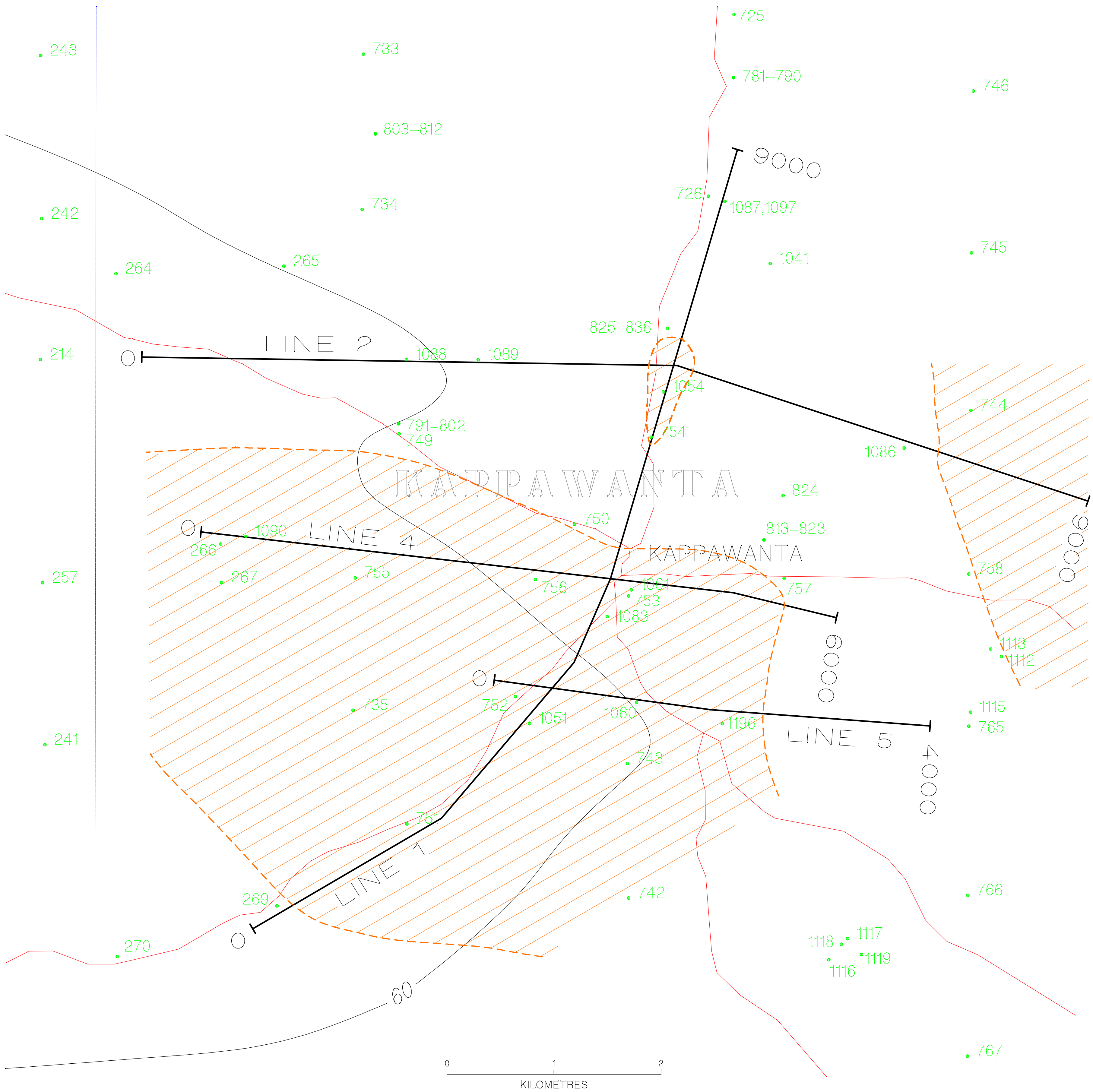
SHERINGA B LENS BORES, TEM LINES AND INTERPRETED BASEMENT DEPTH

1996–0978

0 1 2 3 4 5
KILOMETRES

MINES and ENERGY RESOURCES SOUTH AUSTRALIA

Job No. 5900AL.DTA



LEGEND

Shallow basement

40 Depth to basement (metres)

20 Surface elevation (mAHD)

LINE 1 TEM survey lines

489 Well with unit number

Appendix.......D4

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

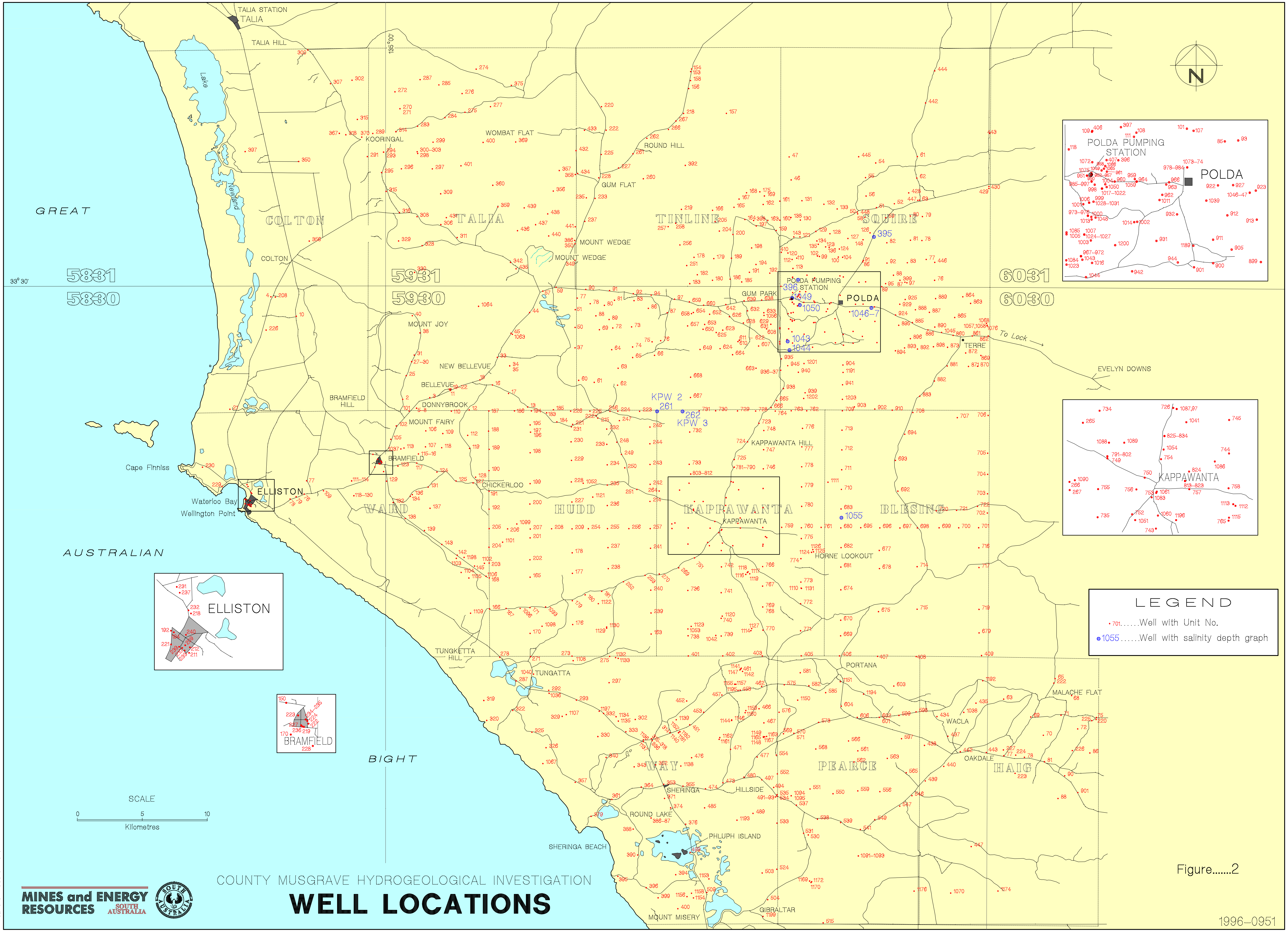
KAPPAWANTA LENS BORES, TEM LINES AND INTERPRETED BASEMENT DEPTH

1996–0979

Job No. 5900AL.DTA

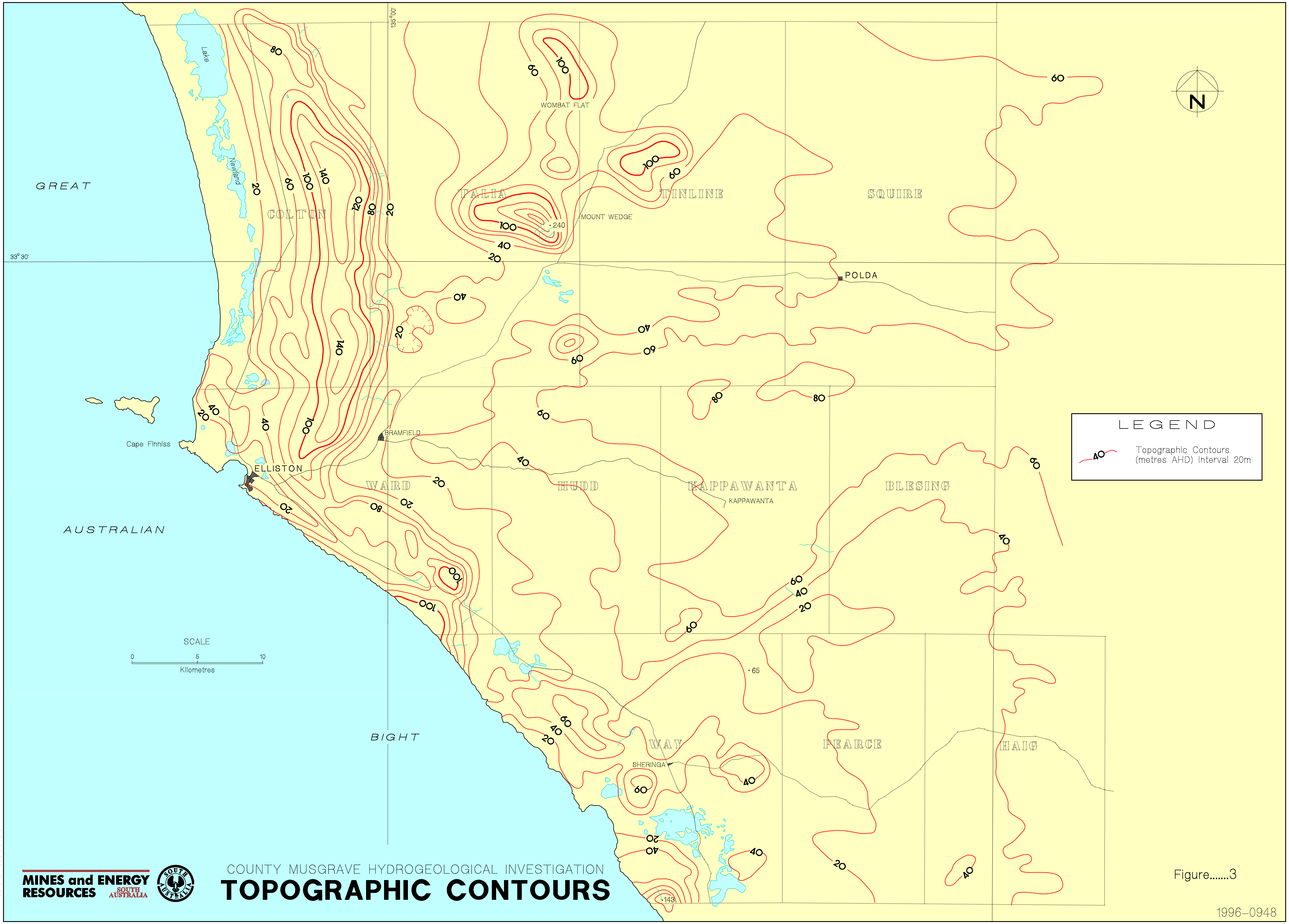
MINES and ENERGY RESOURCES SOUTH AUSTRALIA


COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION
LOCALITY PLAN
MINES and ENERGY RESOURCES SOUTH AUSTRALIA
LEGEND
KPW 51 Geochemistry Survey Wells
TAA 29 Hydrograph Wells
TEM Survey Line
Geological Section
Groundwater lens in Quaternary Limestone with Salinity < 1000 mg per litre
Data Source
1994 Waterlevels
1972 Salinity data
GREAT AUSTRALIAN BIGHT
COLTON
TALIA
TINLINE
SQUIRE
WARD
HUDD
KAPPAWANTA
BLESING
WAY
PEARCE
HAIG
ELLISTON
POLDA
BRAMFIELD
Fig. 6
Fig. 7
Fig. 8
Fig. 9
App. D2
App. D3
App. D4
SCALE
0 5 10
Kilometres
SOUTH AUSTRALIA
Area of Investigation
Figure.......1
1996–0947
Job No. 5900AL.DTA



TALIA STATION
TALIA
TALIA HILL
Lake
Newland
GREAT
AUSTRALIAN
BIGHT
COLTON
TALIA
TINLINE
SQUIRE
WARD
HUDD
KAPPAWANTA
BLESING
WAY
PEARCE
HAIG
KOORINGAL
WOMBAT FLAT
ROUND HILL
GUM FLAT
MOUNT WEDGE
GUM PARK
POLDA PUMPING STATION
POLDA
TERRE
To Lock
EVELYN DOWNS
MOUNT JOY
NEW BELLEVUE
BELLEVUE
DONNYBROOK
BRAMFIELD HILL
MOUNT FAIRY
BRAMFIELD
CHICKERLOO
KAPPAWANTA HILL
HORNE LOOKOUT
Cape Finniss
Waterloo Bay
Wellington Point
ELLISTON
TUNGKETTA HILL
TUNGATTA
PORTANA
MALACHE FLAT
WACLA
OAKDALE
SHERINGA
HILLSIDE
ROUND LAKE
PHLUPH ISLAND
SHERINGA BEACH
MOUNT MISERY
GIBRALTAR
KPW 2
KPW 3
5831
5830
5931
5930
6031
6030
33° 30'
135°00'
N
SCALE
0
5
10
Kilometres
LEGEND
701......Well with Unit No.
1055......Well with salinity depth graph
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION
WELL LOCATIONS
MINES and ENERGY RESOURCES SOUTH AUSTRALIA
Job No. 5900AL.DTA
1996-0951

Figure......2



COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

TOPOGRAPHIC CONTOURS

Figure.......3

1996–0948

Job No. 5900AL.DTA

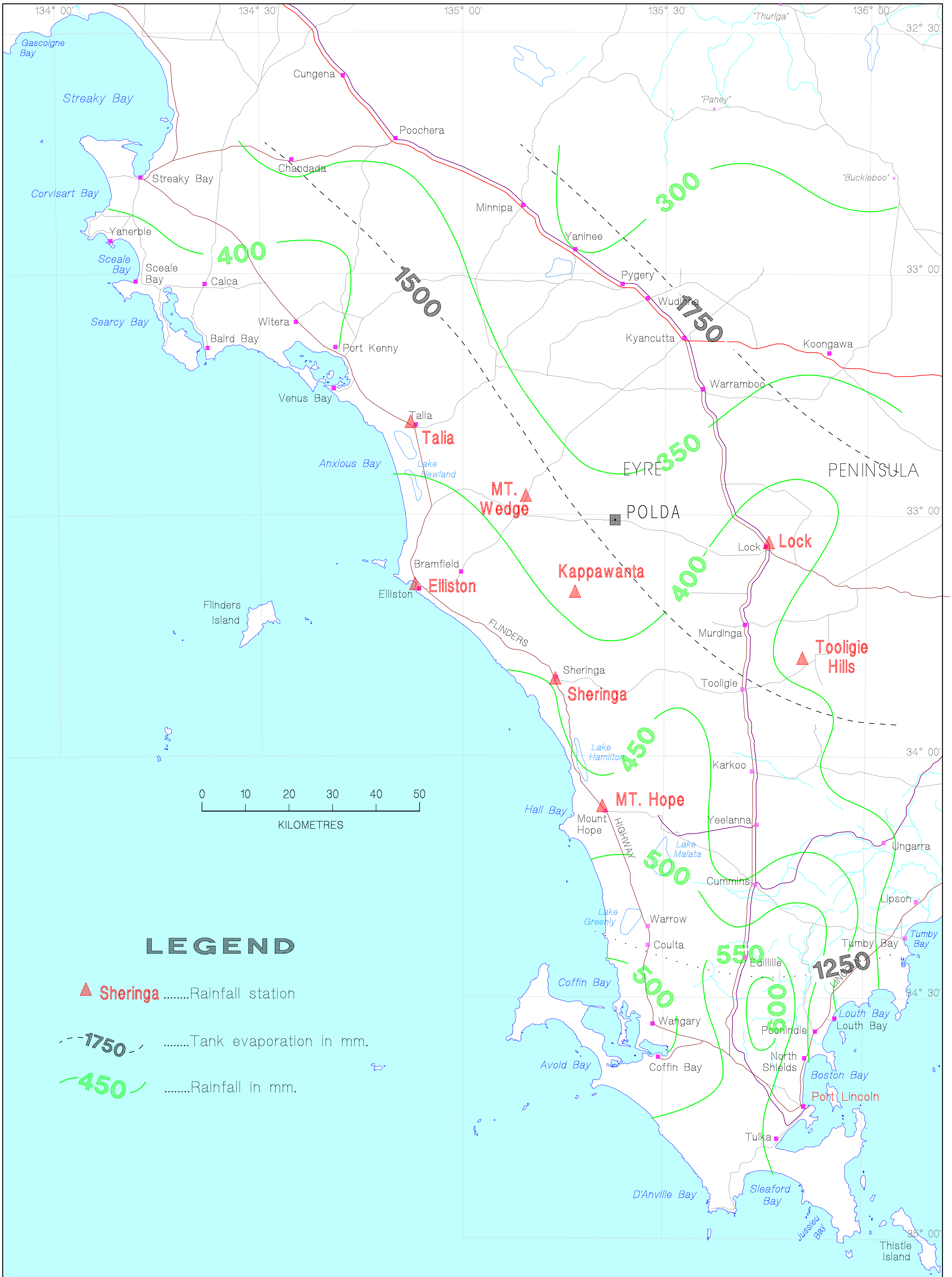


Figure.......4

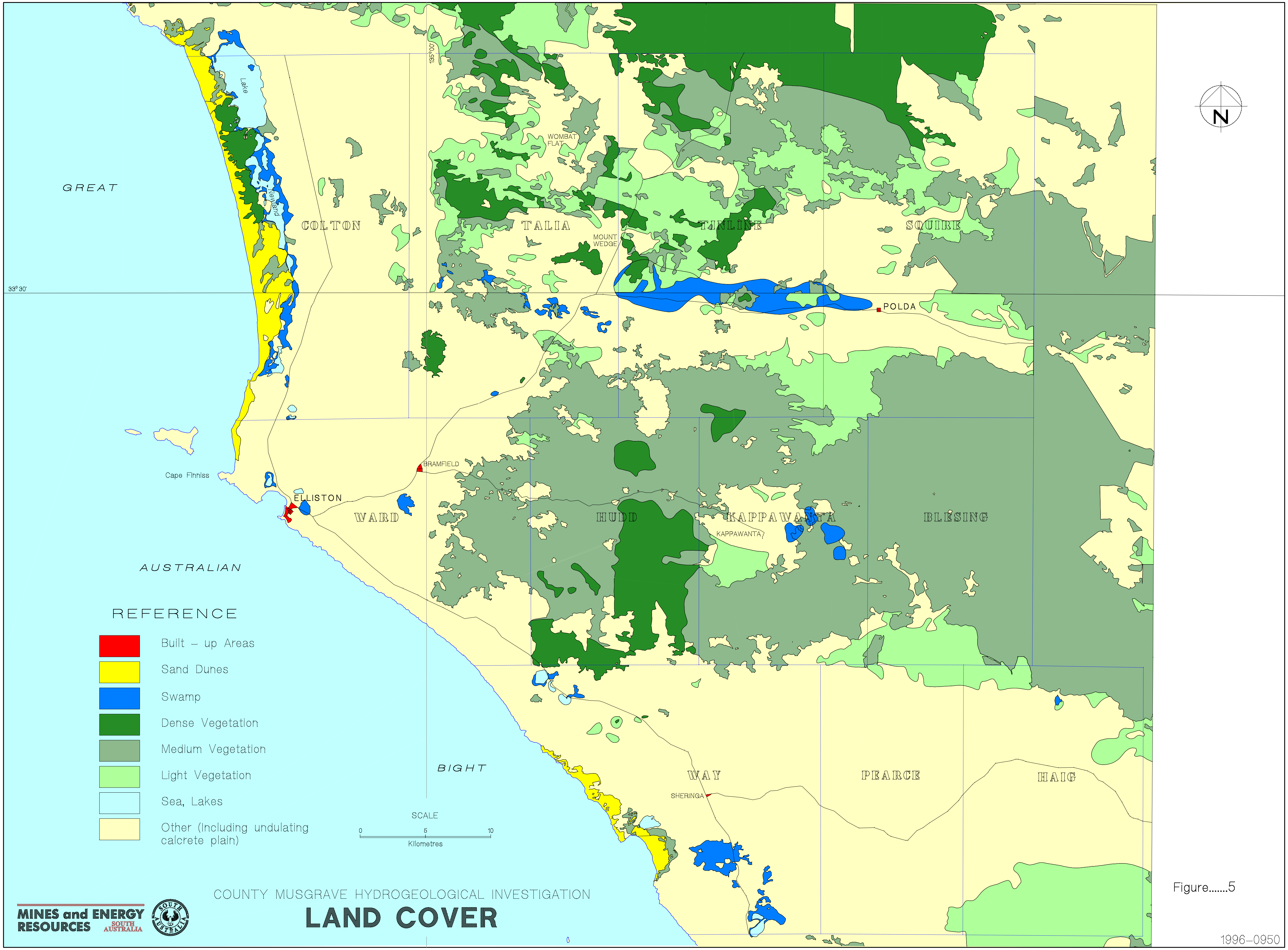
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

RAINFALL ISOHYETS AND EVAPORATION DATA

1996–0949

Job No. 5900AL.DTA

MINES and ENERGY RESOURCES SOUTH AUSTRALIA



COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

LAND COVER

Figure.......5

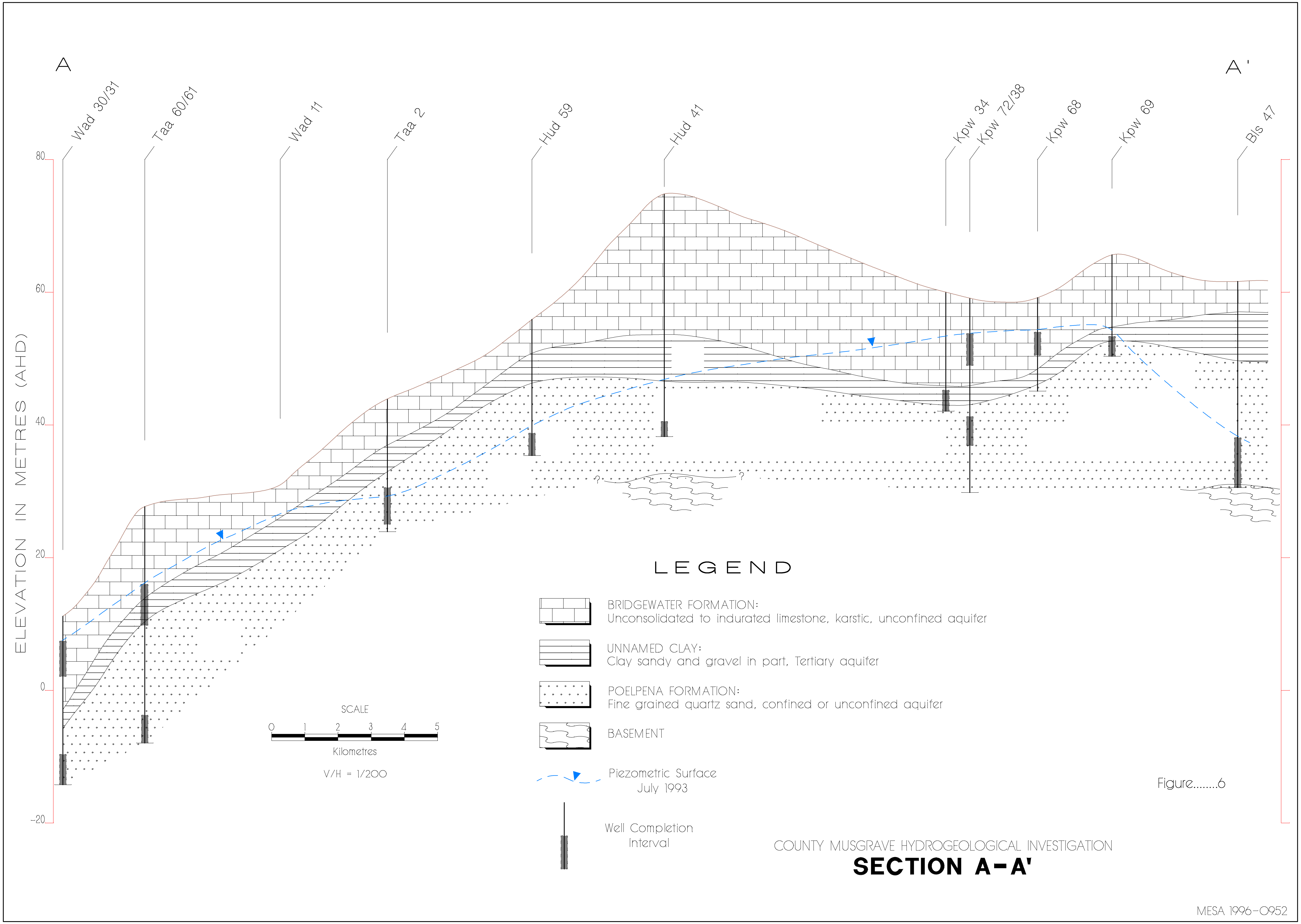


Figure........6

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SECTION A-A'

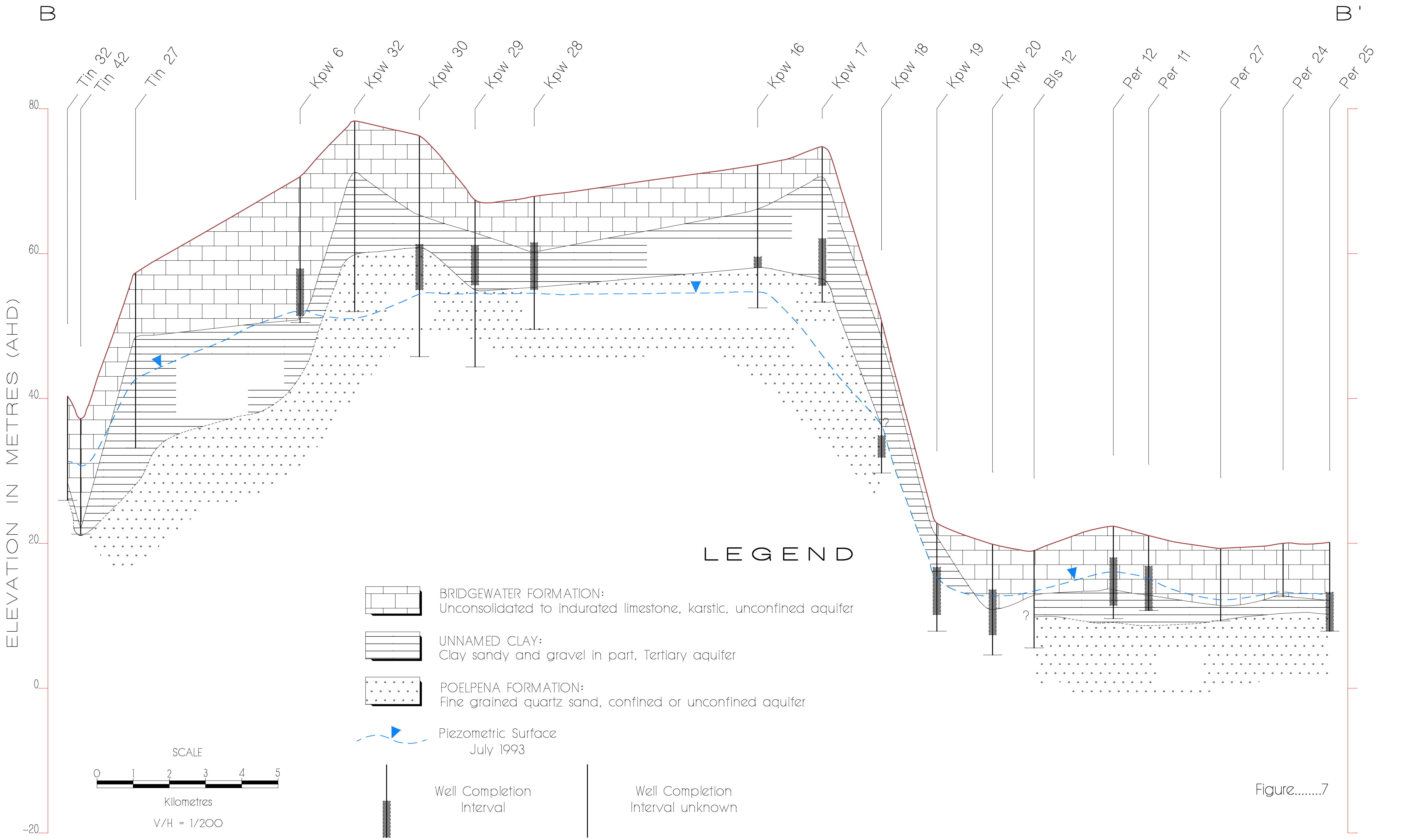


Figure........7

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SECTION B-B'

MESA 1996-0953

Job No. 5900AL.DTA

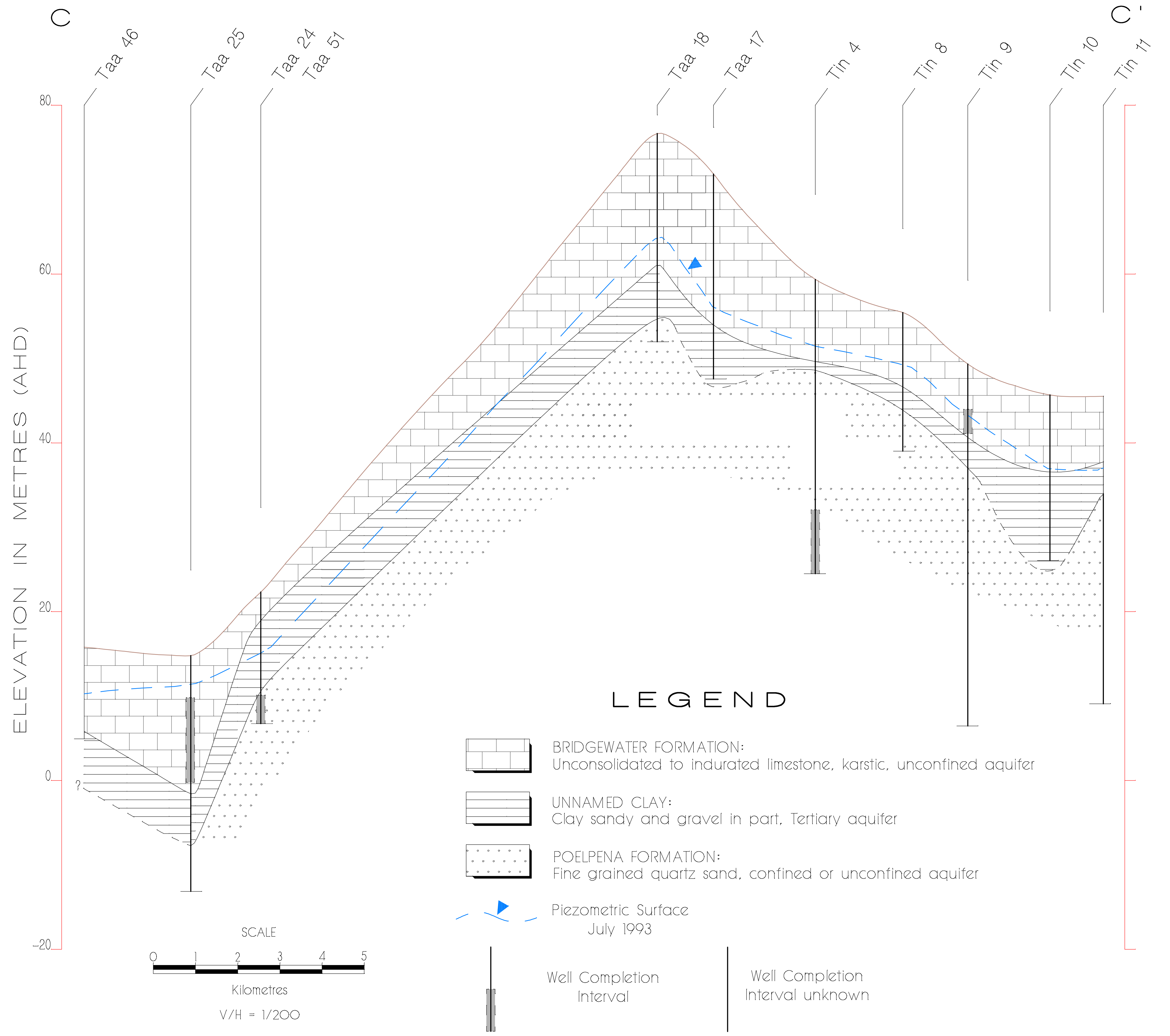


Figure........8

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SECTION C-C'

MESA 1996-0954

Job No. 5900AL.DTA

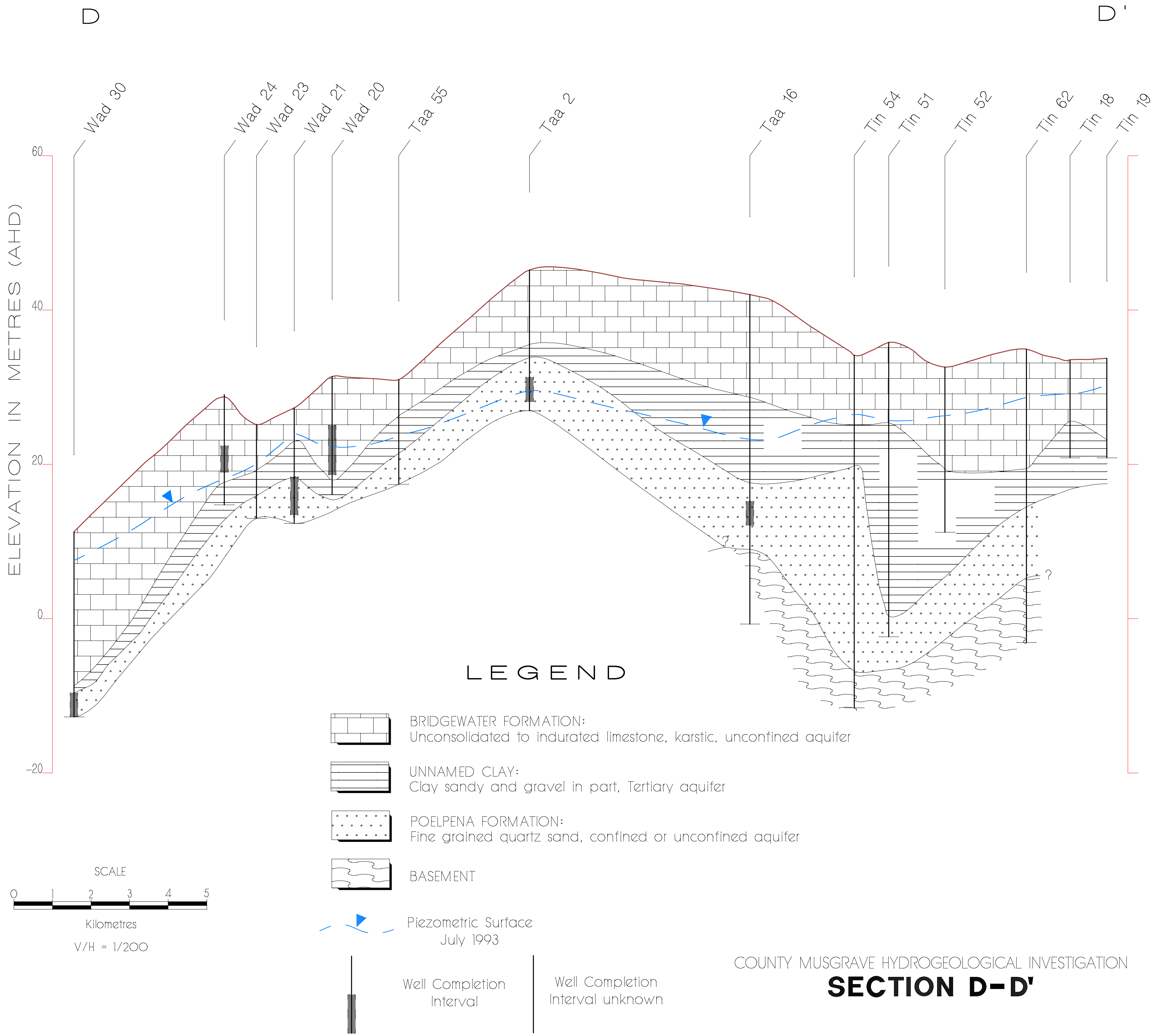


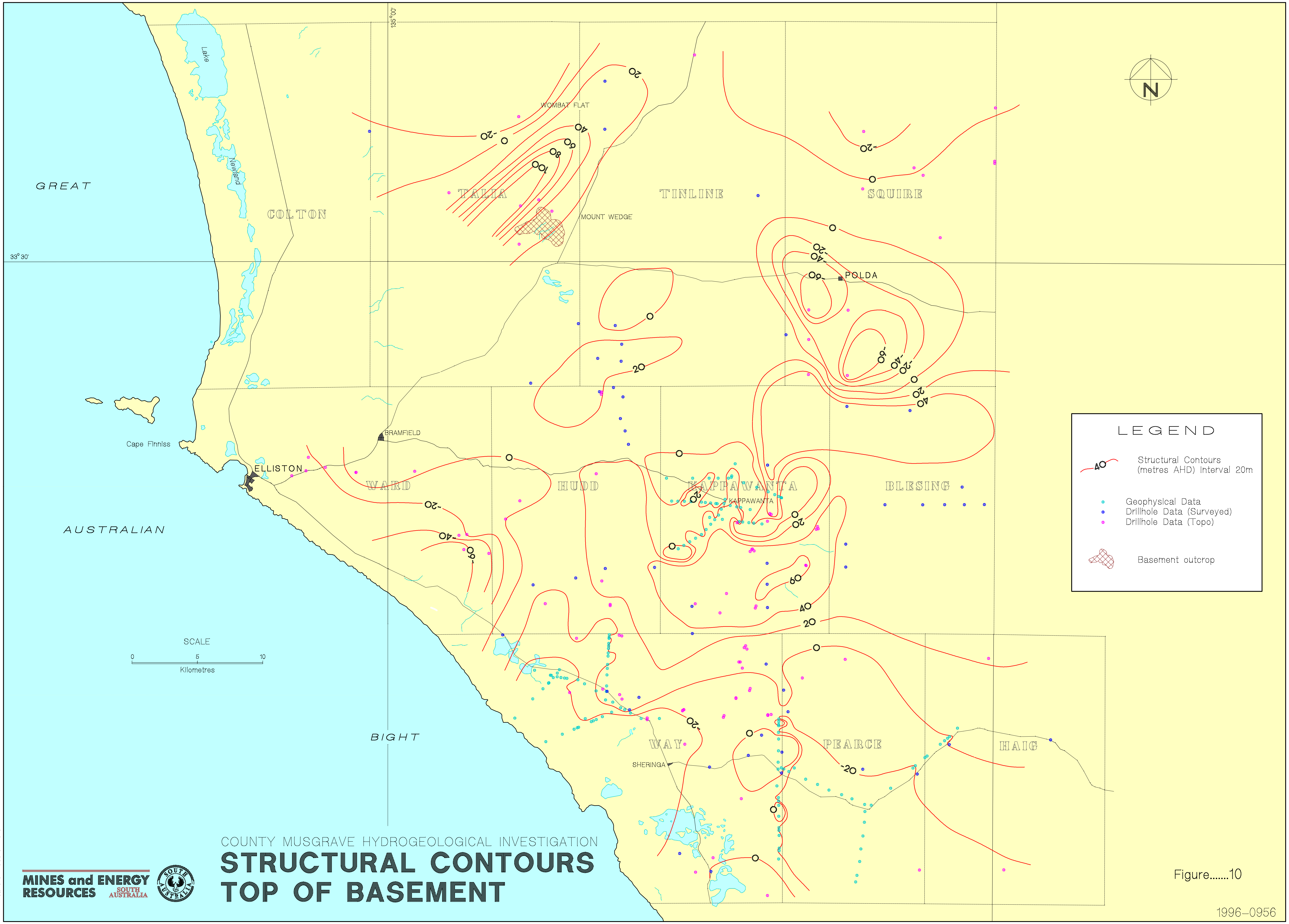
Figure........9

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

SECTION D-D'

MESA 1996-0955

Job No. 5900AL.DTA



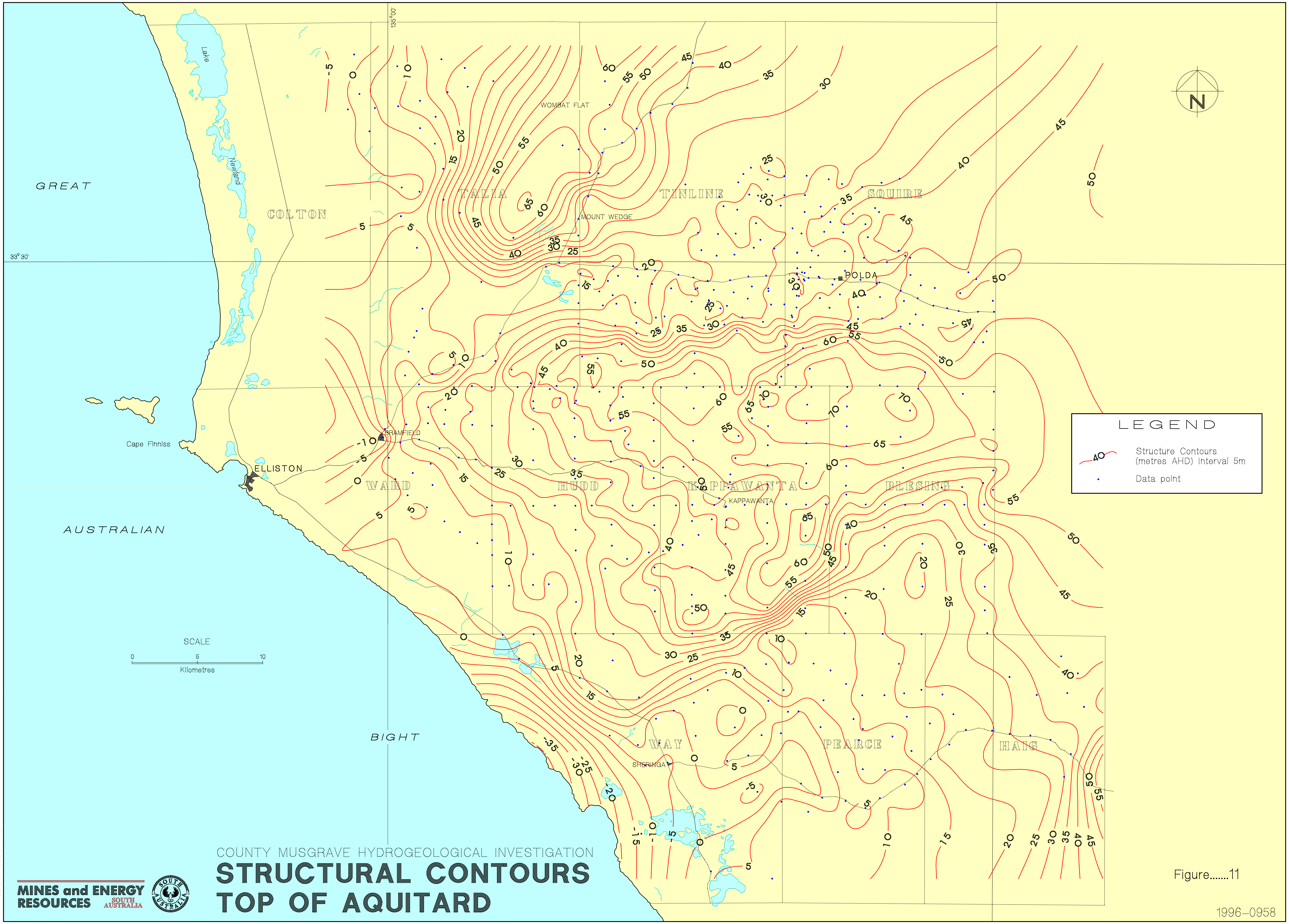
MINES and ENERGY RESOURCES SOUTH AUSTRALIA

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

STRUCTURAL CONTOURS TOP OF BASEMENT

Figure.......10

1996–0956



COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

STRUCTURAL CONTOURS TOP OF AQUITARD

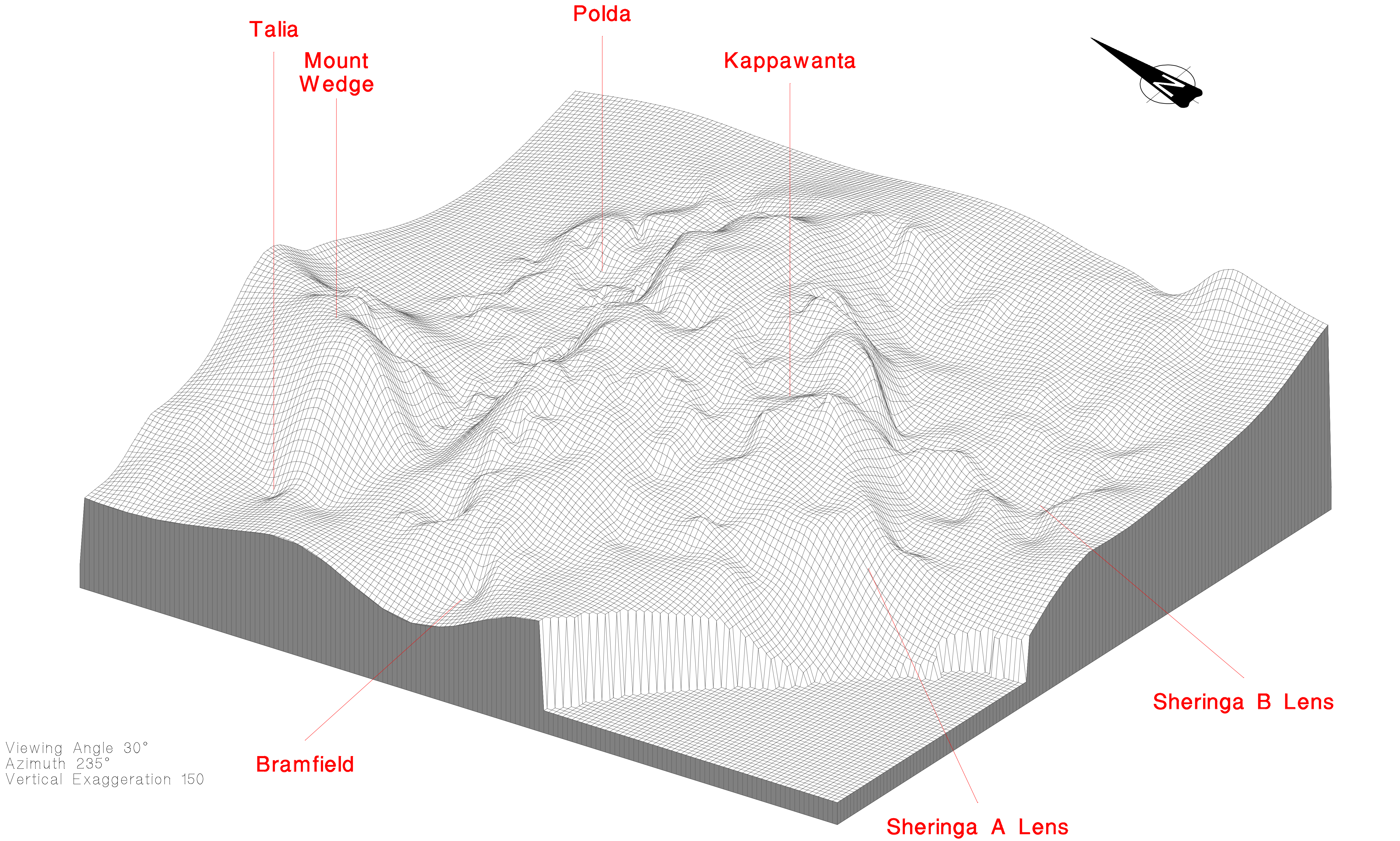


Figure........12

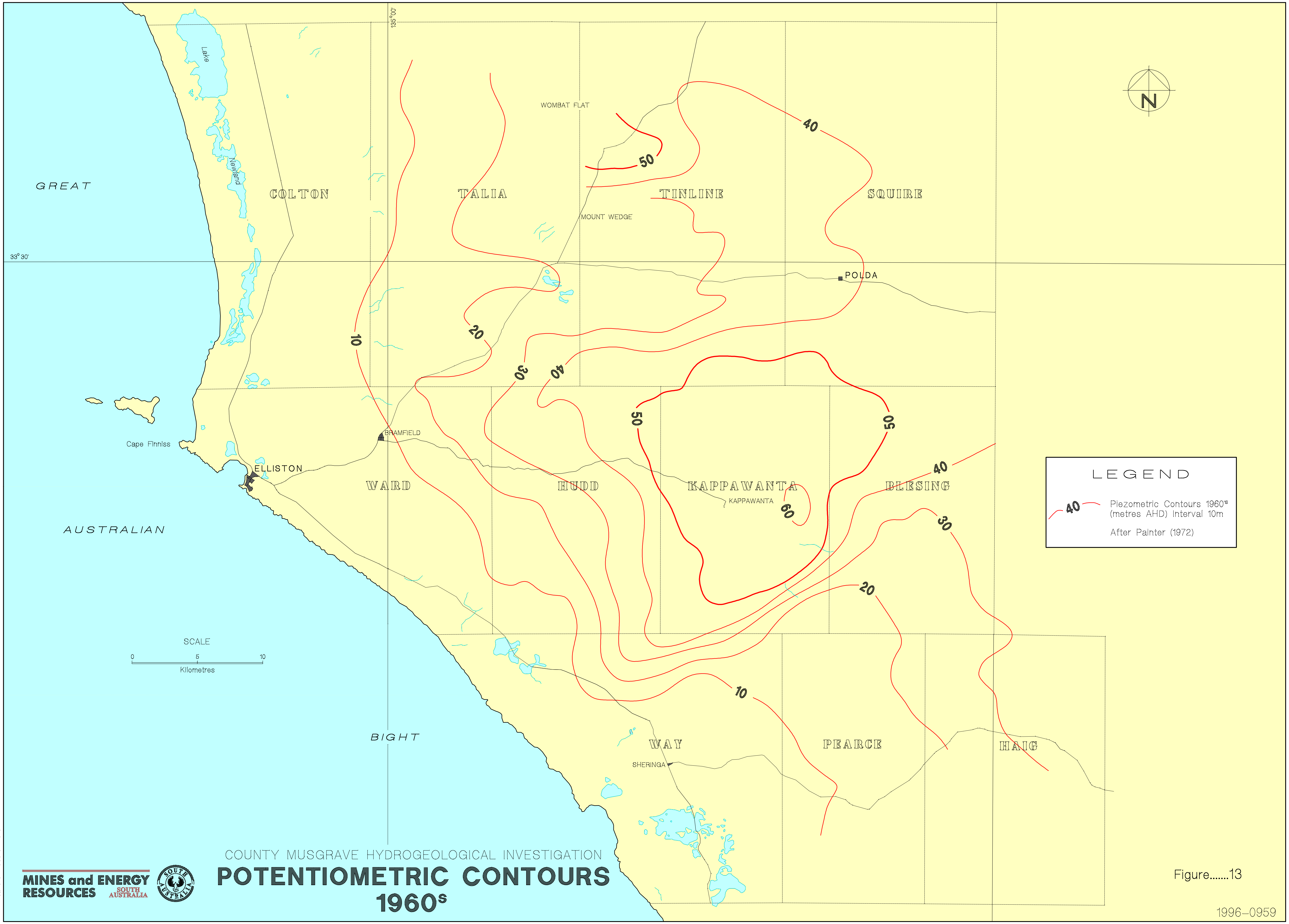
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

PERSPECTIVE VIEW TOP OF AQUITARD

MINES and ENERGY RESOURCES SOUTH AUSTRALIA

Job No. 5900AL.DTA

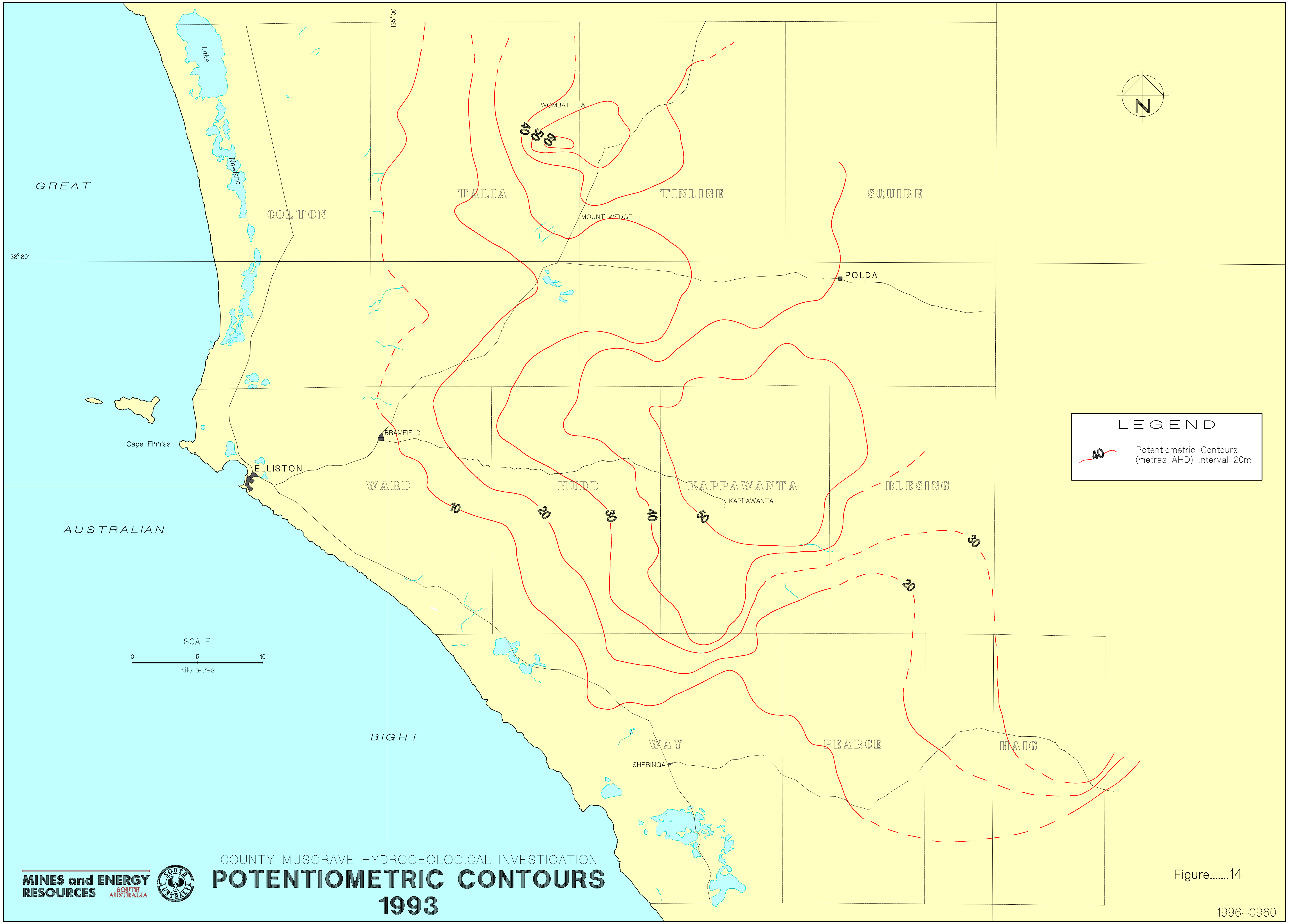
1996–0957



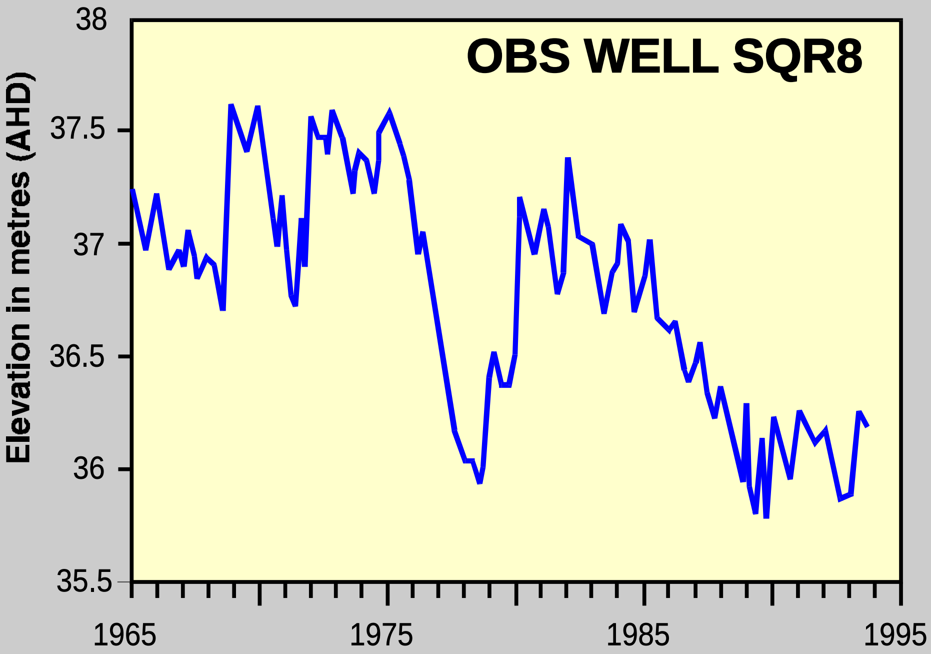
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

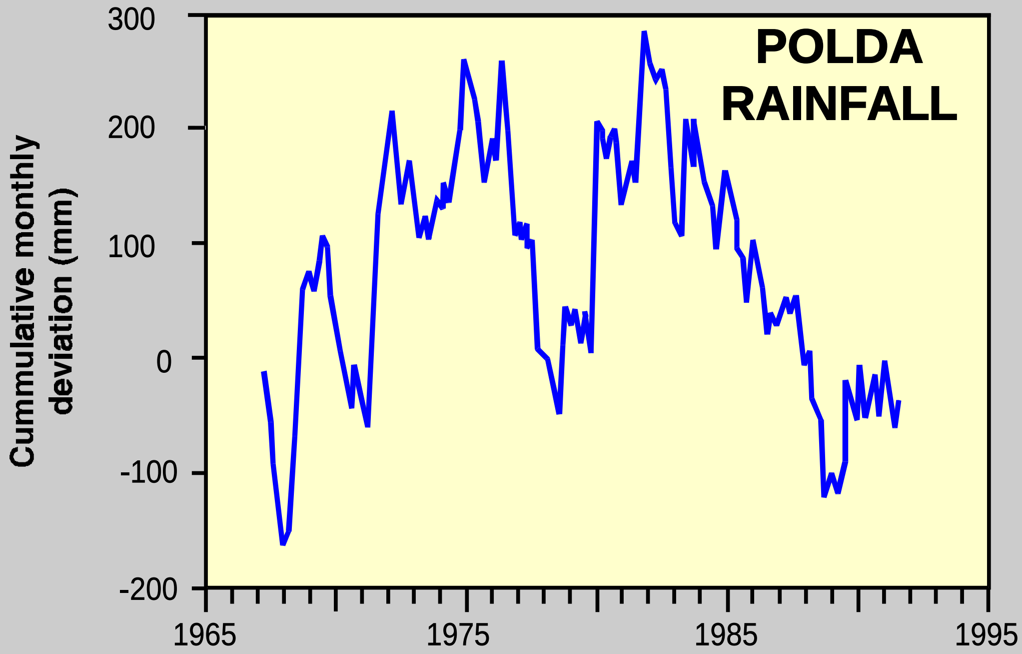
POTENTIOMETRIC CONTOURS 1960s

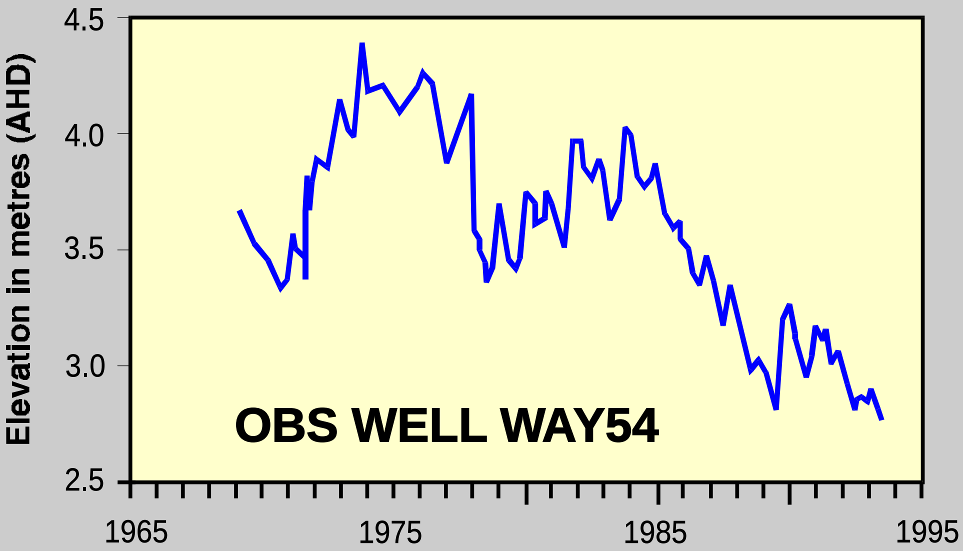
Figure.......13



Job No. 5900AL.DTA







HYDROGRAPHS AND POLDA RAINFALL STATISTICS

Figure........15

1996-0961

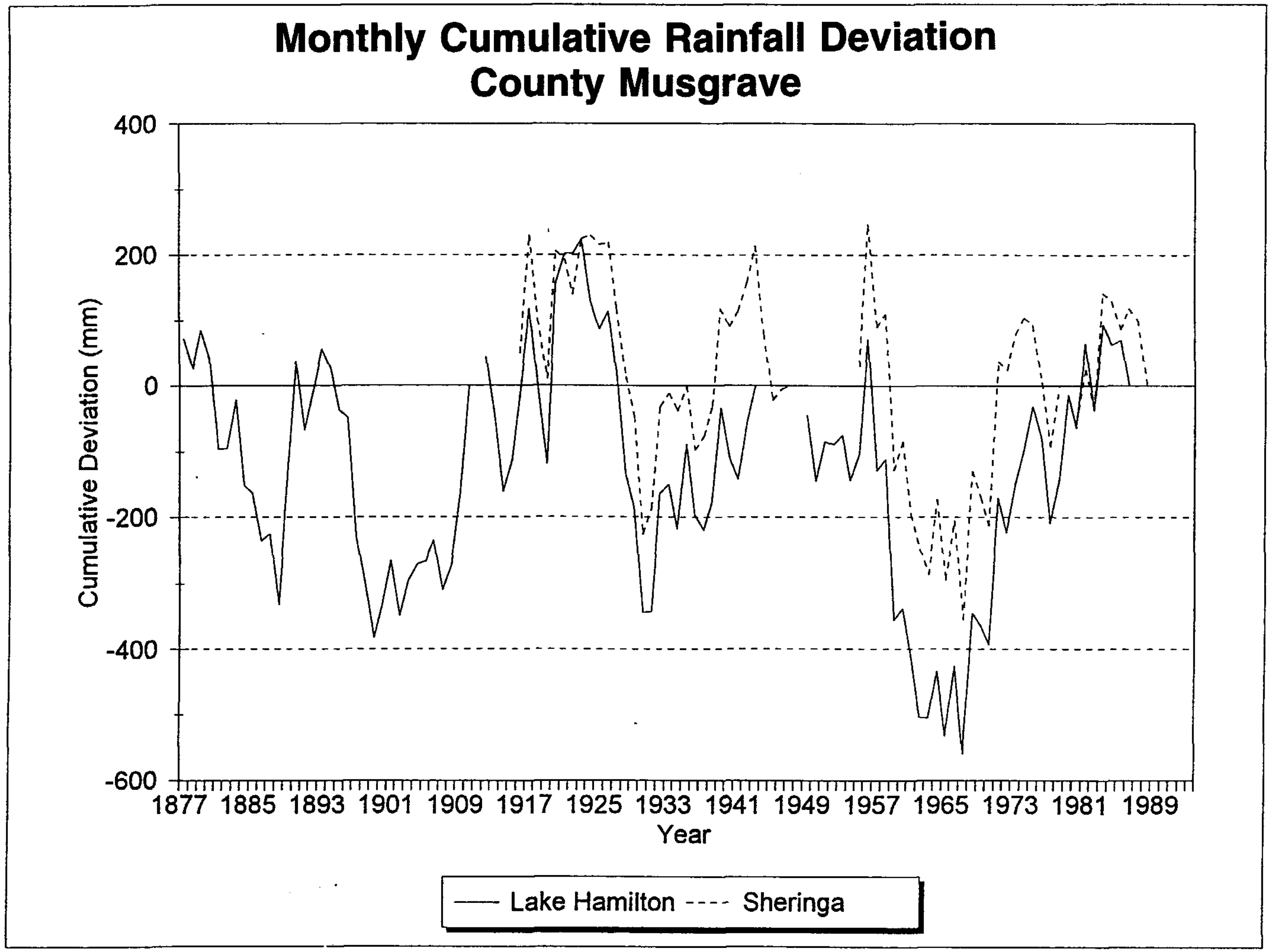


Figure........16

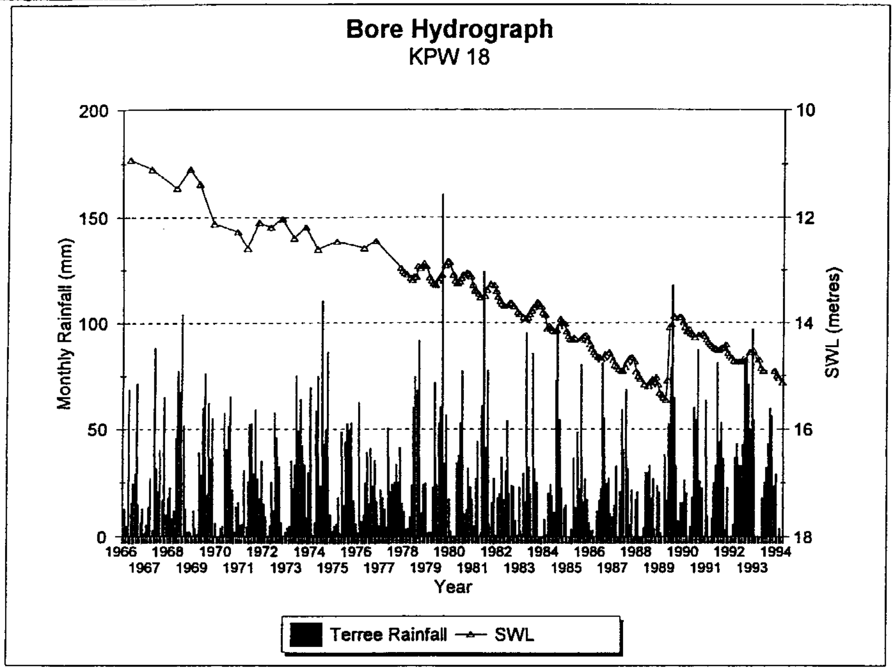
Job No. 5900AL.CDR

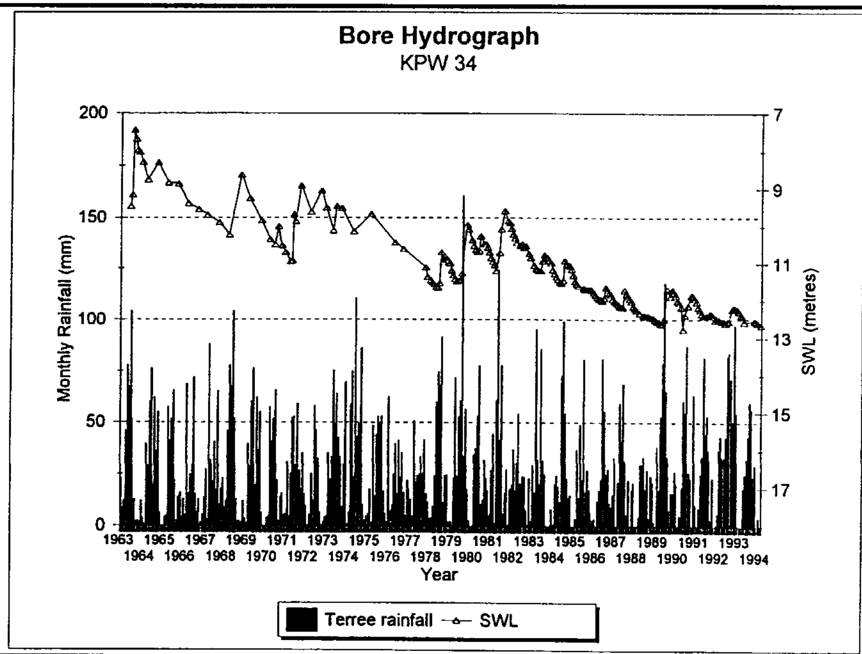
MINES and ENERGY
SOUTH AUSTRALIA

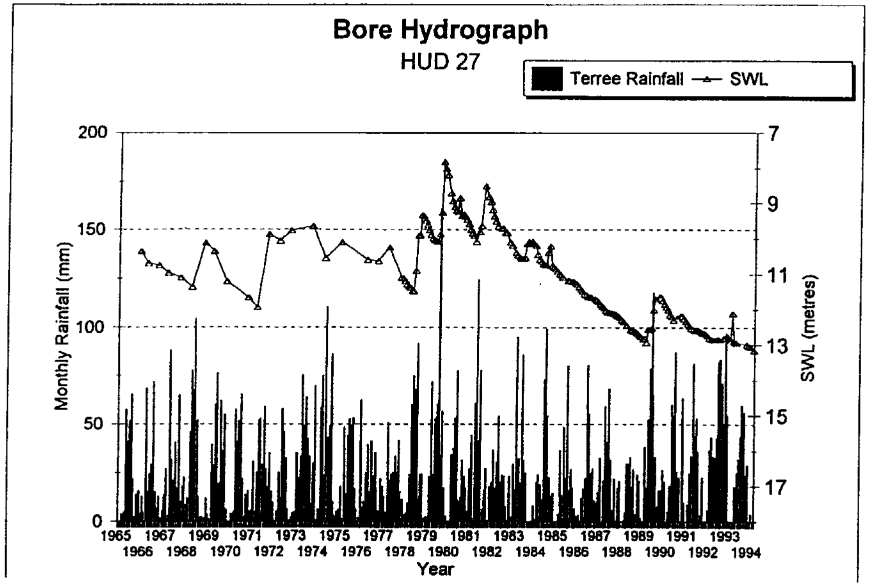
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

RAINFALL STATISTICS LAKE HAMILTON & SHERINGA

1996-0962







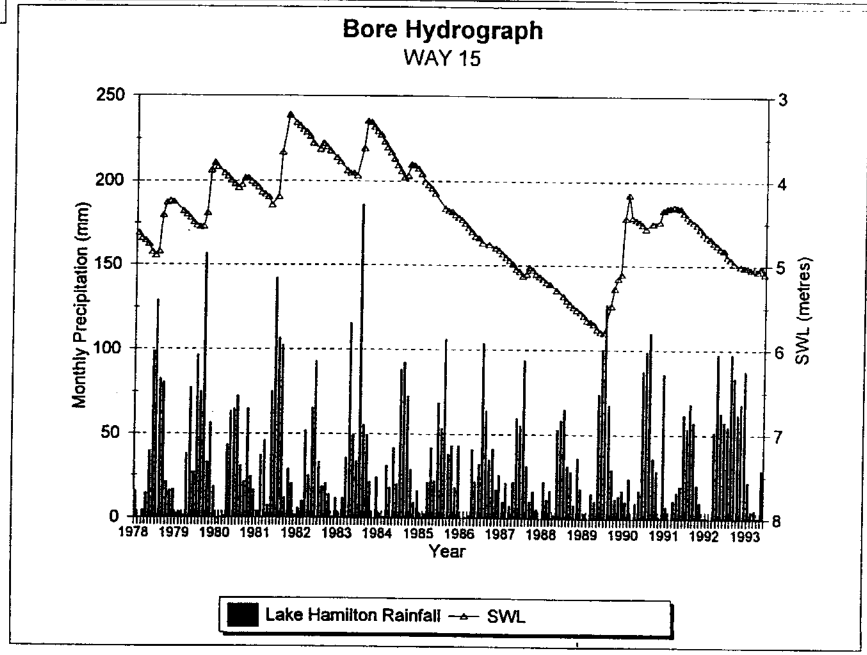


Figure........17

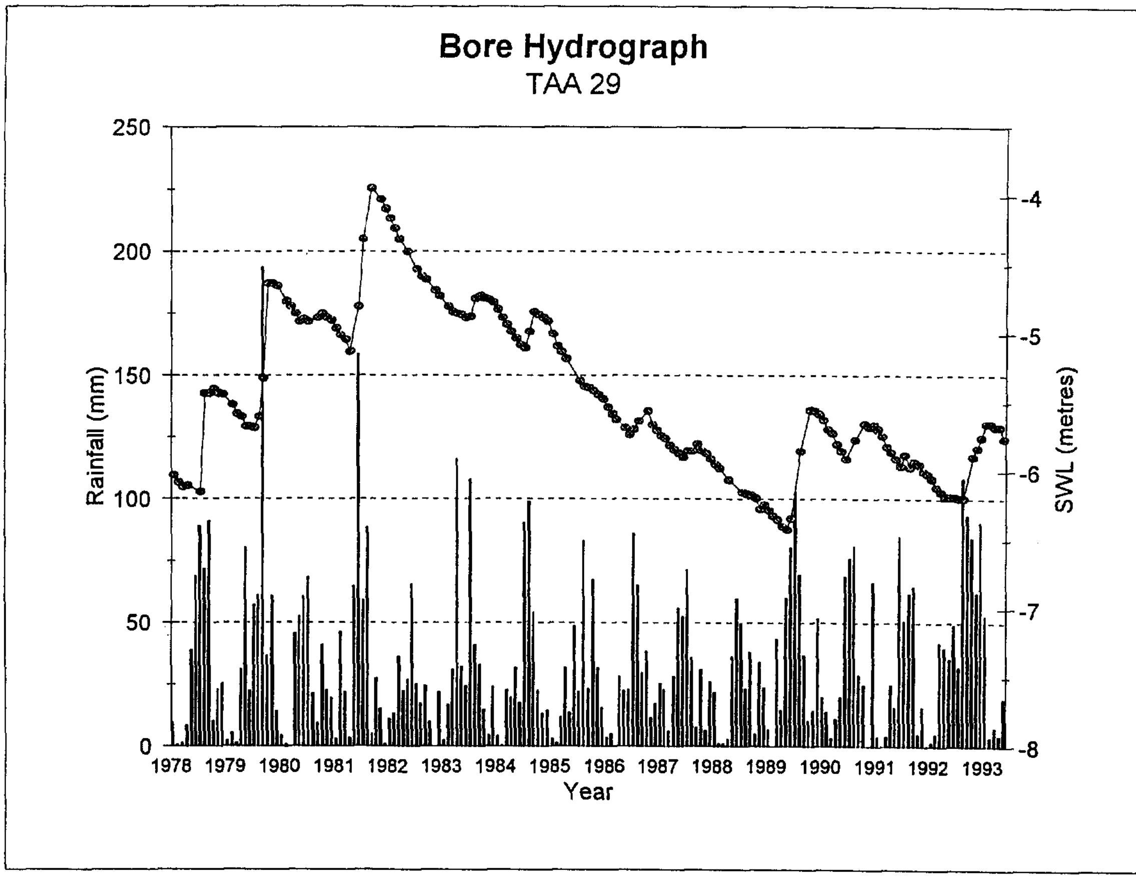
Job No. 5900AL.CDR

MINES and ENERGY
SOUTH AUSTRALIA

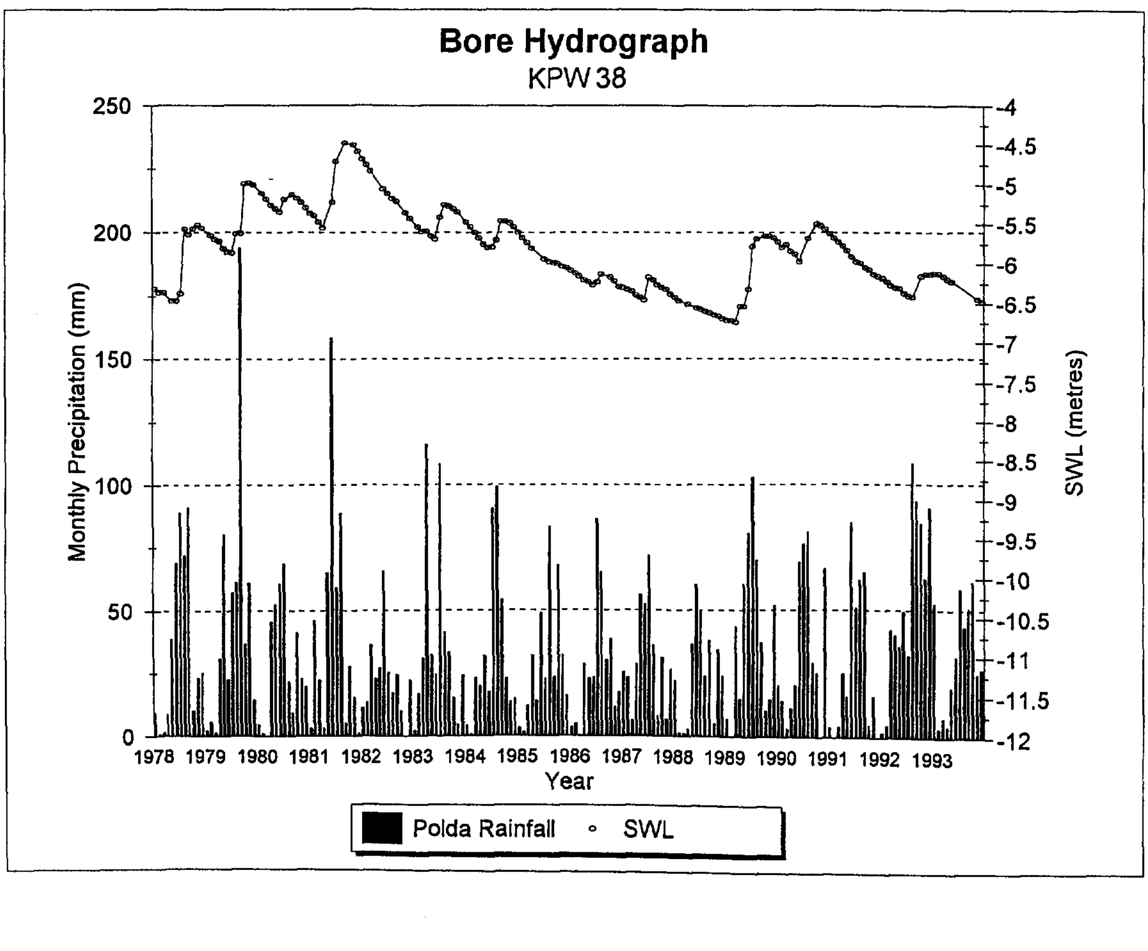
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

HYDROGRAPHS

1996-0963

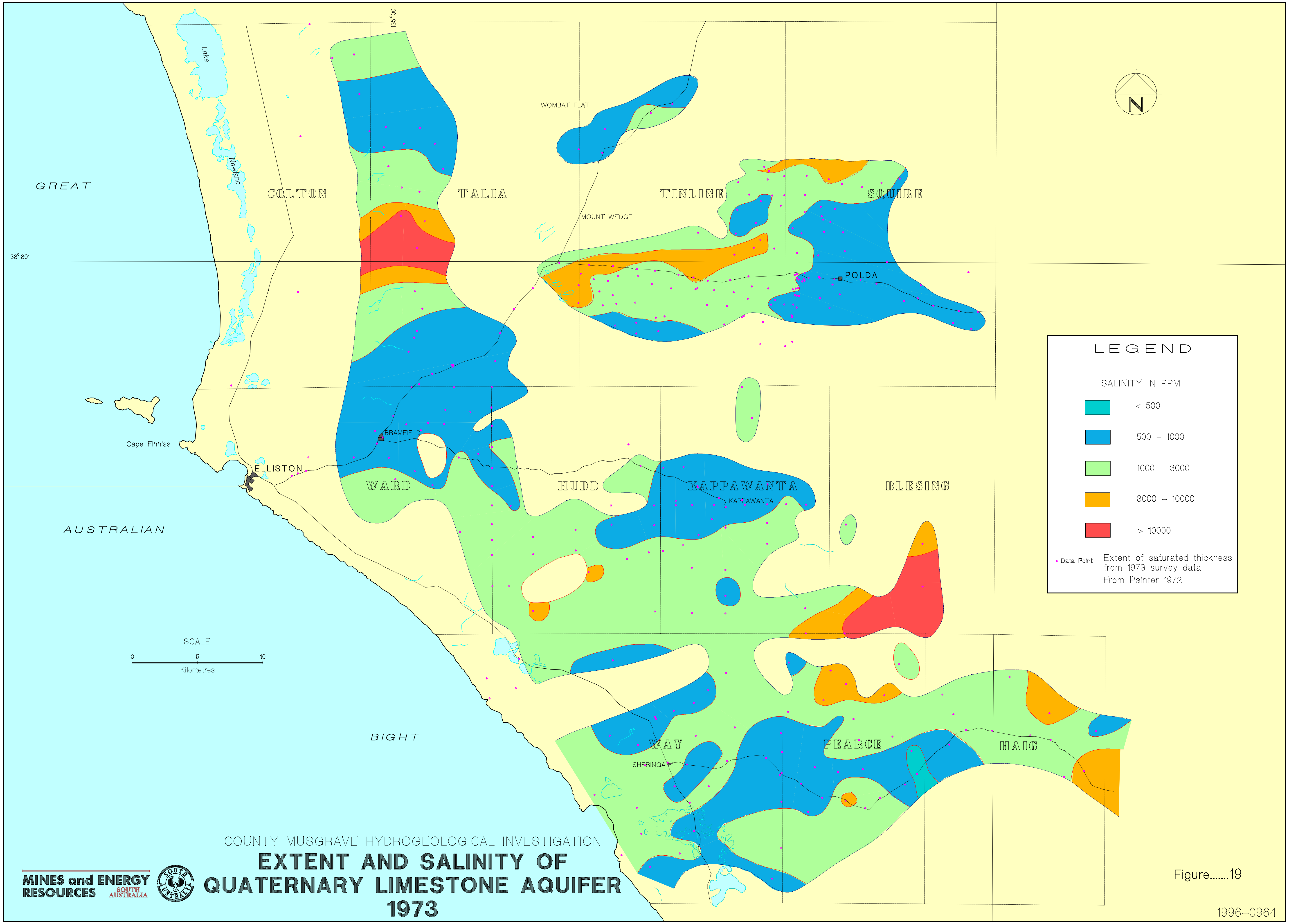


Bore Hydrograph
TAA 29
Rainfall (mm)
SWL (metres)
Year
250
200
150
100
50
0
-4
-5
-6
-7
-8
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993

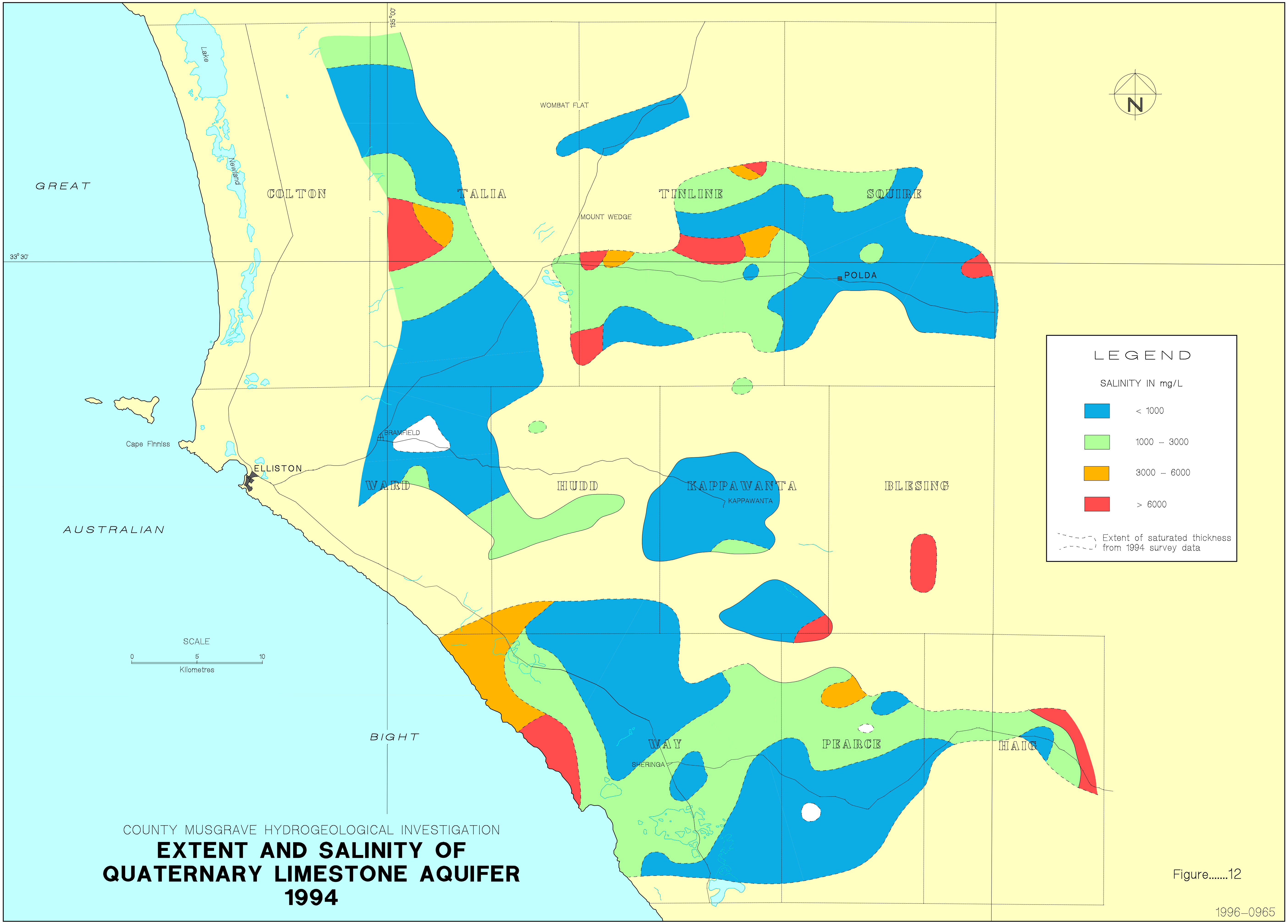


Bore Hydrograph
KPW38
Monthly Precipitation (mm)
SWL (metres)
Year
250
200
150
100
50
0
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
-8.5
-9
-9.5
-10
-10.5
-11
-11.5
-12
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993
Polda Rainfall
SWL

Figure 18



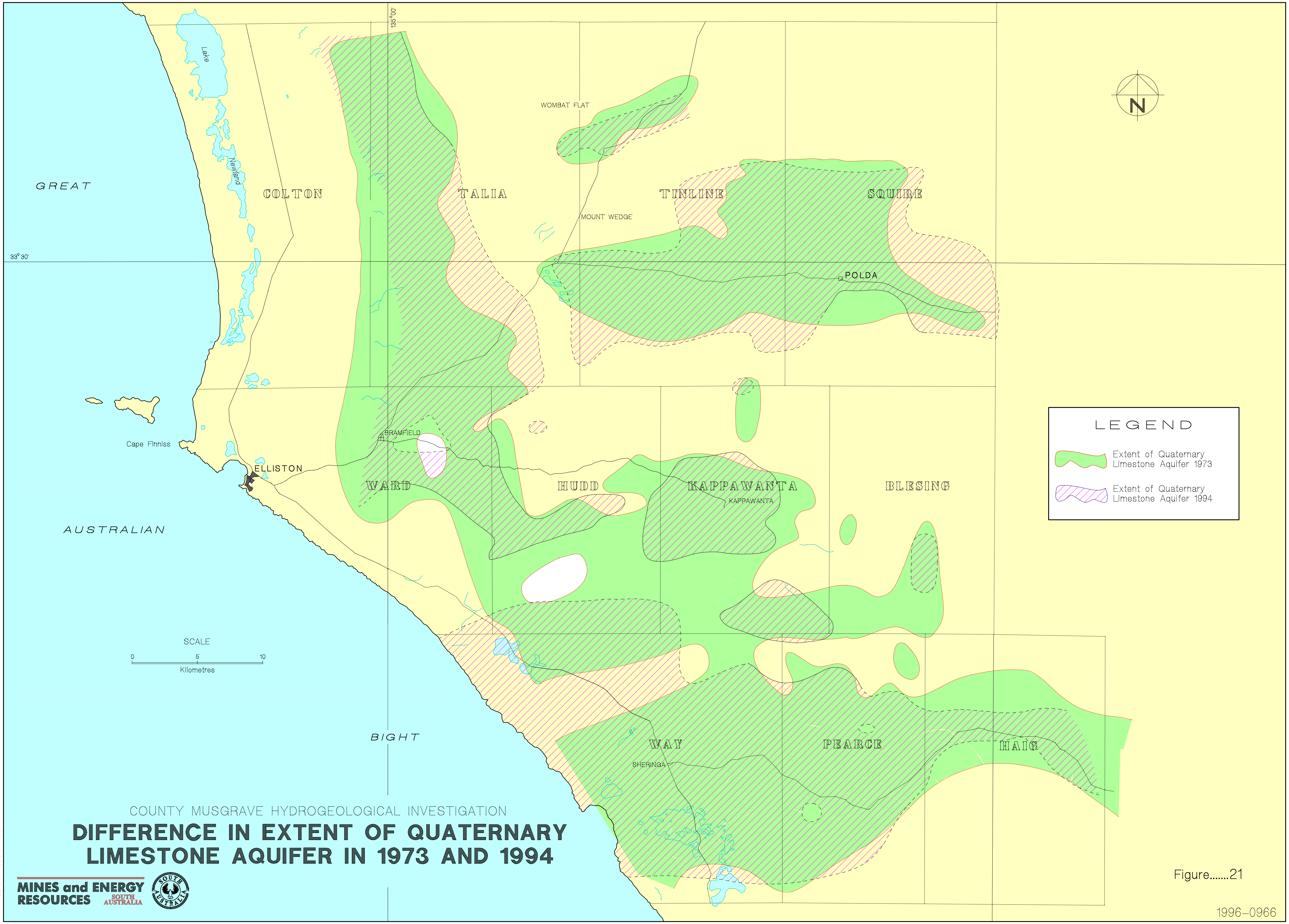
GREAT
AUSTRALIAN
BIGHT
Lake Newland
Cape Finniss
ELLISTON
BRAMFIELD
WOMBAT FLAT
MOUNT WEDGE
POLDA
KAPPAWANTA
SHERINGA
COLTON
TALIA
TINLINE
SQUIRE
WARD
HUDD
KAPPAWANTA
BLESING
WAY
PEARCE
HAIG
135°00'
33°30'
N
LEGEND
SALINITY IN PPM
< 500
500 – 1000
1000 – 3000
3000 – 10000
> 10000
Data Point
Extent of saturated thickness from 1973 survey data
From Painter 1972
SCALE
0
5
10
Kilometres
Job No. 5900AL.DTA
MINES and ENERGY RESOURCES
SOUTH AUSTRALIA
COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION
EXTENT AND SALINITY OF QUATERNARY LIMESTONE AQUIFER
1973
Figure.......19
1996–0964



COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

EXTENT AND SALINITY OF QUATERNARY LIMESTONE AQUIFER 1994

Figure.......12



COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

DIFFERENCE IN EXTENT OF QUATERNARY LIMESTONE AQUIFER IN 1973 AND 1994

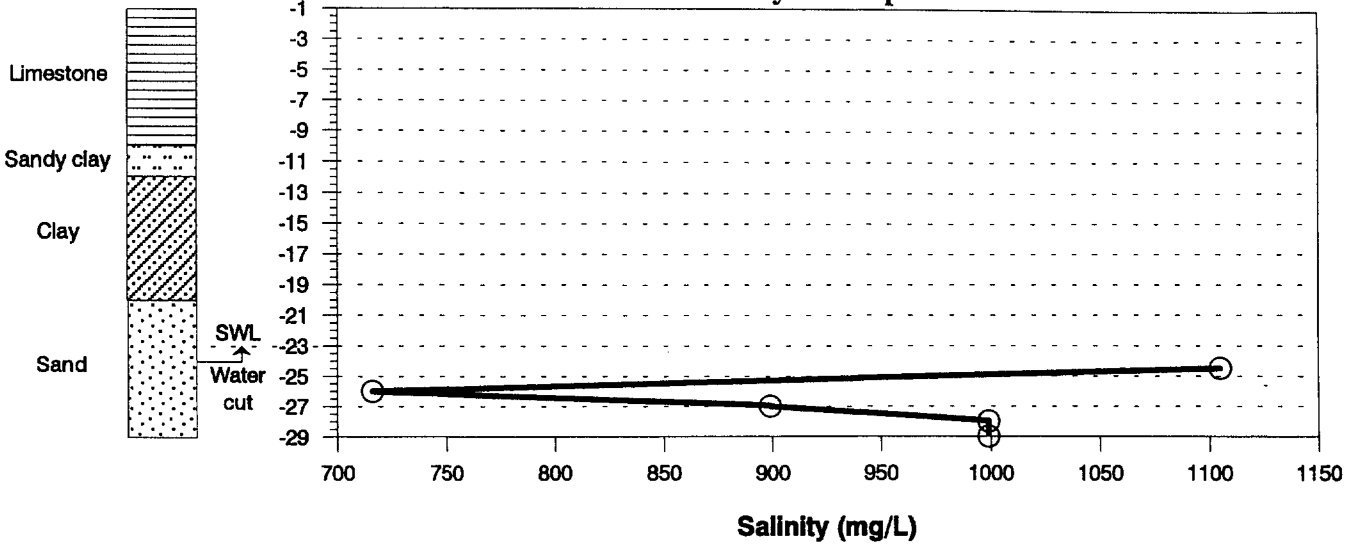
MINES and ENERGY RESOURCES SOUTH AUSTRALIA

Figure.......21

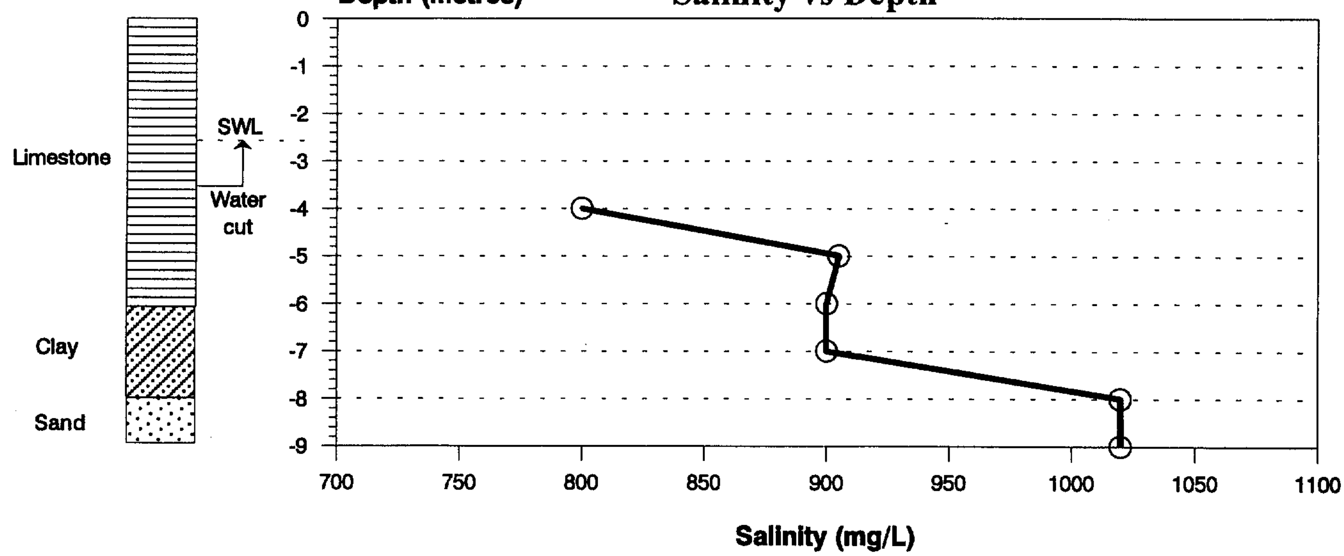
1996–0966

Job No. 5900AL.DTA

5930-1055
Salinity vs Depth



5931-396
Salinity vs Depth



5930-1044
Salinity vs Depth

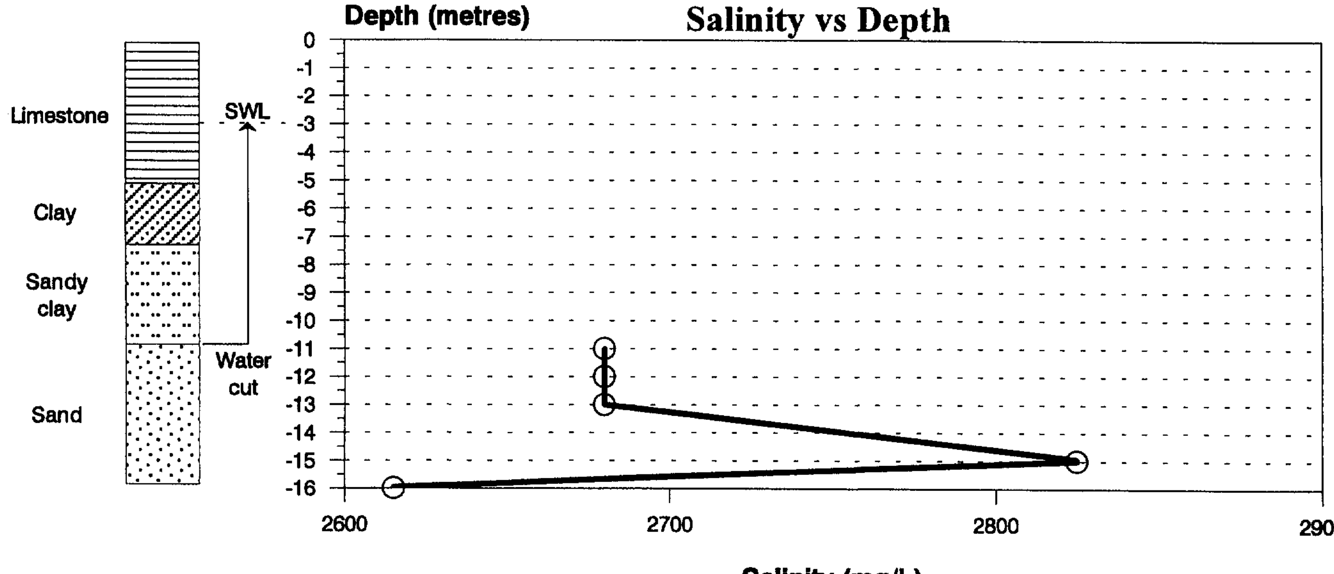


Figure 22

MINES and ENERGY
SOUTH AUSTRALIA

SALINITY DEPTH GRAPHS

1996-0967

Job No. 5900AL.PRS

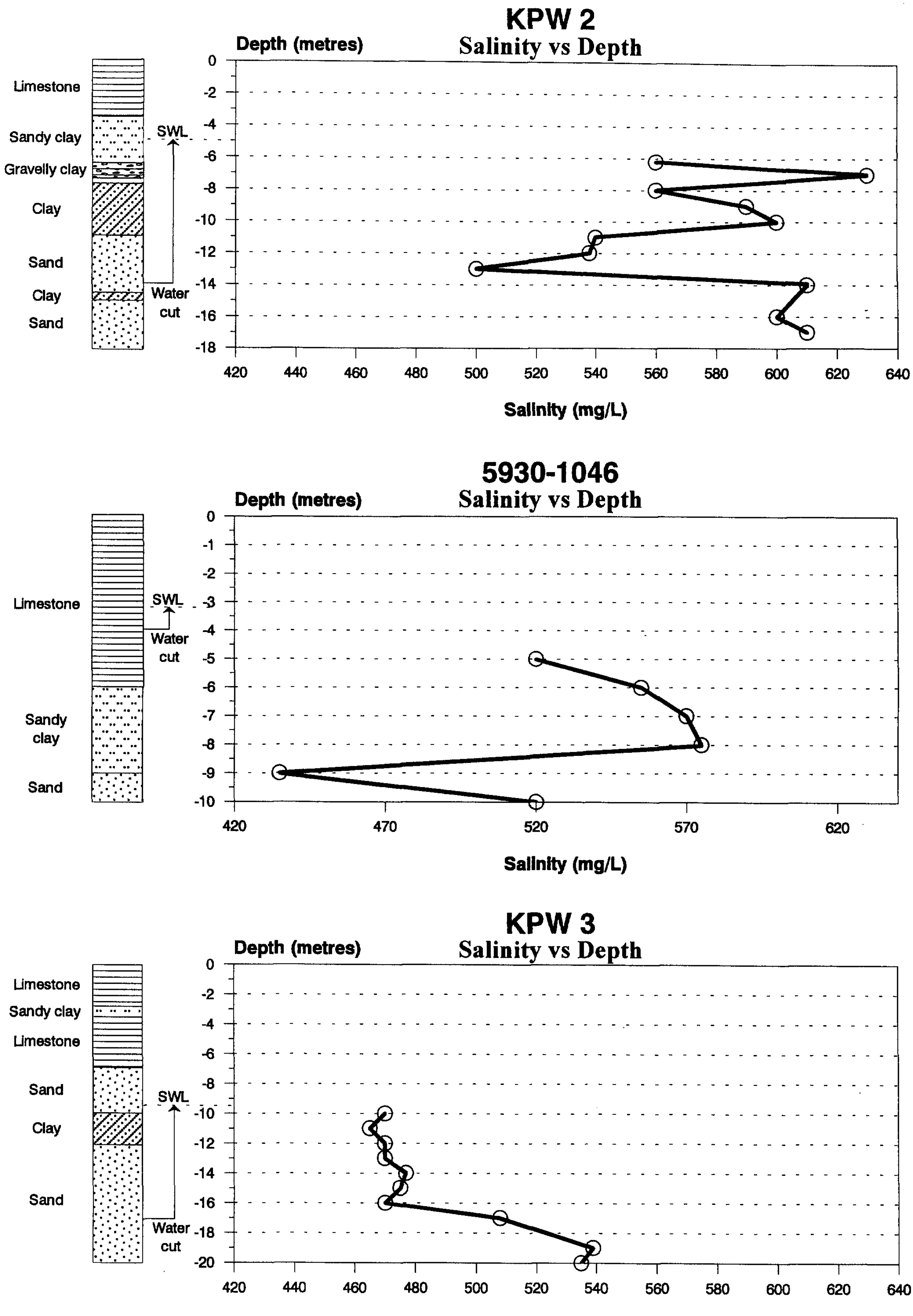


Figure 23

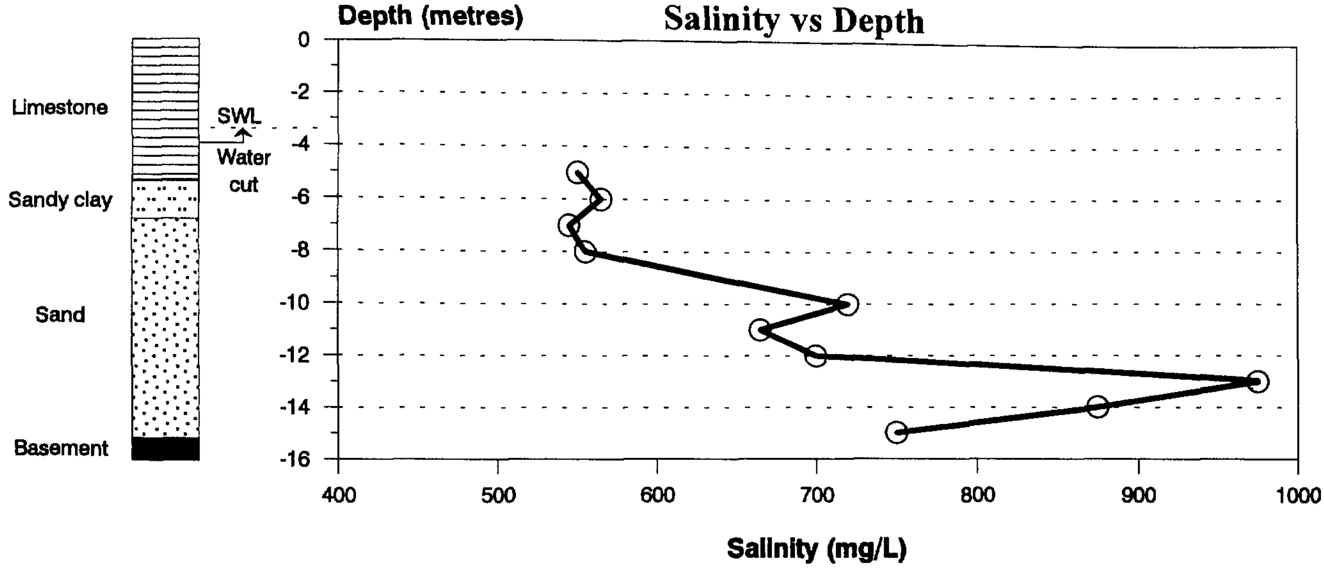
MINES and ENERGY
SOUTH AUSTRALIA

SALINITY DEPTH GRAPHS

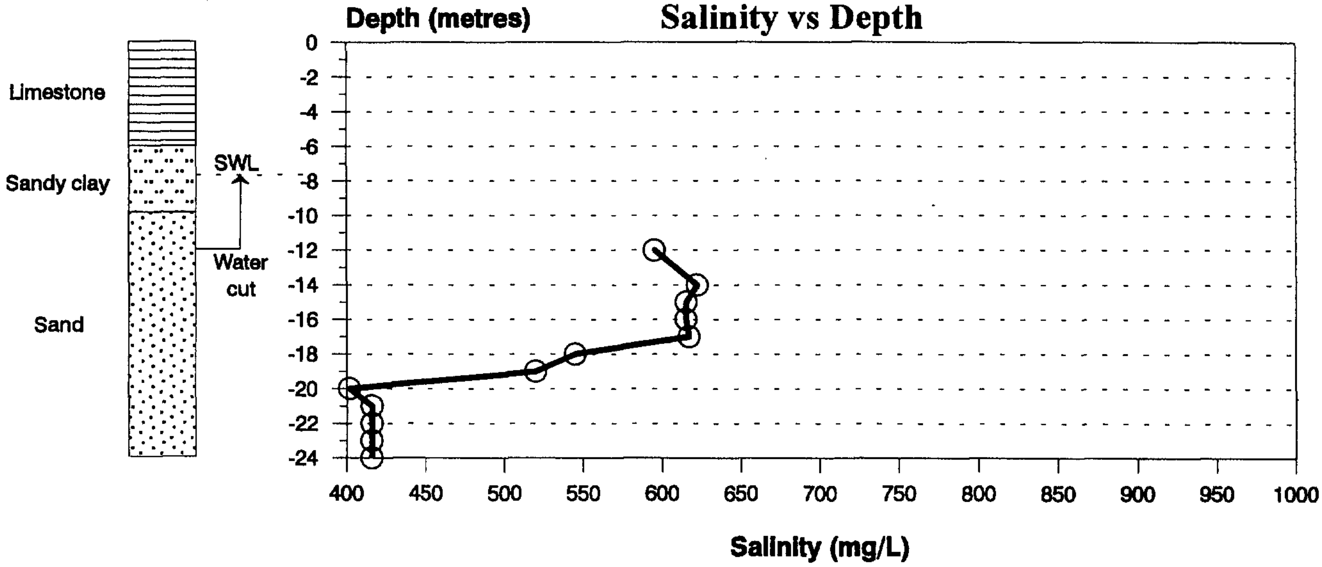
1996-0968

Job No. 5900AL.PRS

5930-1047
Salinity vs Depth



5931-395
Salinity vs Depth



5930-1050
Salinity vs Depth

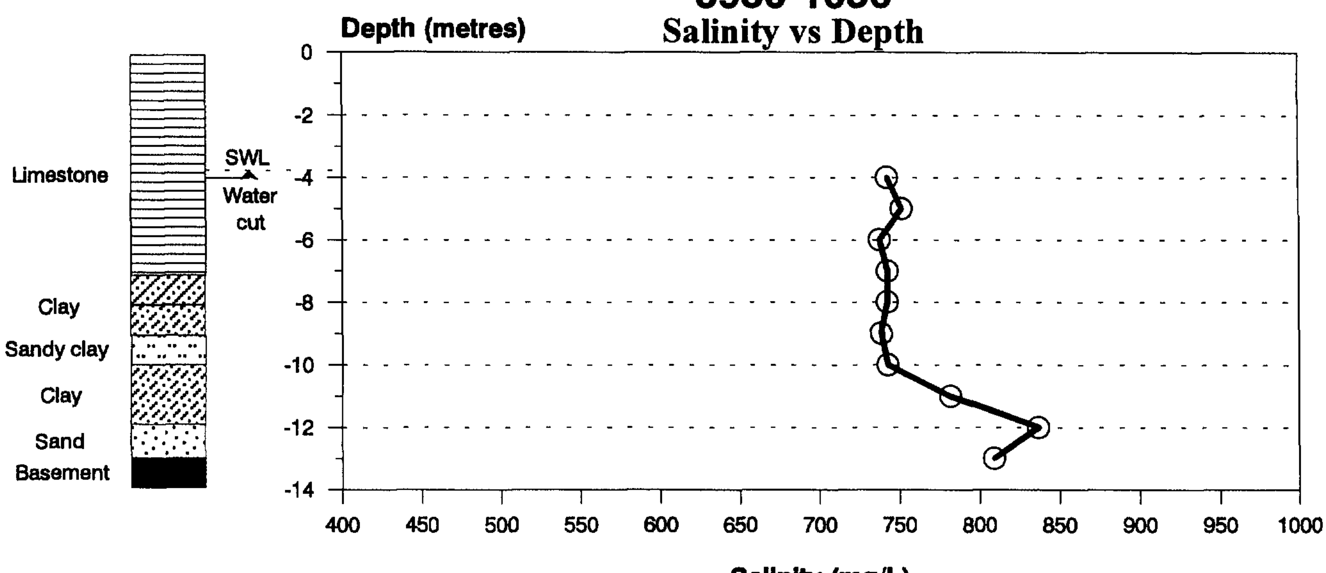


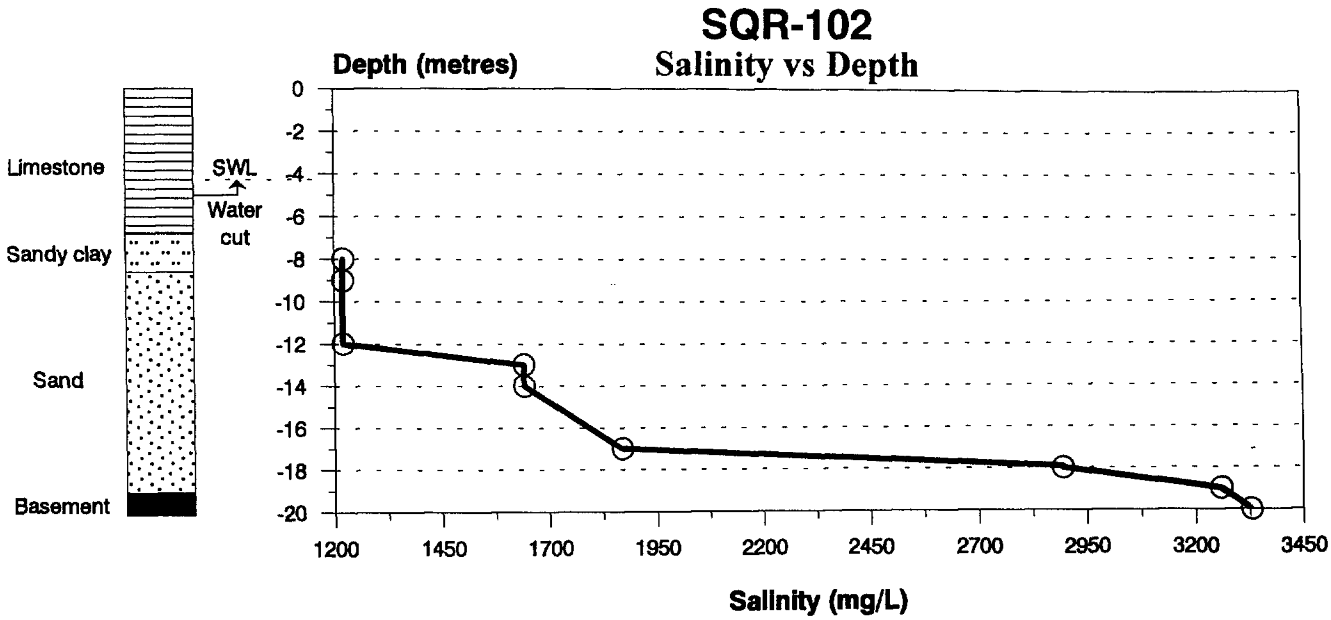
Figure 24

Job No. 5900AL.PRS

MINES and ENERGY
SOUTH AUSTRALIA

SALINITY DEPTH GRAPHS

1996-0969



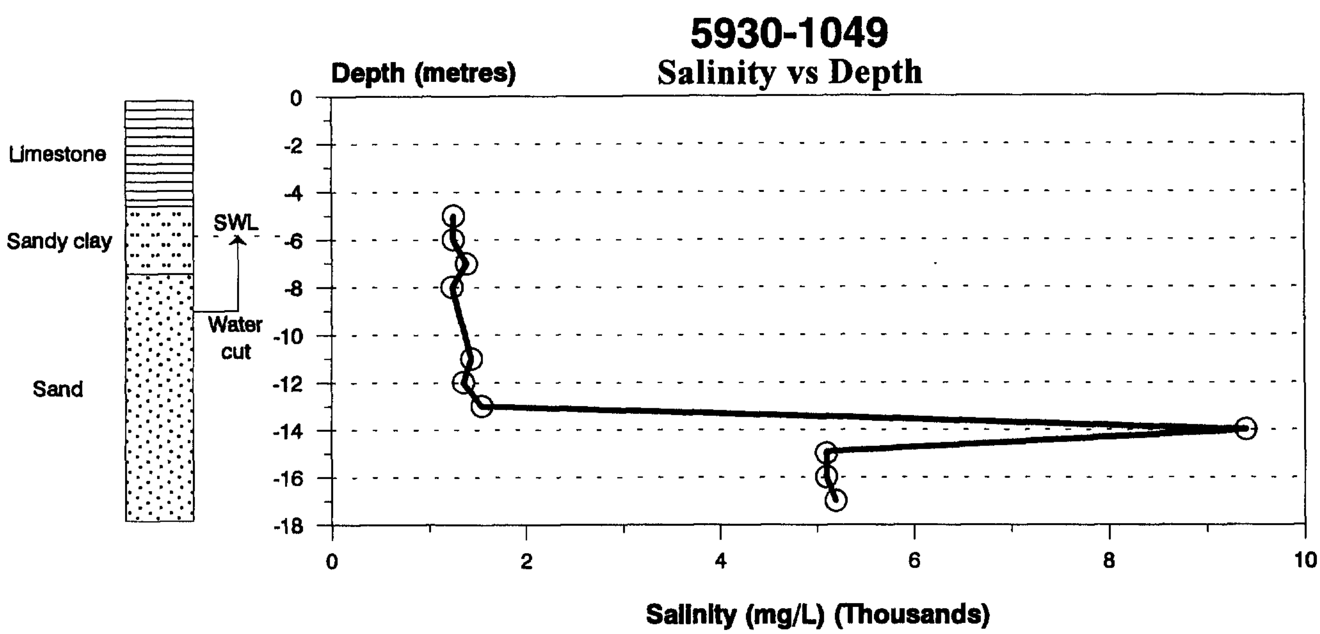


Figure 25

Job No. 5900AL.PRS

MINES and ENERGY
SOUTH AUSTRALIA

SALINITY DEPTH GRAPHS

1996-0970

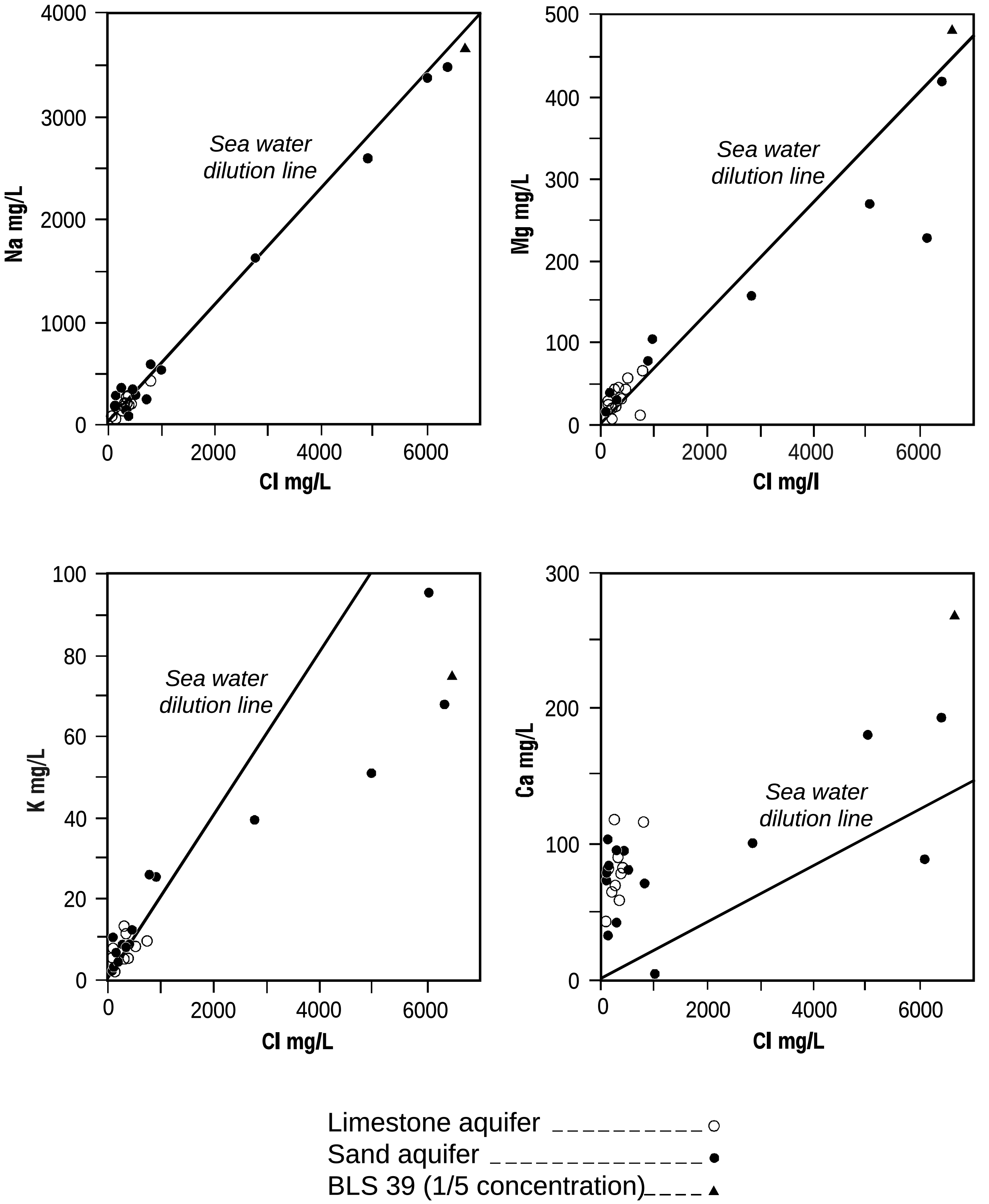


Figure........26

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

Major cations vs chloride

96-0972 MESA

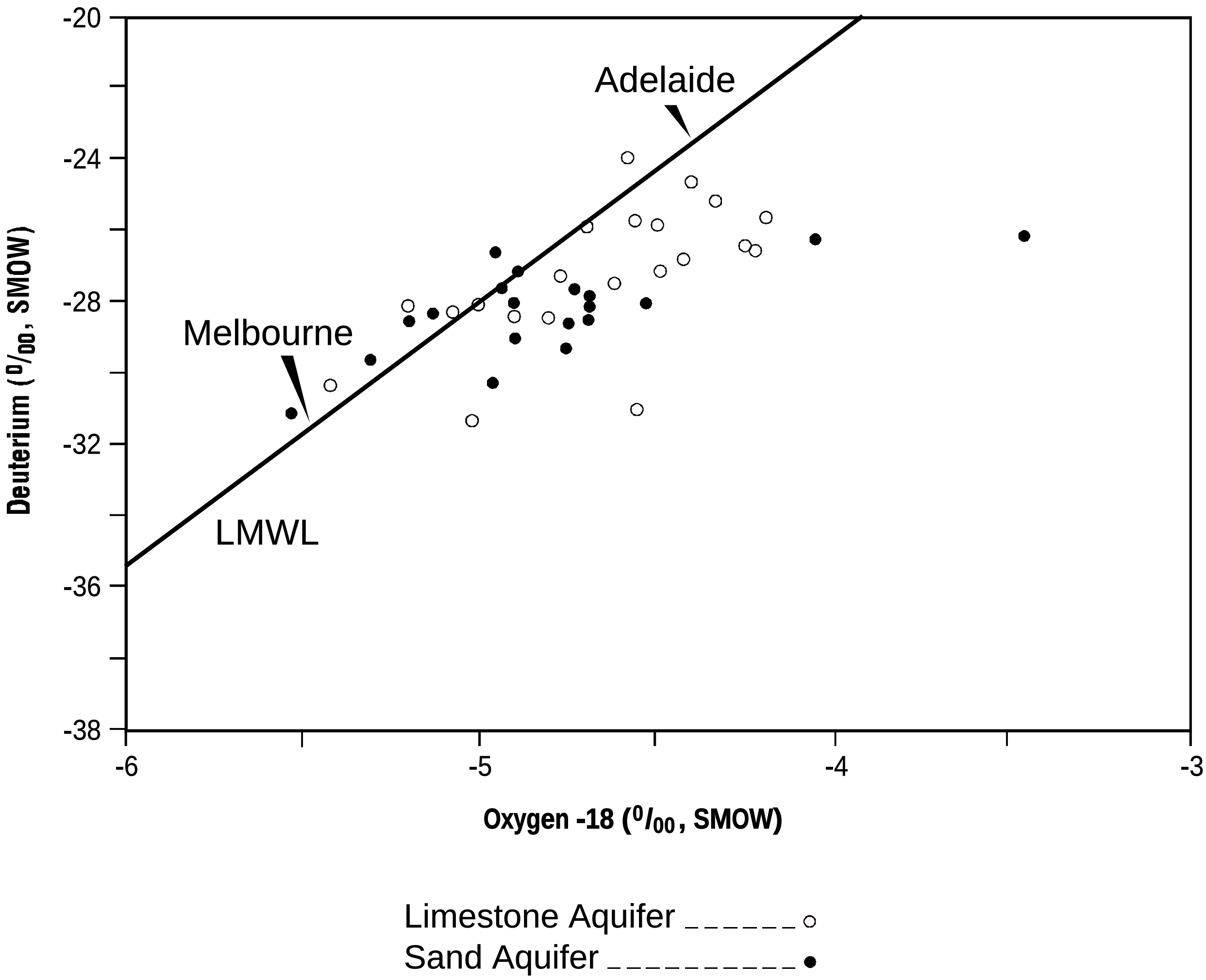


Figure........27

COUNTY MUSGRAVE HYDROGEOLOGICAL INVESTIGATION

Deuterium vs oxygen 18

96-0974 MESA

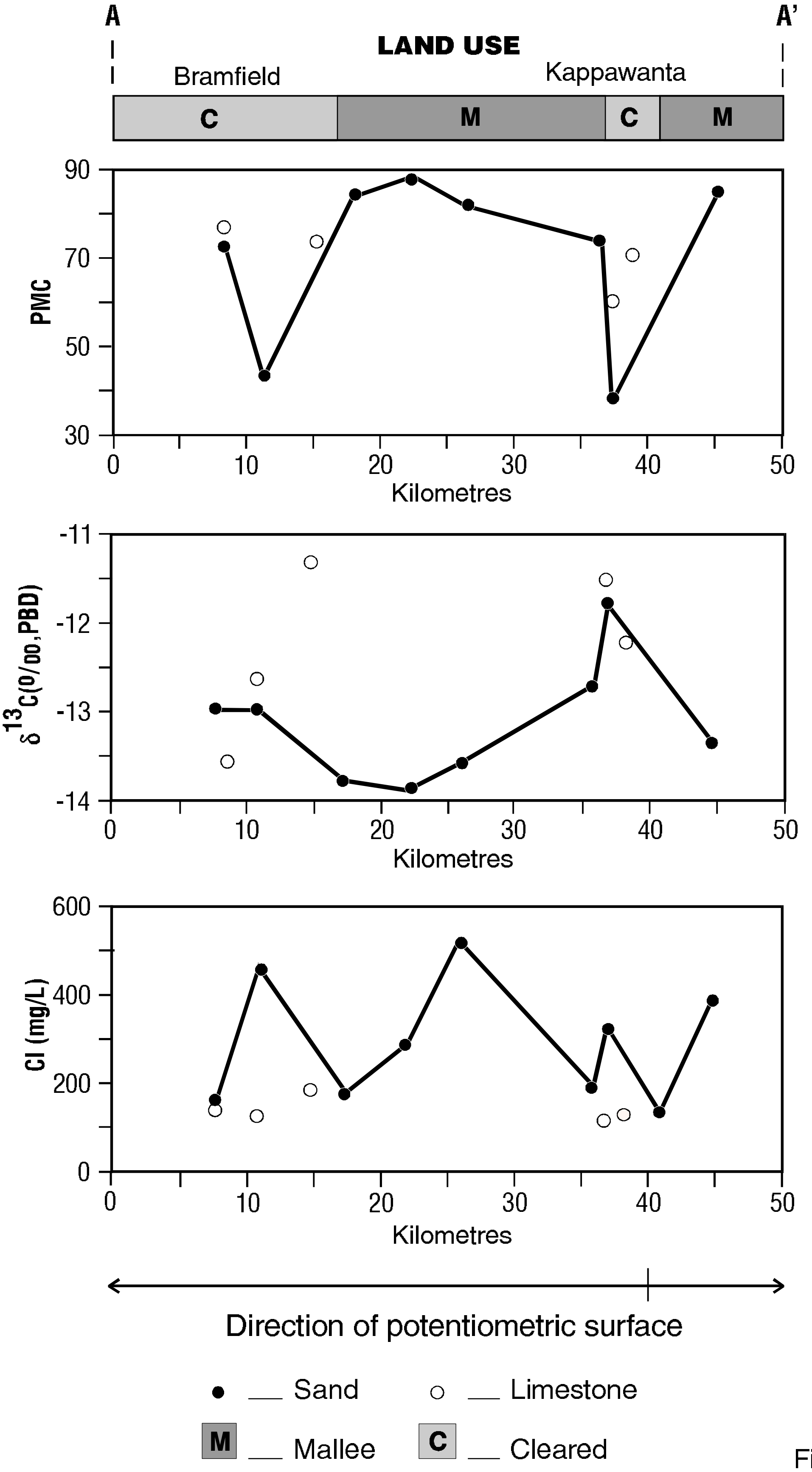


Figure........28

Percent modern carbon, carbon 13, and chloride transects for section A–A'

96-0975 MESA