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1. Summary

Geophysical surveys and drilling were used to investigate a saline valley on Allandale Research Farm. These techniques showed that the geology is controlling the location of two main areas of saline seeps and they identified another area at risk of increased salinity. They were also used to obtain information on the groundwater system and to assist in making management recommendations.

Electromagnetic terrain conductivity surveys showed that the most saline soils occurred upstream of a cross-cutting magnetic anomaly caused by a dolerite dyke. A seismic survey showed that the anomaly coincided with a bedrock rise. This bedrock rise restricts groundwater flow through the catchment and forces saline groundwater to the surface where it evaporates causing salts to build up in the soil profile. A second area of saline surface soils occurs further downstream. Outcrops of granite in the creek indicate that another bedrock rise is the cause for the location of this seep. A third area in the valley upslope from the main saline area has a high subsoil conductivity and is immediately upslope of a second magnetic anomaly. This area may become more saline in the future.

Drilling confirmed the seismic profile near the dolerite dyke in the main saline area. It also indicated that deep groundwater pressures are above ground level along the whole of the valley/ becoming higher with increased distance downstream. The quality of the groundwater ranged from 3,500 to 6,500 mg.Cl^{-1}/L.

Three recommendations are made for the area:

(i) the construction of an interceptor drain/ upslope of each saline area, to reduce waterlogging;

(ii) fencing the saline areas, and revegetating to salt tolerant grasses, bushes and trees;

(iii) limiting recharge on coarse textured soils in the catchment above the valley by growing crops and/or trees with high evapotranspiration potentials.

2. Introduction

2.1 Location

Allandale Research Farm is owned and managed by The University of Western Australia. It is 63 kilometres east of Perth (31°47'S, 116°22'E, **Figure 2.1**) immediately north of the Great Eastern Highway. To the south-west, lies the resort property, 'El Caballo Blanco', and to the north-east lies the Wundowie industrial area.

Two tributaries of Wooroloo Brook cross the farm in the north-west and in the south-east **(Figure 2.1)**. The north-western valley is affected by secondary salinity and was the area studied in this report.

2.2 Aim

The aim of this study was to define the extent and cause of the location of soil salinity in the north-western valley of Allandale Research Farm, using geophysical methods (magnetics, electromagnetic terrain conductivity and seismic survey). It was also aimed to check some of the geophysical interpretations by drilling and make management recommendations for controlling the salinity.

3. Materials and Methods

3.1 Survey methods

The magnetic and electromagnetic terrain conductivity measurements were carried out along 8/340 m of survey lines, both across and along the valley (**Figure 3.1**). The lines were located on an aerial photograph using readily observed features (e.g. fence lines). The first member of the survey party measured distances with a measuring wheel, marking the ground every 20 metres (the station interval for the readings). Three other members of the party followed keeping a 20 metre separation between the instruments to prevent interference.

Data from the survey were transferred to a base plan and hand contoured. An initial survey on September 26, 1986 located the main anomalies. Additional traverses were carried out on November 3, 1986 to fill in areas not clearly defined by the first survey. A seismic survey was carried out in the valley by Curtin University of Technology students during this second visit to the farm.

3.2 Magnetic method

The utility of the magnetic method depends on the principal magnetic minerals magnetite, ilmenite and pyrrhotite, which are widely distributed in the earth's crust. Geological formations containing these minerals will behave like large buried magnets and have associated with them a magnetic field (Nagata 1961, Strangeway 1967). Measurements of the magnetic field taken in the vicinity of such formations will show an anomaly in the earth's magnetic field. These anomalies could be large or small and could be either an increase or a decrease of the earth's field. The intensity of the anomaly will depend upon the depth of burial, the degree and direction of magnetisation and the attitude of the formation in relation to the direction of the earth's field at that location.

Magnetometers are the instruments used for measuring the magnetic field and by virtue of their sensitivity and range are able to distinguish between two rock types with small differences in magnetic mineral content. A magnetic dolerite dyke intruding into granite produces a prominent anomaly. This is because dolerite generally contains a higher concentration of the principal magnetic minerals compared with granite and therefore has a higher magnetic susceptibility and a greater intensity of induced magnetism.

A "Geometries"* G856 portable proton precession magnetometer with its sensor mounted on a two metre pole was used to survey the total magnetic field. A base station was visited periodically during the survey to account for diurnal changes and fluctuations in the earth's magnetic field.

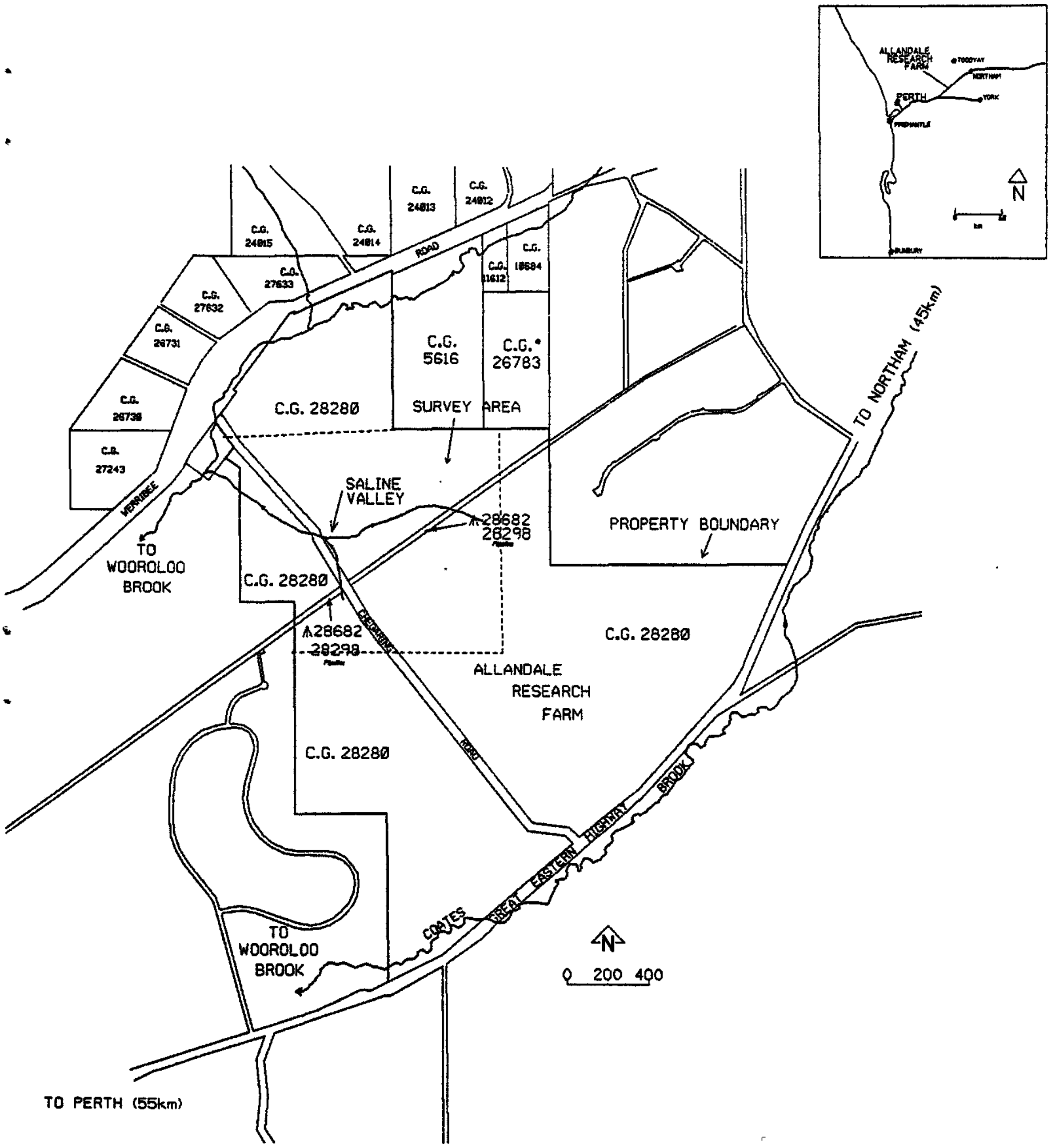

Figure 2.1. Location map of saline valley, Allandale Research Farm. [Inset: Location map of Allandale Farm]

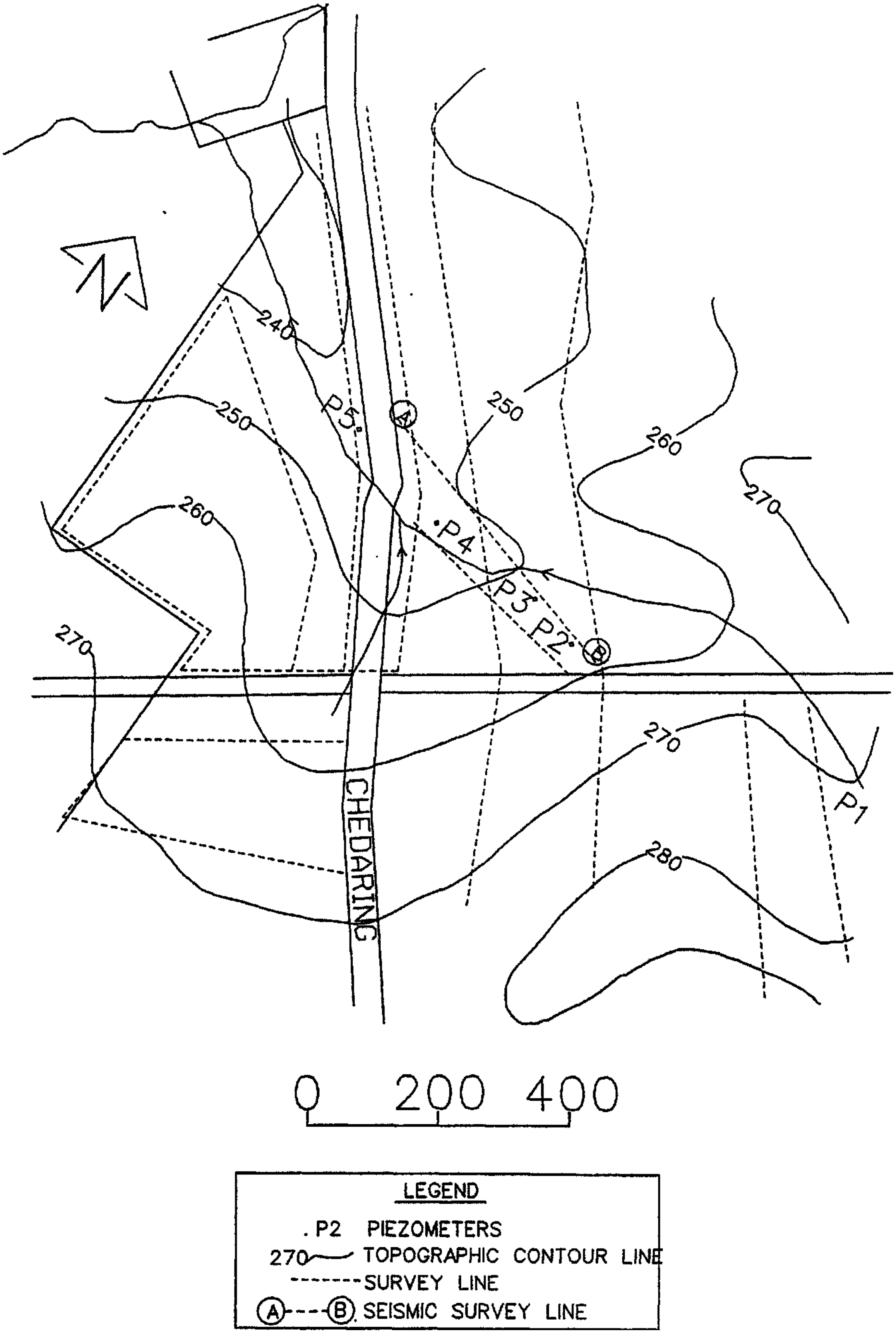

Figure 3.1. **Location of survey lines and piezometer nests.**

3.3 Electromagnetic terrain conductivity

Electromagnetic terrain conductivity surveys were carried out using "Geonics"[*] EM31 and EM38 instruments. Both have a transmitter and receiver coil, which are 3.7 m apart on the EM31 and 1.0 m apart on the EM38. The EM31 has a theoretical maximum depth of measurement of 6 m with decreasing sensitivity with increasing depth below the surface. It provides a measure of sub-surface salinity. The EMS8 has a theoretical maximum depth of measurement of 1 m and provides a measure of surface salinity (McNeill 1980).

The transmitter coil produces a primary electromagnetic field, which penetrates the ground. A secondary electromagnetic field is induced in the ground in such a manner that its amplitude is directly proportional to the terrain conductivity (reciprocal of resistivity). The ratio between the primary and secondary magnetic fields is measured by the voltage induced in the receiver coil. The instruments display the conductivity reading on a meter.

In electromagnetic terrain conductivity surveying, the conductivity of formations can be studied in relation to depth or spatial extent. Electromagnetic soundings measure the conductivity in relation to a maximum depth of current penetration. Alternatively, a conductivity map shows the conductivity to a maximum depth over an entire area. Within an area it is often useful to use several maps with different depths of investigation.

3.4 Seismic method

A 12 channel refraction system with an ocillograph was used. A 60 gelignite detonated in shallow (0.5 to 1.0 m) auger holes was used as the source of energy.

The length of the geophone spreads was 100 m with geophone intervals of 10 m. Four shots per seismic spread were fired; one at each end of the spread and one at 20 m offsets from each end. Reciprocal geophones were used to record the shot point to shot point travelling times. The travelling time from the offset shot point to its complementary shot point was also recorded (i.e. the reciprocal time).

Using the reciprocal method of interpreting the results, the deepest refractor detected was computed in terms of the time ("time depth") under each geophone (Palmer 1981). The "time depth" multiplied by a depth conversion factor (which is a function of the overburden materials) gives the depth to the high velocity refractor (usually bedrock).

3.5 Drilling

Bore holes were drilled using a rotary air blast drilling rig at five locations within the saline valley. Piezometers were installed in the deepest holes by inserting 50 mm PVC tubing, which was slotted over the bottom two metres to enable groundwaters to

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[*] Trade name

enter the tubing. The piezometers measure groundwater pressures at depth within the aquifer. To prevent groundwaters under pressure leaking up the annulus outside the tubing, a bentonite clay slurry was placed in the annulus to form a seal. Cement was used to seal some holes at the surface. Shallow wells were also installed at each site. These consisted of fully slotted bores without a bentonite seal. These wells measure groundwater levels in the top two to three metres. Together, the piezometers and wells provide information on vertical hydraulic gradients within the aquifer, indicating zones of recharge (downward gradients) and discharge (upward gradients). The relative levels of the bores were surveyed to enable horizontal gradients in hydraulic head to be calculated.

4. Results

4.1 Magnetic survey

The strongest anomaly (about 300 nT above the background of 58,700 nT) strikes NNW and crosses the valley where the two drainage lines and Chedaring Road meet (**Figure 4.1**). The anomaly is not linear, possibly due to structural disruption to the magnetic body and/or to variations in magnetic strength along the body. Limited outcrops in the valley indicate the anomaly is due to a thin dolerite dyke. In places, the anomaly is slightly offset to the west of the dolerite outcrop in the valley, possibly indicating that the dyke dips in a westerly direction.

A second magnetic anomaly (about 200 nT above background) strikes NNE and crosses the eastern drainage line near the pipeline. Dolerite scree in this area indicates the probable cause for the anomaly is another dyke.

4.2 Electromagnetic terrain conductivity survey

The highest surface soil conductivities (EM38 readings) are associated with the main drainage line upstream from the dolerite dyke and where the drainage line leaves Allandale Farm (**Figure 4.2**). The 40 mS.m^{-1} contour indicates the saline area is widest immediately upslope of the dyke. The anomalies are not highest in the deepest part of the valley, being offset to the south by about 60 m.

The highest subsoil conductivities (EM31 readings) are also offset to the south of the main valley (**Figure 4.3**). The broadest anomaly occurs immediately upslope of the dolerite dyke, as defined by the magnetic anomaly. Conductivities using the EM31 were generally lower than those using the EM38, indicating a concentration of salts in the surface soils. The EM31 map shows an area of high subsoil conductivity where the main valley crosses the pipeline. This anomaly is immediately upslope of the secondary magnetic anomaly (**Figure 4.1**) and is associated with slightly saline surface soils (**Figure 4.2**). It is possible that a second dolerite dyke (or other magnetic body) is causing groundwaters to build up behind a hydraulic obstruction at this point in the valley. This may be an area where secondary salinity will increase in future.

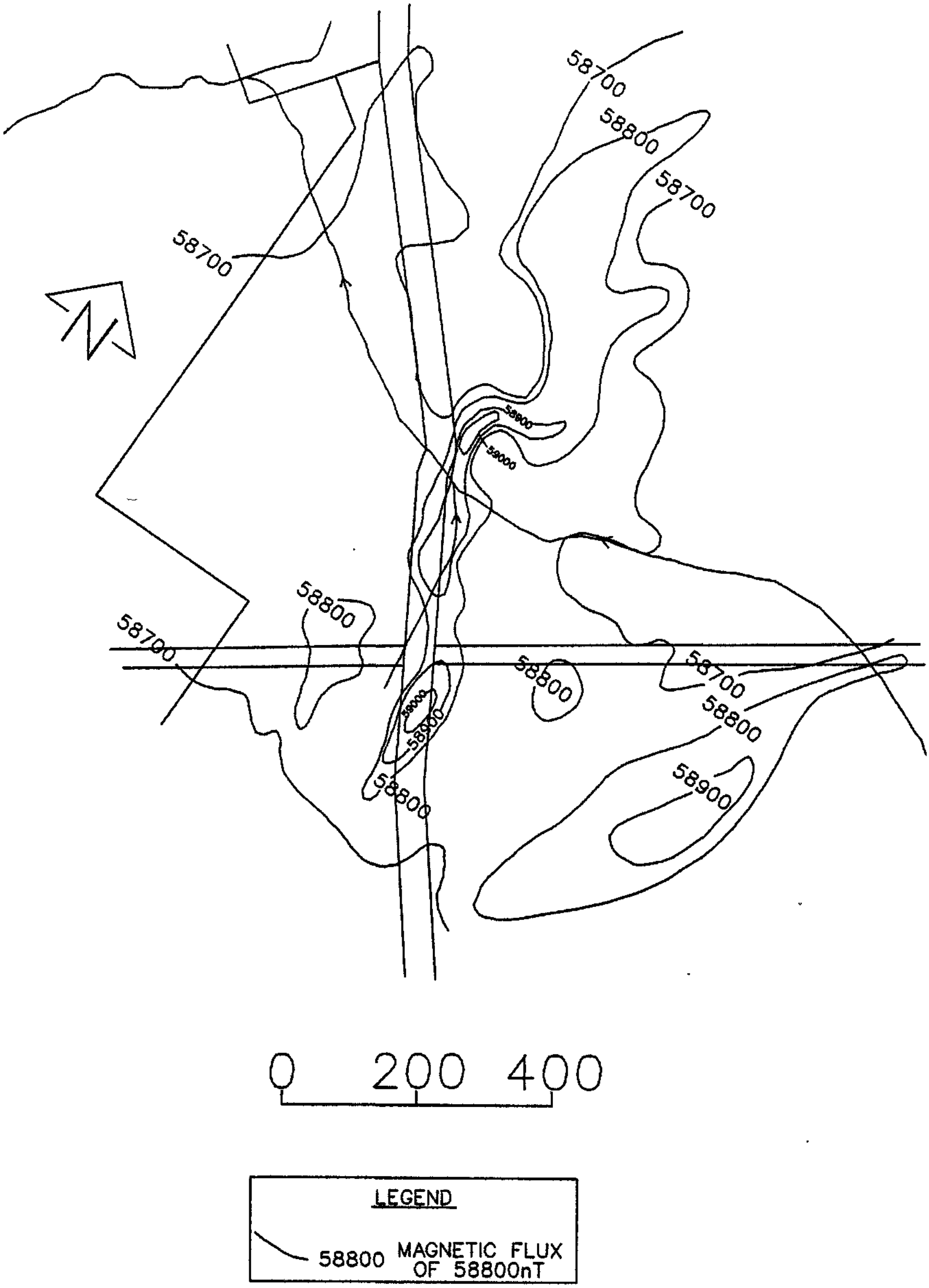

Figure 4.1. Magnetic contour map.

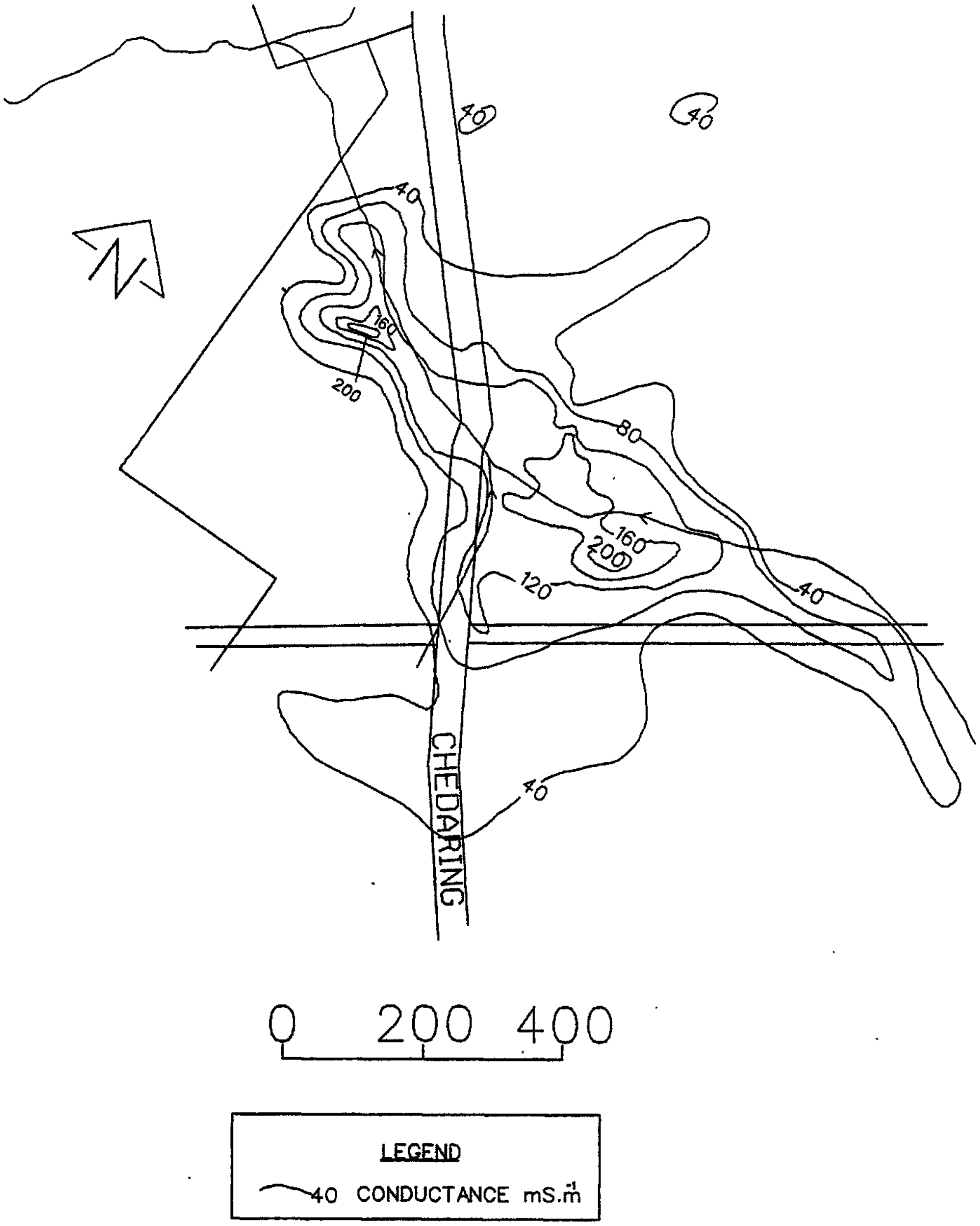

Figure 4.2. EM.38 electromagnetic terrain conductivity of the surface soils.

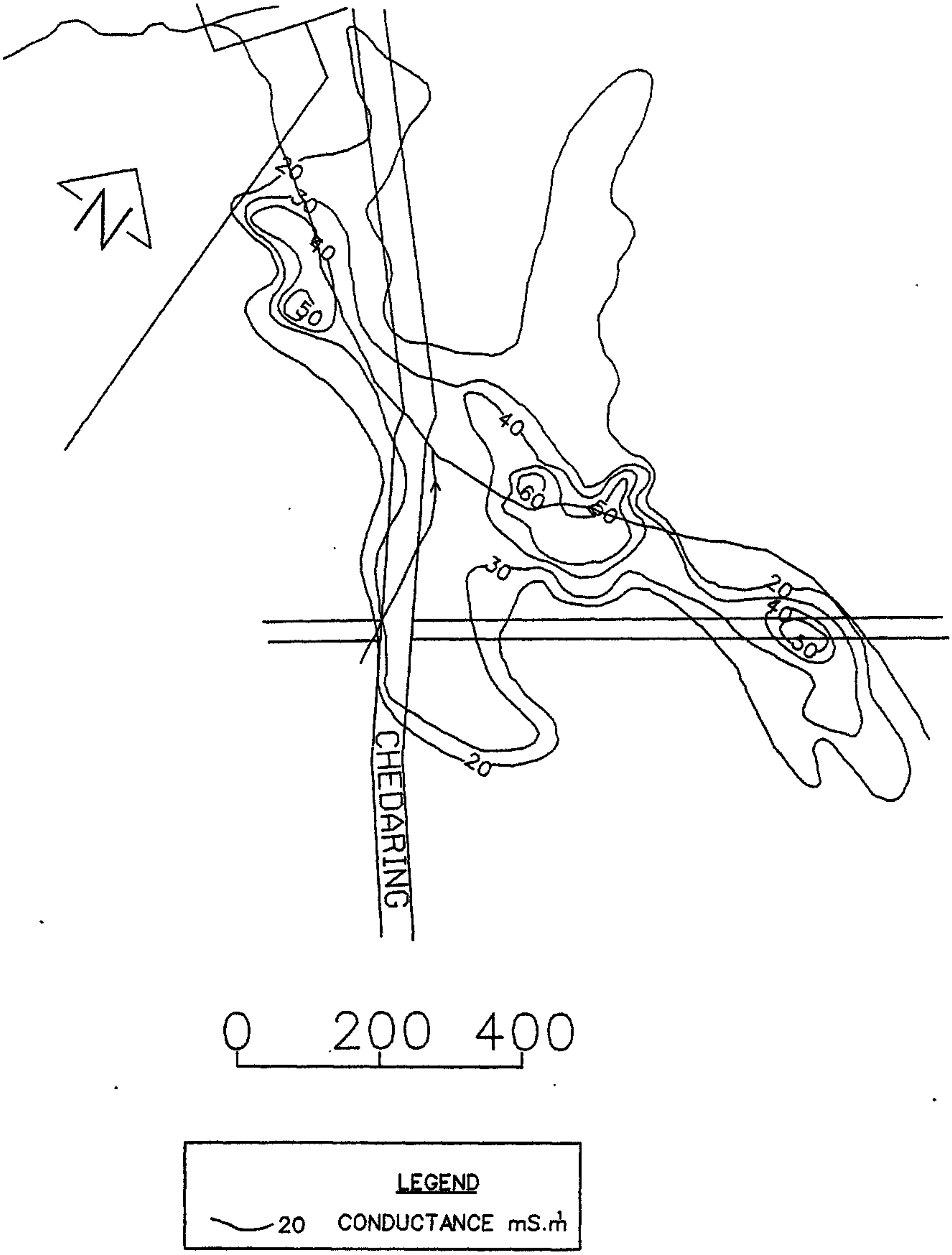

Figure 4.3. EM.31 electromagnetic terrain conductivity of the subsoil.

4.3 Seismic survey

The seismic velocities of the deepest refractor detected (bedrock) varied between 3,900 and 6,100 m.s^{-1}. It was generally greater than 4,600 m.s^{-1}, which suggests it is little weathered. Overburden materials were characterised by seismic velocities between 1,300 and 2,500 m.s^{-1}. These relatively high velocities may be due to the shallow groundwater underlying the valley.

A cross-section between points A and B in the valley was compiled, using data from the seismic refraction survey (**Figure 4.4**). The depth of the basement is 15 to 20 m over the upslope 280 m of the transect but is almost at the surface 60 and 80 m upslope of point A. This represents a marked decrease in transmissivity for the aquifer in the valley.

The magnetic profile along the seismic profile (**Figure 4.4**) shows that the bedrock rise coincides with a magnetic high (part of the magnetic anomaly shown in **Figure 4.1**). Dolerite outcrops and scree occur in the valley indicating the basement high and magnetic anomaly are probably caused by a cross-cutting dolerite dyke.

4.4 Drilling

The five piezometer nests enabled the construction of a geological cross-section of the valley (**Figure 4.5**). The bedrock rise predicted by the seismic survey was confirmed by drilling at P4. The bedrock rise downstream of P5 has been inferred from a number of outcrops of granite in the creek. The outcrops indicate that the granite bedrock rise is broader than the high caused by the dolerite dyke at P4. A third basement high is postulated between P1 and P2 to coincide with the weak magnetic anomaly at this point. Piezometer P1 was located in the area with a high subsoil conductivity (**Figure 4.3**) and encountered the most saline groundwaters (6,500 mg.Cl^{-1}/L). The hydraulic head in the deepest bore was above ground level. Upward gradients at P1 (0.08) were slightly stronger than at P2 (0.07), but less than those at P3 (0.17) and at P5 (0.51). The high gradient at P1 (relative to P2) is further evidence of a decrease in transmissivity between P1 and P2. Concentrations of chloride in deep groundwater were high throughout the cross-section, ranging from 3,500 to 6,500 mg.Cl^{-1}/L. There is a progressive increase in chloride concentrations in the shallow groundwater between P2 and P5 (**Appendix 1**).

The conductivity, pH, chloride and saturation-percentage of drill samples from the four deep holes (P1, P2, P3 and P5) on the transect were measured (**Appendix 2**). Most holes had increasing salt concentrations with increasing depth. P1 had high levels in the top metre due to concentration by evaporation on the saline seeps. The top metre of many profiles had a higher pH, and P5 had higher pH values throughout the profile.

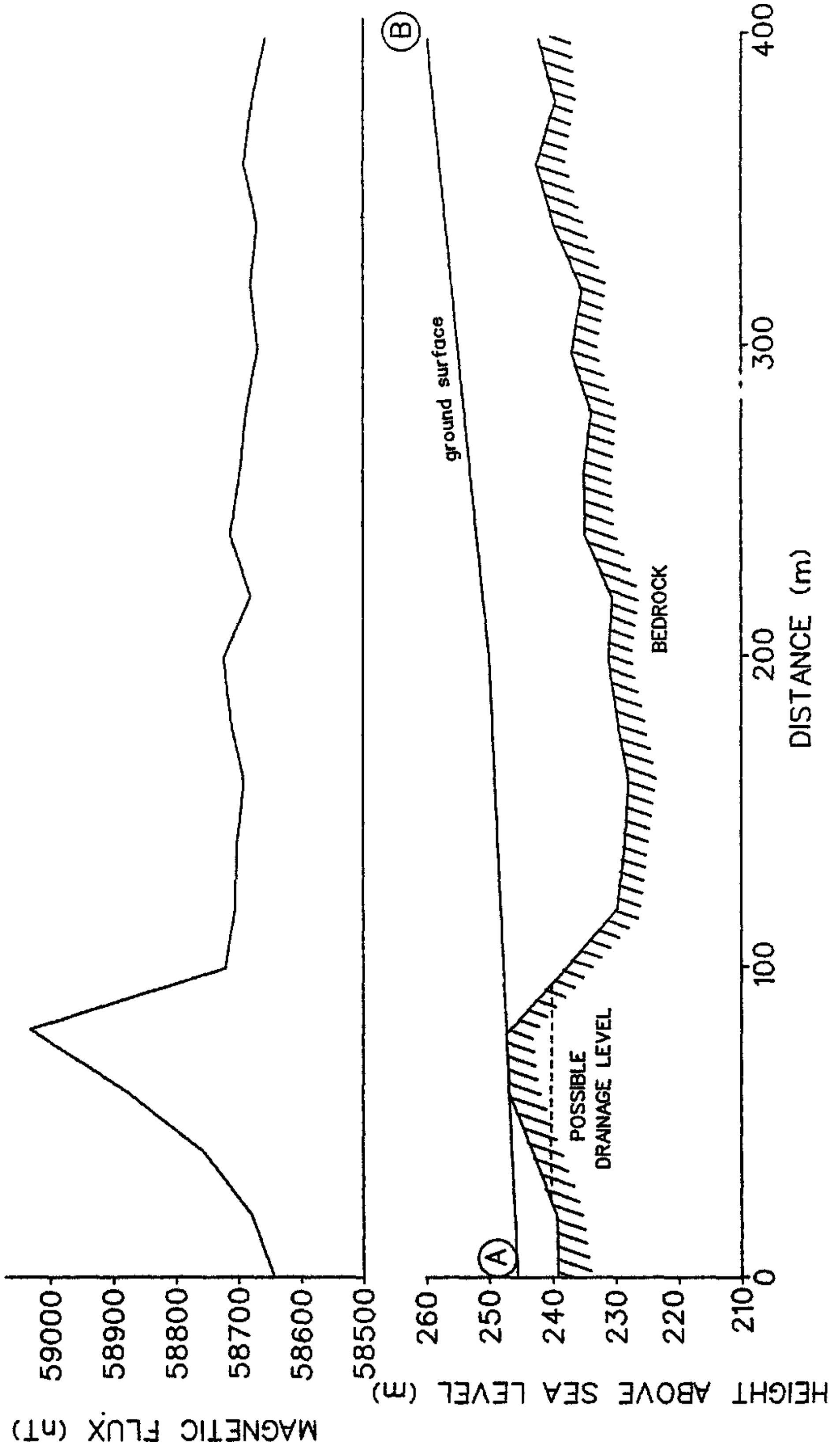

Figure 4.4. Seismic cross-section A-B (below) and magnetic flux profile (above).

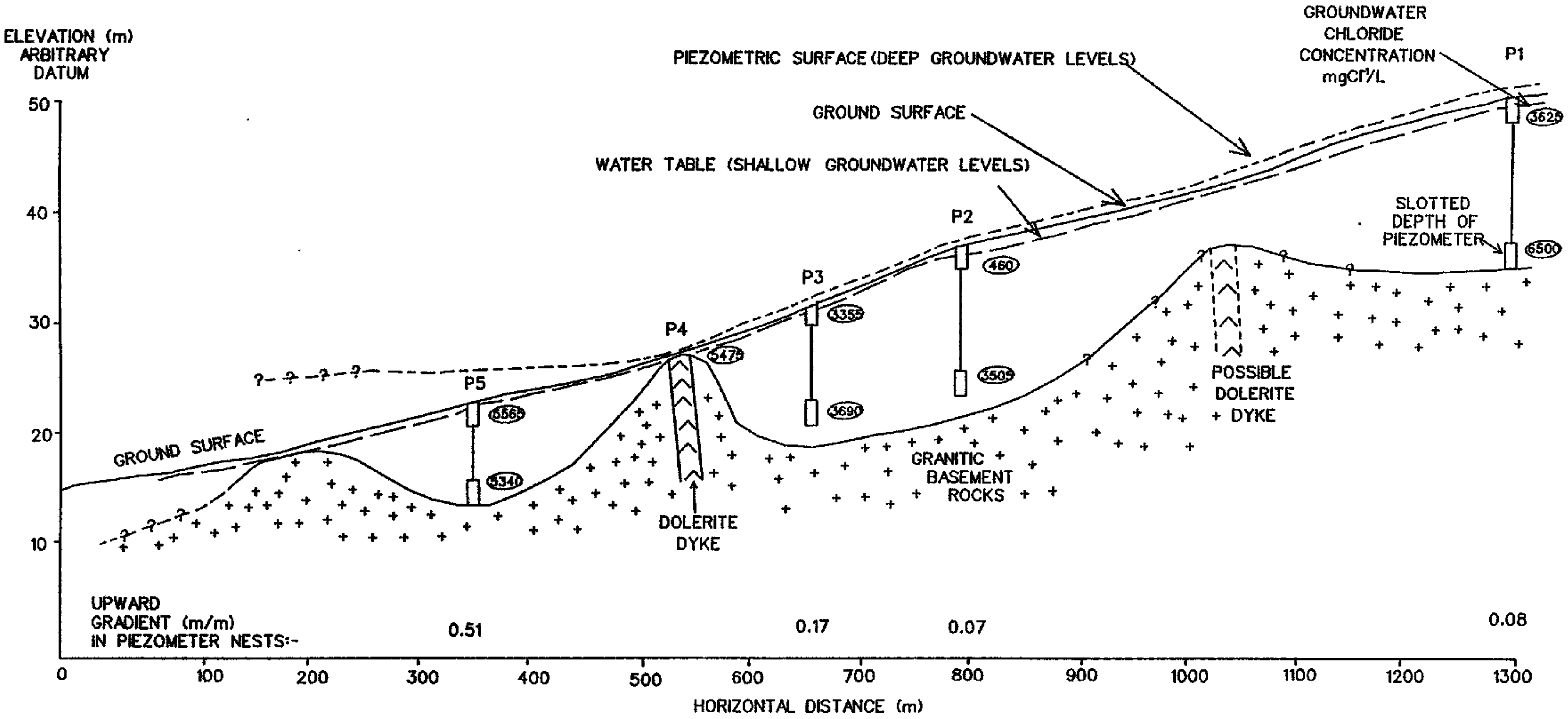

Figure 4.5. Cross-section* A-A1 showing bedrock rises and the plezometric surface.

5. Discussion

Dolerite dykes have been found to cause obstructions to the flow of groundwater flow in other studies (Bettenay 1978, Engel *et al*. 1987). At Yalanbee, the dykes weathered to form clay and rock bars, which inhibited groundwater flow (Bettenay 1978) while at Harrogin, the dykes weathered more deeply than the surrounding country rocks but produced less permeable weathering products (Engel *et al*. 1987a). Mineralogically, dolerite would be expected to weather more deeply than granite or granitic gneiss (Carroll 1970). However dolerite usually has a less open rock fabric than granite and granitic gneiss, which would inhibit the entry of weathering fluids. Thin dolerite dykes may have more cooling cracks, which aids water entry. In the Narrogin area, dolerite commonly outcrops (with contact granite) on hillsides but weathers more deeply in the valleys. This may be due to differences in the weathering environments in upland and lowlands areas, or to a difference in the competence of the country rock in the two areas. At Allandale, the dolerite dyke appears to be more resistant to weathering than the surrounding country rocks, despite being in a lowland area. In the York-Beverley area, large granite outcrops occur in upland areas with more weathered dolerite dykes traversing them. Whether the dolerite dykes are a positive or negative bedrock feature therefore appears to be due to a number of factors; namely the nature of the country rocks/ their position in the landscape and possibly their thickness (which affects cooling cracks).

Subsoil conductivities were greater than 20 mS.m^{-1} over the dyke, even outside the valley floor. This could be due to saline groundwaters being forced towards the ground surface over the dyke, but could also be due to higher clay contents over the dyke retaining more salt. Williams and Hoey (1987) found a good correlation between terrain conductivity and clay and salt content.

The geophysical surveys have provided information for evaluating management options. Discharge from the deep saline sumps, which have formed behind the bedrock rises, may be increased by draining, siphoning or pumping. The seismic section provided information on the quantity of soil and rock needing removal to reduce groundwater levels upslope of the dyke. If the granite high downslope of P5 is broad, it may be more feasible to blast to crack the rock rather than to excavate a drain through the rock itself. Because dolerite weathers to a low permeability clay, blasting may be insufficient to breach the hydraulic barrier at P4. Tube drainage would probably clog with ferrihydrite gel (evident in seepage waters) and is not a feasible solution. Even if an open drain were constructed through the barriers, the low permeability of the material around the drains may limit drawdowns. Pump tests would be needed to determine aquifer transmissivities to estimate the drawdown around the drains. The high upward gradients at PS may indicate that siphoning is feasible. However, if the gradients are due to low permeability material, the effect of the siphoning would be limited in area. All drainage options require a safe disposal site for the saline effluent.

A complementary option for the catchment is to reduce recharge to the groundwater by shortening crop rotations, by growing crops with high water use and/or by planting more trees in recharge areas (Nulsen 1983). Recharge areas can be inferred from soils maps to an extent. Electromagnetic terrain conductivity maps have also been used to infer areas with differing recharge mechanisms (Engel *et al*. 1987b). Given that three saline seepages (and bedrock rises) occur within 900 m, it is likely that the most economical solution is to construct a surface drain upslope of each seep to limit waterlogging (McFarlane 1985) before fencing the seepage areas and establishing salt-tolerant trees and pastures.

6. Conclusions

The extent of the surface salinity appeared to be well mapped by the shallow terrain conductivity method (EM38). The deep terrain conductivity method (EM31) located three main saline areas within the valley, two of which were immediately upslope of cross-cutting magnetic anomalies. A seismic survey across the main magnetic anomaly showed a bedrock rise, which was confirmed by drilling. Outcrop and scree showed that the bedrock rise and magnetic anomaly were probably due to a dolerite dyke. Outcrops of granite in the creekline below the lowest saline area show this seepage area is probably caused by a broad basement high. Piezometers in the valley had upward gradients and saline groundwaters throughout.

The presence of three bedrock rises within 900 m and the high iron content of the groundwaters probably limit drainage options for the saline valley. Efforts should be made to reduce recharge above the valley and to establish salt-tolerant plants in the saline areas, once conditions in these areas have been improved by interceptor drains (for waterlogging control) and fencing (for stock control).

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8. Acknowledgements

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9. Appendix

Appendix 1. Relative elevation of piezometer sites, water levels, vertical gradients and chloride concentrations

NB: All elevations are relative to the ground level at piezometer 1 (P1)

A bores are shallow, B bores are deep.

Piezometer	Elevation ground level (m)	Slotted depth Elevation	Water level 3/6/1987	Vertical gradient (m/m)	Groundwater mg.Cl-1/L (m/m) 31/7/1987
P1 A	50.00**	47.88 – 49.63	49.32	+0.08	3625
P1 B		34.90 – 36.90	50.35		6500
P2 A	36.82	35.49 – 36.74	36.05	+ 0.07	460
P2 B		23.34 - 25.34	36.88		3505
P3 A	31.50	29.00 – 30.50	31.37	+ 0.17	3355
P3 B		19.01 - 21.01	32.99		3690
P4 A	27.40	26.35 - 27.28	27.20	N.A.	5475
P5 A	22.61	20.33 – 22.33	22.26	+ 0.51	5565
P5 B		13.43 - 15.43	25.76		5340

*	+ = upward gradient
**	arbitrary datum
N.A.	= not applicable

Appendix 2. Chemistry of soil samples from four deep drill holes

Site	Depth metres	pH 1:5H$_2$0	EC$_{1:5}$ mS/m	%Cl$_{1:5}$	Sat %	EC$_e$ mS/m
P1	0- 1	5.9	18	0.03	26.1	272
	1- 2	5.4	30	0.05	39.4	256
	2- 3	4.7	25	0.04	40.5	245
	3- 4	3.9	29	0.08	52.5	208
	4- 5	3.4	54	0.08	65.9	328
	5- 6	3.5	85	0.14	64.2	401
	6- 7	3.8	94	0.15	64.8	544
	7- 8	3.7	104	0.16	59.8	589
	8- 9					
	9-10	4.0	95	0.27	65.7	1212
	10-11	3.9	64	0.21	61.6	1040
	11-12	4.0	101	0.22	57.0	1131
	12-13	3.8	183	0.30	54.1	1452
	13-14	4.0	128	0.21	47.7	1186
	14-15	4.3	183	0.31	41.0	1483
	15-15.5	4.4	114	0.18	37.5	1205
P2	0- 1	6.1	7	0.01	26.0	118
	1- 2	4.6	14	0.02	47.6	113
	2- 3	4.9	10	0.01	41.8	88
	3- 4	4.9	8	0.01	50.3	62
	4- 5	4.4	10	0.01	54.3	60
	5- 6	4.5	11	0.02	52.6	69
	6- 7	4.9	17	0.03	57.0	131
	7- 8	4.4	31	0.05	63.6	234
	8- 9	4.3	81	0.12	58.2	652
	9-10	4.2	191	0.32	60.1	1315
	10-11	4.4	129	0.20	61.5	953
	11-12	4.1	132	0.21	57.3	961
	12-13	4.1	133	0.21	57.8	960
	13-14	4.1	111	0.17	49.3	929
	14-15	4.2	115	0.18	52.0	908
	15-16	4.3	123	0.19	43.6	1377
	16-17	4.3	131	0.21	47.3	910

	17-18	4.6	96	0.15	47.8	794
P3	0- 1	4.0	184	0.29	29.7	2150
	1- 2	4.3	31	0.04	35.8	349
	2- 3	4.0	46	0.07	43.9	416
	3- 4	4.0	53	0.08	42.3	483
	4- 5	4.4	78	0.12	42.1	853
	5- 6	4.5	97	0.15	41.6	916
	6- 7	4.4	94	0.14	39.4	808
	7- 8	4.5	103	0.16	41.7	1033
	8- 9	4.6	79	0.12	41.3	788
	9-10	4.6	71	0.11	40.1	666
P5	0- 1	6.1	52	0.08	37.5	553
	1- 2	5.4	21	0.03	36.2	250
	2- 3	5.2	38	0.05	45.4	375
	3- 4	5.2	75	0.12	52.3	683
	4- 5	5.9	82	0.13	52.2	735
	5- 6	5.9	167	0.29	55.5	1352
	6- 7	6.3	224	0.42	61.2	1818
	7- 8	6.5	187	0.33	55.2	1510
	8- 9	6.5	178	0.31	53.3	1483
	9-10	6.5	156	0.26	54.1	1296
	10.6	6.2	148	0.25	53.0	1404