CHAPTER 4

FIELD RESULTS AND INTERPRETATION

4.1 FIELD PROGRAM

4.1.1 SITE SELECTION

The field area for this study was chosen after discussion and a field reconnaissance (Trip 1) with Dr Graham Allison of CSIRO Division of Soils (later Chief, Division of Water Resources) and Mr Don Armstrong of the South Australian Department of Mines (SADME). The most intensively investigated region is in the Olympic Dam Project borefield A area, south of Lake Eyre South, shown with the location of holes drilled in figure 4.1.1. Local topography and features of each site are recorded in appendix 1. It is an economically important water supply area, where leakage of the the pressurised Great Artesian Basin aquifer (Cadna-owie Formation / Algebuckina Sandstone) was known to be significant, the geometry and piezometry of the hydrogeology fairly well known, and the climate arid so that the method of Allison and Barnes (1983) was likely to be applicable. Most holes were drilled in the borefield proclaimed area, and the subsidiary site near Hamilton Hill and its associated mound springs. Holes 5, 6 and 7 were of an exploratory nature to the west of Lake Eyre, where the aquifers are no longer artesian and vertical leakage to the water table is not currently occurring (the water table is in or slightly above the aquifer itself; locations given in figure 1.2.2). It is possible that such areas were artesian in the past, and that the isotopic composition of gypsum crystallisation water might have "frozen in" an evaporative profile from those times.

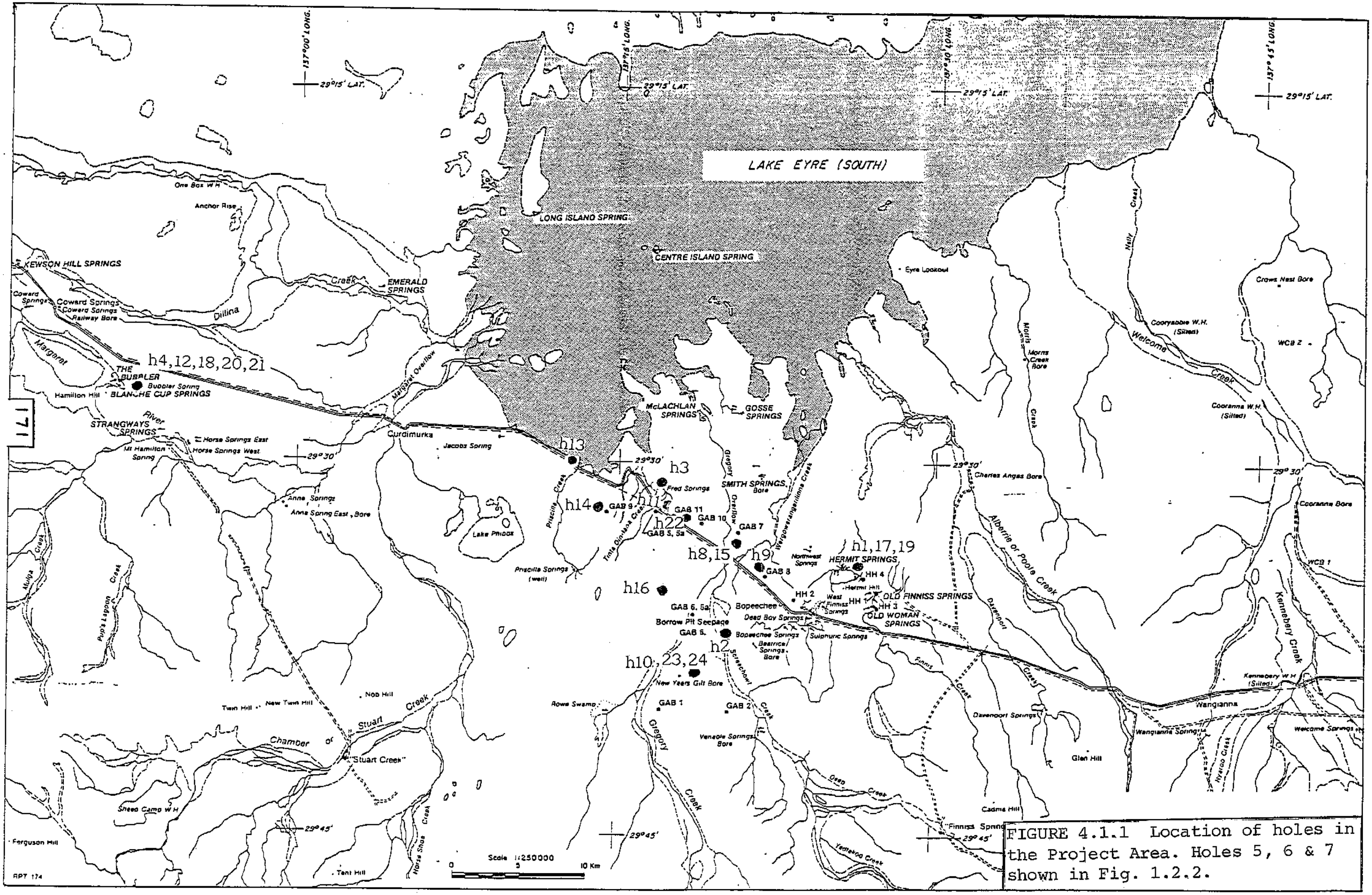

FIGURE 4.1.1 Location of holes in the Project Area. Holes 5, 6 & 7 shown in Fig. 1.2.2.

4.1.2 SAMPLING

Drilling was carried out using 100 and 75mm diameter hand augers (holes 1-7 and 17-20) and by rotary drilling with the Division of Soil's "Investigator" drilling rig, using hollow-stemmed augers and wireline recovery equipment (Plate 4.1). Repeated holes at the same site and same time are given an alphabetical character suffix (12A, 12B, etc). Rig drilled holes generally had poor recovery for the first 10 to 25 cm, and so samples in this interval were taken by spade in small pits adjacent to the deep hole. Where possible continuous coring was carried out, although there are some gaps in the rig drilled profiles where samples were lost. A small aliquot was taken of each interval sampled, for water and gypsum content and chloride analysis, and stored in small air-tight plastic containers (chippettes). The major aliquots were stored in 500ml glass jars with airtight, rubber-sealed metal twist lids, additionally sealed with P.V.C. electricians' tape. Where possible, groundwater samples were taken, usually by lowering a sponge down the hole on string and wringing it out into a plastic bottle. The lithology of the samples was described in the laboratory rather than the field, since the samples were also to be analysed for stable isotopes and so had to be bottled with all haste to avoid fractionation by evaporation or exchange with atmospheric water vapour. Descriptions were simplified from the manner of Folk (1980).

The results of the drilling programme are summarised in table 4.1.1.

TABLE 4.1.1

Summary of Drilling Results

					Pore Water Isotopes			Gypsum Water
Hole	Date	Method	Depth m	Sample	δD	$\delta^{18}O$	Suction	Isotope(s)
1	8-9-86	manual	1.35	no	yes	yes	yes	no
2	"	"	0.45	no	yes	yes	yes	no
3	"	"	1.20	no	yes	yes	no	yes
4	"	"	2.70	yes	yes	yes	no	no
5	"	"	2.60	no	no	no	no	no
6	10-9-86	"	0.90	no	no	no	no	no
7	"	"	0.60	no	no	no	no	no
8	28-10-86	rig	7.35	no	yes	no	no	yes
9	"	"	6.30	no	yes	no	no	yes
10	29-10-86	"	4.40	no	yes	yes	no	yes
11	"	"	4.75	no	yes	yes	no	yes
12	30-10-86	"	1.90	yes	yes	yes	no	no
13	"	"	5.15	no	yes	no	no	no
14	20-7-87	"	12.70	no	yes	yes	no	yes
15	21-7-87	"	5.60	no	yes	no	no	no
16	22,3-7-86	"	11.00	yes	yes	yes	no	yes
17	23-7-87	manual	1.20	no	yes	yes	yes	no
18	"	"	2.80	yes	yes	yes	yes	no
19	29-3-88	"	2.45	yes	yes	no	yes	no
20	"	"	2.58	no	yes	no	yes	no
21	19-4-89	"	2.00	yes	yes	no	yes	no
22	"	"	0.40	no	yes	no	yes	no
23	20-4-89	"	1.00	no	yes	no	yes	no
24	"	"	1.70	no	yes	no	yes	no

4.2 SURFACE HYDROLOGY

4.2.1 GENERAL CONDITIONS AND OBSERVATIONS SEPTEMBER 1986 TO MARCH 1988

As reported by Kotwicki (1986) the tributary streams of Lake Eyre South are generally dry and may not flow for several years between major rain events. One such event was in 1985, and the winter of 1986 was also fairly wet, so that at trip 1 (8-10th September 1986), some saline pools were still present in the major waterways and some depressions, although apparently not flowing. Lake Eyre South contained a large amount of water, though it was far from full. Some road-construction borrow pits contained water, as did a dam in an interdune clay pan at site 5. The latter was fresh and muddy, with an electrical conductivity of about 660 $\mu S\ cm^{-1}$ (i.e. about 400 $mg\ l^{-1}$ TDS). Further west towards Coober Pedy the landscape was drier, but lush vegetation showed that most creeks had flowed that winter season.

By trip 2 (27-31 October 1986) most surface water had dried up except for small pools in Stuarts Creek and Margaret River. These were sampled and found to be quite saline (see table 4.5.1 for short analyses). The Bubbler Spring, the largest in the Hamilton Hill group, continued to support a short creek of about 1000 m length and some wetlands. No water was visible on Lake Eyre South from its shore. Vegetation was still green, although starting to dry off. Some light showers of rain during the passage of a cold front were encountered between the borefield and Olympic Dam.

Nine months later in July 1987 (trip 3) the landscape was quite dry except around the springs, and in pools in creeks near the springs. A pool in the Margaret River at Hamilton Hill had an EC of 43 000 $\mu S\ cm^{-1}$, close to that of shallow groundwater nearby in hole 18, 52 000 $\mu S\ cm^{-1}$.

PLATE 4.1 Investigator drilling rig on bare gibber plain, at hole 8. October 1986

PLATE 4.2 Site GAB 6, looking north from hole 23 on a slight rise to hole 24 in a slight depression, with vegetation beyond. April 1989

Such pools appear to be supplied by local, shallow, saline groundwater between flood events.

Trip 4 was made at the end of the summer season in late March 1988. Pools of water in creeks near springs still existed, but were considerably smaller. The mixing of spring water with local shallow groundwater was followed along the trail from a vent of spring HOF 081 at Hermit Hill. The EC varied from 6 800 $\mu S\ cm^{-1}$ near the vent to 8 200 $\mu S\ cm^{-1}$ in a pond about 60 m distant. Shallow groundwater 0.07 m below ground and stream level and only about 0.5 m away from the flowing stream had an EC of 40 000 $\mu S\ cm^{-1}$. Some 200 m away in hole 19 the EC was 148 000 $\mu S\ cm^{-1}$. The springs have only a local freshening effect on the saline local groundwater of the district.

Rain began on the return trip to Adelaide, and was heavy enough near Roxby Downs to cause local flooding and prompt the closure of the main unsealed road south to Woomera.

4.2.2 THE MARCH 1989 FLOOD EVENT

Over March 1989, moist air intruding from the north-west lead to record rainfalls in much of northern South Australia (Fig. 4.2.1). March rainfall was between 200 and 300 mm in the project area (Fig. 4.2.2), greatly exceeding the annual average total. Even higher falls were recorded in the northern Flinders Ranges. Most of the rain fell on about 10 rain days (Bureau of Meteorology 1989b), Lake Torrens fully flooded for the first time in recorded (European) history, and Lake Eyre South filled and flowed into Lake Eyre North via Goyder Channel (Hacker, 1989).

When the roads were reopened, trip 5 was made in late April 1989. All salt lakes and clay pans (fresh water) north of Port Augusta contained water, as did most creekbeds, and there was much evidence of

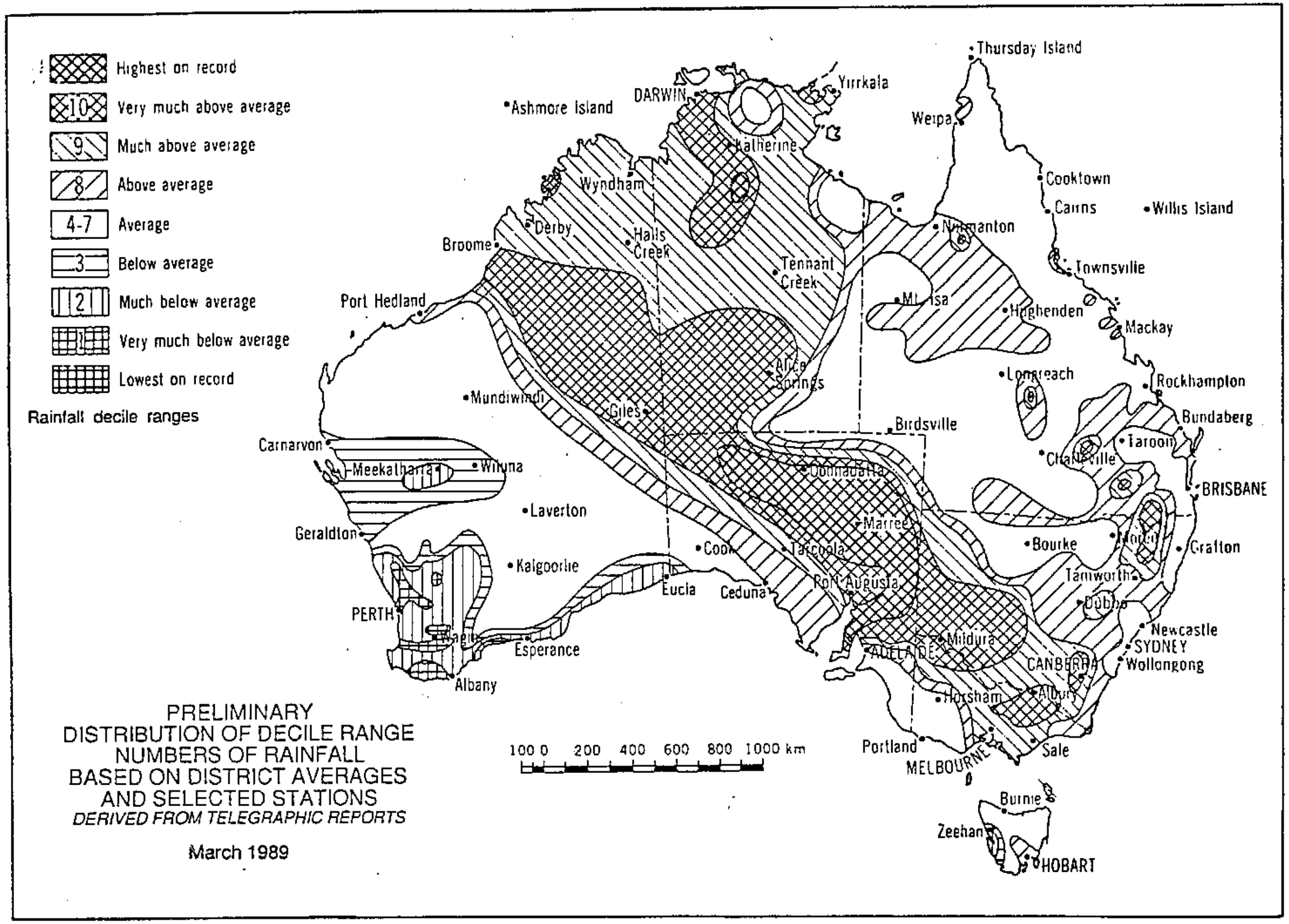

FIGURE 4.2.1 Distribution of Decile Range Numbers for March 1989 Rainfall in Australia Bureau of Meteorology, 1989a.

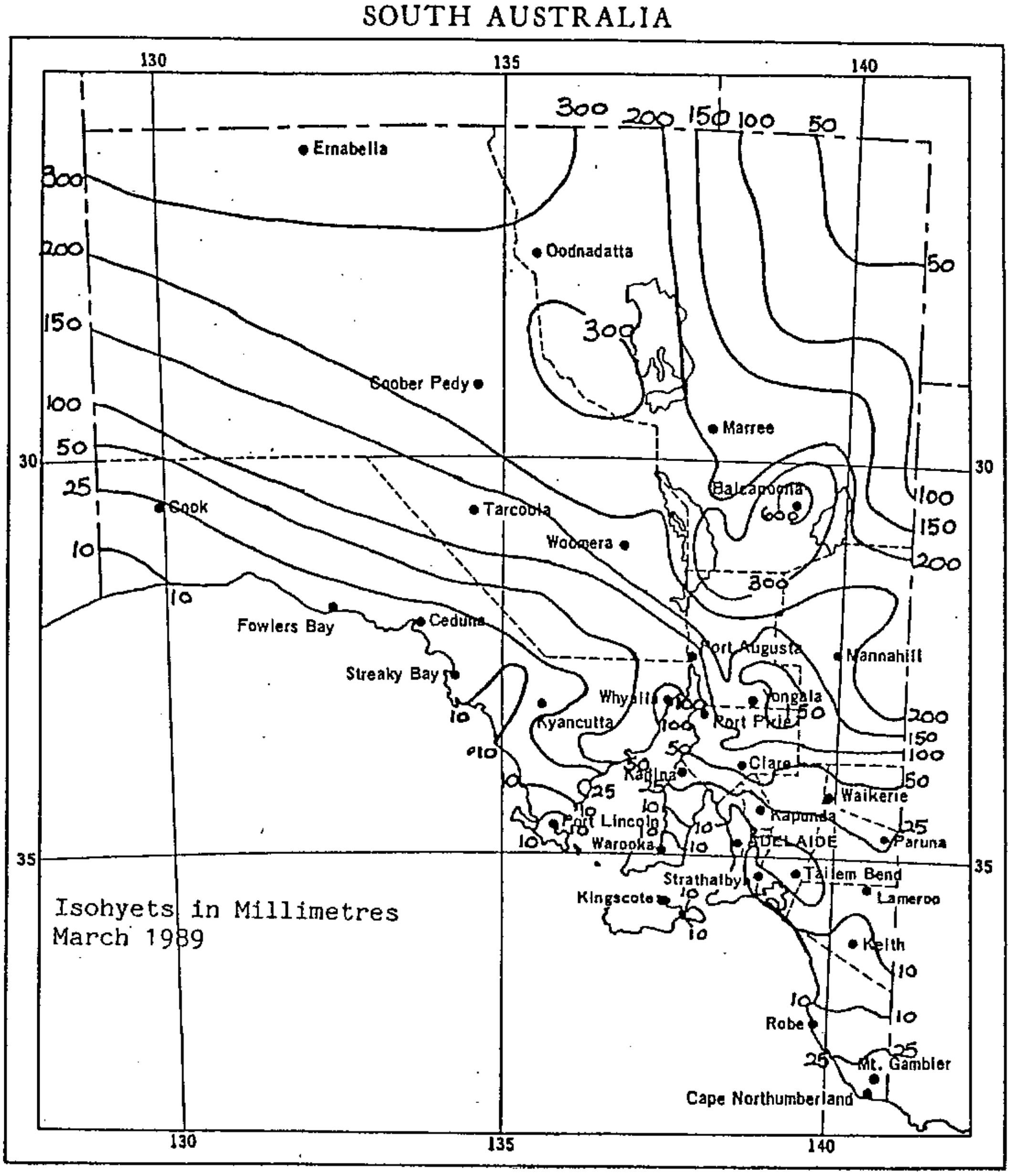

FIGURE 4.2.2 Isohyetal Map of Rainfall in South Australia, March 1989. Bureau of Meteorology, 1989b.

recent large flows of floodwater. The beginnings of lush vegetative growth were evident everywhere, except on some fairly large expanses of gibber plain in the project area (Plate 4.2). These patches are explained as areas where even the record rainfall received did not flush enough salt out of the surface soil to enable plant growth (see data on holes 22, 23 and 24 in section 4.4).

The larger creeks of the project area were flowing and some (stagnant) water holes evident. Smaller creeks showed clear evidence of recent flows and were lush with vegetation. Most of the larger creeks had healthy vegetation on their banks, but were bare or had dead vegetation near water level (Plate 4.3). This was explained once the EC of the creek waters was measured (Fig. 4.2.3). Only one waterhole contained fresh water, 940 $\mu S\ cm^{-1}$ (about 560 mg l^{-1}), in the Screechowl Creek complex near the main Marree - William Creek road. Remaining creeks contained saline water, between EC 28 000 and 50 000 $\mu S\ cm^{-1}$.

PLATE 4.3 Screechowl Creek flowing with saline water towards Lake Eyre South to the north.

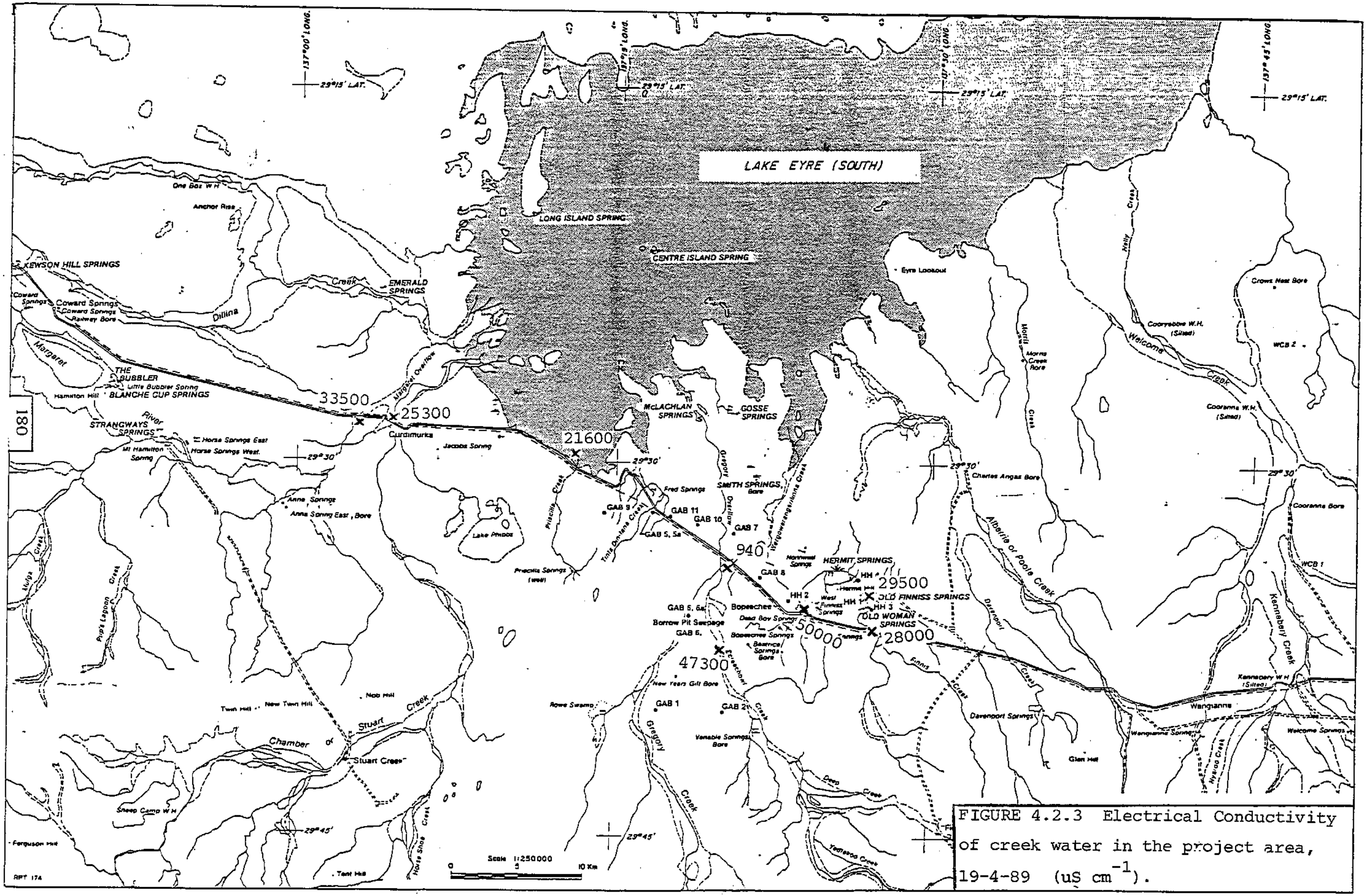

FIGURE 4.2.3 Electrical Conductivity of creek water in the project area, 19-4-89 (uS cm^{-1}).

The fact that the creeks were still flowing more than a month after the flood event is taken to be due to baseflow sustained by drainage of shallow groundwaters, known to be saline before the event (ECs between about 40 000 and 90 000 $\mu S\ cm^{-1}$). Some bank storage could contribute to the flow, but cannot be distinguished from longer-term groundwater inflow. It is proposed that there was widespread, though patchy (section 5.1.3) recharge to the shallow aquifer, causing the water table to rise above the bases of the slightly incised creekbeds (0.5 to 2 m below the general plain level), so that the deeper creeks become drains.

The water in Lake Eyre South at the same time had a field EC of 21 600 $\mu S\ cm^{-1}$, fresher than its tributaries. Most of the water entering the lake must have been quite fresh, as a large amount of salt is stored in the lake, 30 Mt since the last flood in 1984 (Allen *et al.*, 1986). The water level on the southern shore was about 0.5 m below the apparent maximum, marked by a sand bank, but it is recognized that winds can affect water levels in Lake Eyre South by 0.2 m (Kotwicki, 1986, quoting Dr John Bye of Flinders University), so that the 0.5 m may not be an accurate figure for the overall drop of the lake water level since its peak.

4.3 HYDRAULIC ESTIMATES OF LEAKAGE

The vertical leakage from the main GAB aquifers may be estimated conventionally by Darcy's law if all the necessary parameters are known or can be estimated. Darcy's law may be written

$$\frac{Q}{A} = -K_v \frac{d\psi}{dz} \qquad (4.1)$$

where Q/A is the flux per unit area, K_v the vertical hydraulic conductivity, ψ the potential of water (as approximated by head or water level), and z vertical distance. In the borefield area, $d\psi/dz$ may be estimated by the drop in head between the aquifer and water table and the distance between the two. Hydraulic conductivity is poorly known. Analysis of flow-test data from several bores gave apparent K_v of 2.0 to 13×10^{-4} m day^{-1} (A.G.C., 1984). The accuracy of these estimates is considered to be of order-of-magnitude only, but support the value of 2.7 $\times 10^{-4}$m day^{-1} (3.1×10^{-6} m s^{-1} or 100 mm yr^{-1}) adopted to give the best result in the numerical model (ibid.). The estimate is an "average" taken over a large area, including both faulted zones and less permeable inter-fault area, but at least gives a value worth using in hydraulic calculations.

The top of the aquifer is at between about 30 and 150 m depth in the borefield area, being deeper towards Lake Eyre and shallower near the springs, reaching the surface at the outcrops shown in figures 1.2.8 and 1.2.16. The water table is taken to be about three metres below the surface for this exercise, based on results of this drilling; the exact value does not affect the accuracy of the estimates. The calculation requires potentials rather than measured heads, so that strictly a correction for the higher density of the near-surface brine should be made. This would be less than a 5% correction, similar in magnitude to the error in the distance between the aquifer and water table (say 2 m in 30 to 150m) and much less than the error in K_v, so is not attempted. Using the data of A.G.C. (1984), vertical leakage is estimated for several of the Olympic Dam Project bores and one railway bore in table 4.3.1.

TABLE 4.3.1

Hydraulic Estimates of Diffuse Vertical Leakage in the Project Area

Bore	nearby project hole	depth to top of aquifer m bgl	shut in head m agl	$\frac{d\psi}{dz}$ m m^{-1}	$\frac{Q}{A}$ mm yr^{-1}
FS 1	h3	34	>18	>0.677	>68
HH 4	h1 ,17 ,19	31	9	0.427	43
GAB 6	h10	92	22.5	0.287	29
GAB 7	h8	94	18	0.231	23
GAB 8	h9, 15	80	8	0.143	14
GAB 9	h14	145	24	0.190	19
GAB 11	h11	55	21	0.462	46
Curdimurka	–	124	37	0.331	33

bgl = below ground level, agl = above ground level

These estimates are very rough, as K_v is probably underestimated near the springs where the shale aquitard is likely to be fractured by faulting, and overestimated (perhaps by an order of magnitude) elsewhere. K_v may also incorporate leakage vertically down from the aquifer as well as vertically up. The high vertical gradients illustrate the great potential for upward leakage of artesian water where the aquifer is near the surface at the edge of the basin, and leakage estimates are quite high. The total diffuse discharge of the basin would be accounted for by an average leakage of 20 mm yr^{-1} over an area equivalent to only 1.5% of the basin, or a strip only 18 km wide along the 1400 km southern edge (c.f. section 1.2.5, Importance of Diffuse Discharge).

4.4 FIELD SOIL PROFILES

4.4.1 LITHOLOGY AND MINERALOGY

4.4.1.1 General

The lithology of the holes drilled are given individually in appendix 1. The profiles fall into two groups. The first, on the gibber plains surrounding Lake Eyre, have a shallow soil layer (about 0.3 to 0.6m deep), of light brown, aeolian loess or sand, with a surface armouring of siliceous pebbles, the stony tableland soil of Jessup (1960a,b). The soil profile generally contains crystalline gypsum towards its base. It is underlain by weathered Bulldog Shale to the maximum depth of drilling (11.67m). The shale becomes fresher and darker with depth, ranging from light brown to light grey, with crystalline gypsum immediately below the soil, to dark grey or greenish-grey with depth, with occasional veins of clear gypsum. The shale is sometimes fractured, with iron oxide stains on the fracture surfaces, a feature usually associated with water movement. Occasional small fossil molluscs (pelecypods) up to 10mm in length were found in the fresh shale, along with plentiful traces of small burrows (c.f. Ludbrook, 1966).

The mineralogy of the soils was not closely investigated, other than the determination of approximate halite (NaCl) and gypsum contents, which are discussed in section 4.4.1.3. One sample of surface soil from Hole 10, 0.15-0.20 m was examined by X-ray diffraction (XRD) and was found to contain mainly quartz, with minor amounts of the clays kaolinite and illite, and a trace of halite. A sample of shale from hole 1 (w23, 1.1-1.15m) was examined. The sand-silt sized fraction was mainly quartz, with secondary calcite and possibly feldspar, and minor illite and a sulphide mineral, possibly cubite ($CuFe_2S_3$). The fine silt and clay fraction contained quartz and a layer silicate, possibly a member of the montmorillonite group, traces of illite and feldspar and possibly some glauconite. The shale has been noted elsewhere as predominantly montmorillonite (Lock, 1988). Organic carbon was determined on two other samples of shale, as 0.3 and 0.5%; the latter was less weathered than the first and closer to the range of 0.8 to 2.0% reported as average for the Bulldog Shale by McKirdy *et al.* (1986).

Two samples of weathered shale from Hole 14 were examined for particle size by the pipette method. The percentages of clay (< 2 µm), silt (2-20 µm) and sand (> 20µm) were 9, 53, 38 % and 39, 39, 22 %, an illustration of why the shale is usually reported to be a mudstone, not a claystone.

One other mineral occurrence deserves mention, the comprehensive cementation or replacement of shale by carbonate in hole 15 below the water table at about 5.6m depth. The drilling rig was unable to penetrate more that 0.2 m into this material using a tungsten carbide rock drilling bit. The material was not encountered at other sites, but may have caused drilling problems at the bottom of hole 9 some 15m away that were thought due to a gypsum vein at the time.

The second group of profiles are those that penetrate recent flood-plain sediments of the Margaret River at Hamilton Hill (holes 4, 12, 18, 20, 21), Wergowerangerilinna Creek at Hermit Hill (holes 1, 17, 19) and Screechowl Creek (hole 2). Those at Hermit Hill and Screechowl Creek penetrate into the underlying Bulldog Shale, but not those at Hamilton Hill. The lithology at Hamilton Hill is more varied, consisting of interbedded alluvial clays, sands and clayey sands. The fairly rare natural zeolite mineral **analcime** was identified in the surface crust at Hamilton Hill, along with the common mineral quartz, with minor amounts of calcite, and feldspar, trace clays (at the surface, they dominate in some layers), and the evaporite minerals halite and sodium carbonate sulphate, $Na_6CO_3(SO_4)_2$.

An exception to the Gibber Plain - Flood Plain categorization is hole 5, in an interdune flat west of William Creek, which appears to pass into coarse sands of the Cadna-Owie Formation.

4.4.1.2 Water, Gypsum, and Halite

At all sites water, approximate gypsum and halite profiles were determined. Gravimetric water content and gypsum contents were determined as per section 3.1, and halite by calculation knowing the excess of chloride over saturation in a sample. Water and gypsum contents are shown in the graphic profiles of figures 4.4.1 to 24.

Water contents varied from about 0.024 $g\ g^{-1}$ in very dry, sandy surface layers at the end of summer, to greater than 0.5 $g\ g^{-1}$ in clayey material near the water table. The variation of θ_g with depth gives a fair indication in the flood plain holes particularly of the layering of sandy and clayey layers, e.g. hole 4. In many holes the water table was not apparent by the presence of water in the holes, due to the very low hydraulic conductivity of unfractured Bulldog Shale. In these cases the position of the water table has been inferred from the water content profile, in conjunction with a distinct drop in chloride concentration if apparent (e.g. holes 8 and 9). Note that gravimetric water content is shown in the graphic profiles and appendix 2, as measured, but volumetric water contents used in the calculations of chapter 5.

Gypsum was present in all Gibber Plain holes but not those on flood plains. It is suggested that the flood plains are leached with water often enough to prevent the build up of the sparingly soluble gypsum

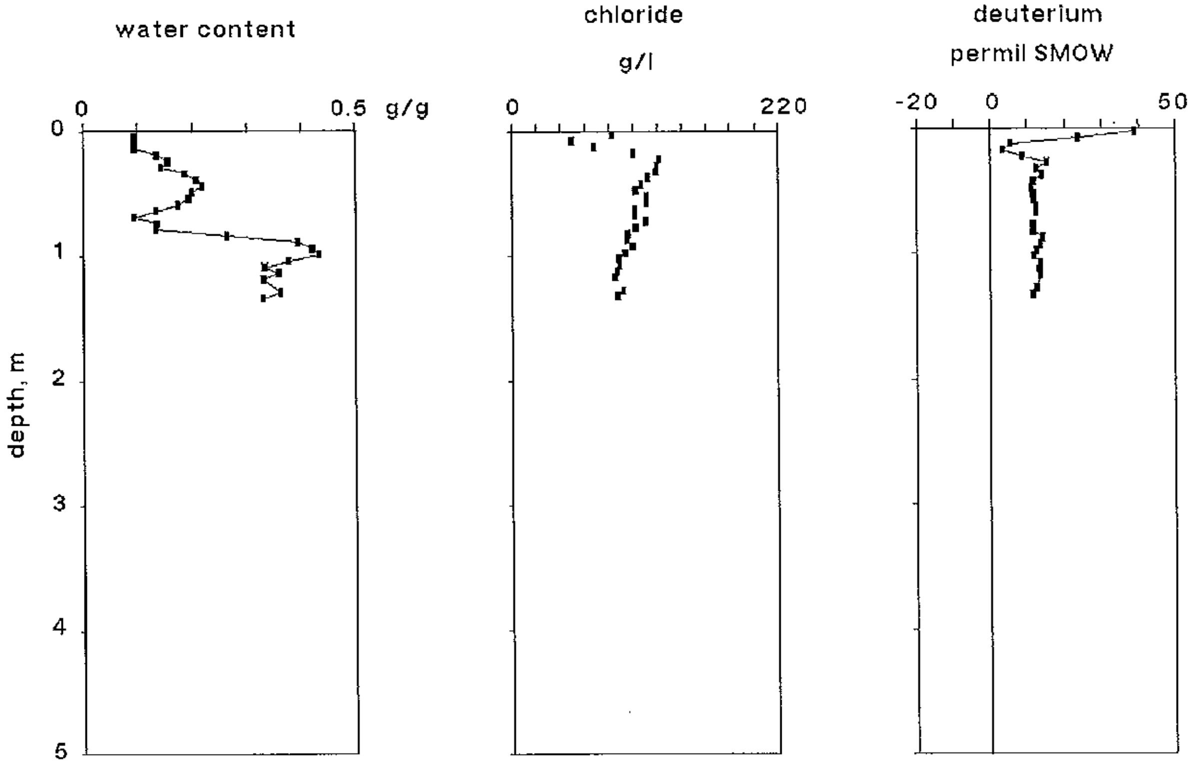

FIGURE 4.4.1 Water, Chloride and Deuterium Profiles, Hole 1 Flood Plain at Hermit Hill

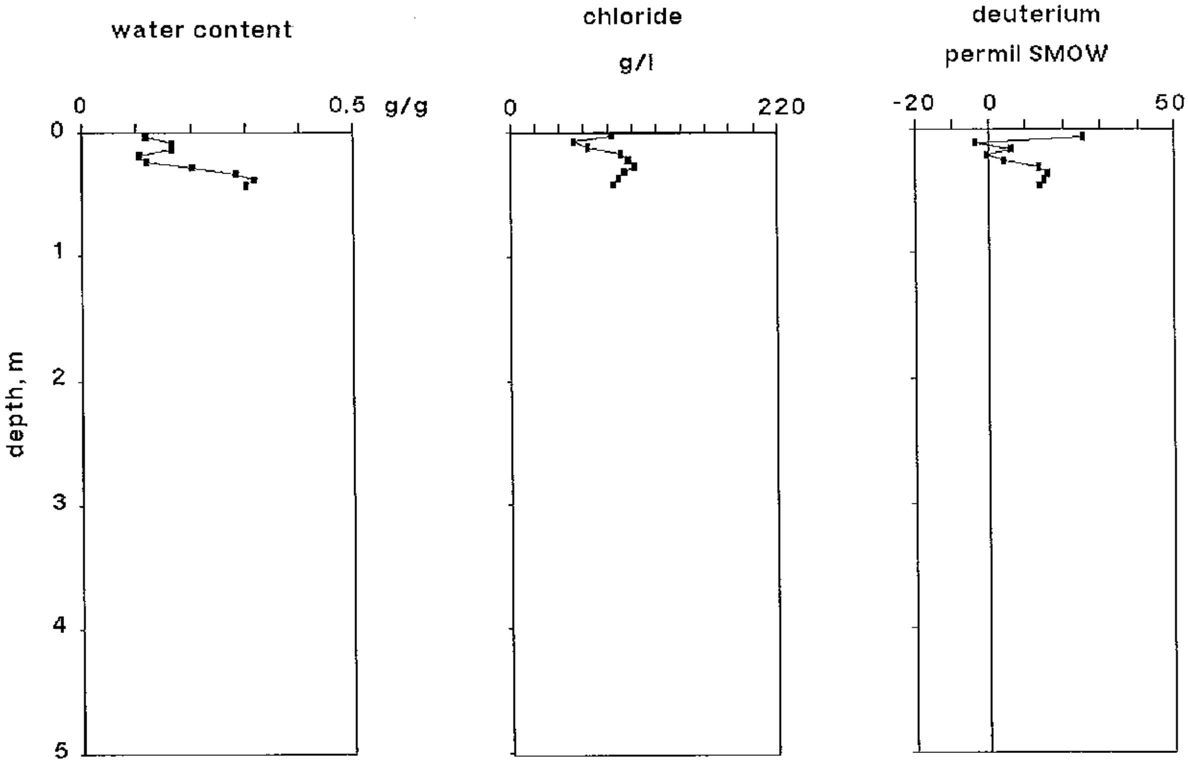

FIGURE 4.4.2 Water, Chloride and Deuterium Profiles, Hole 2 Flood Plain in Screechowl Creek

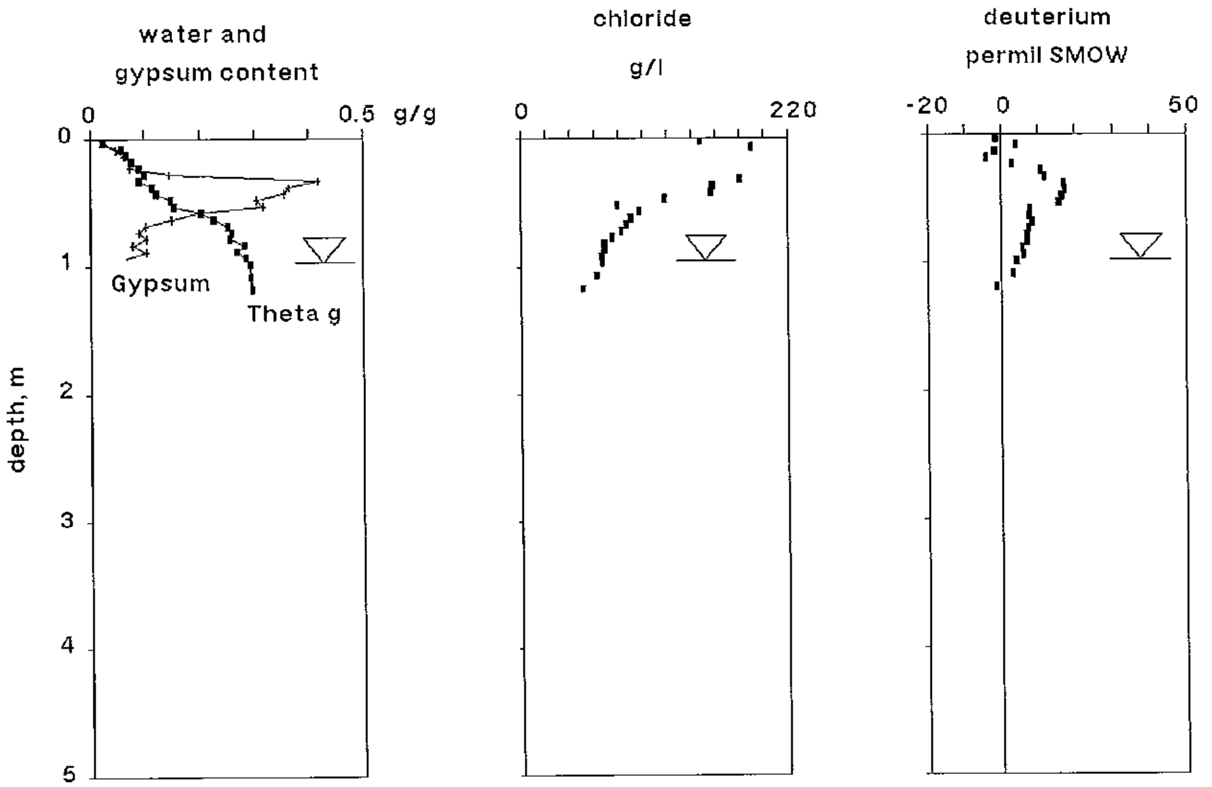

FIGURE 4.4.3 Water, Chloride and Deuterium Profiles, Hole 3 Gibber Plain near Fred Springs

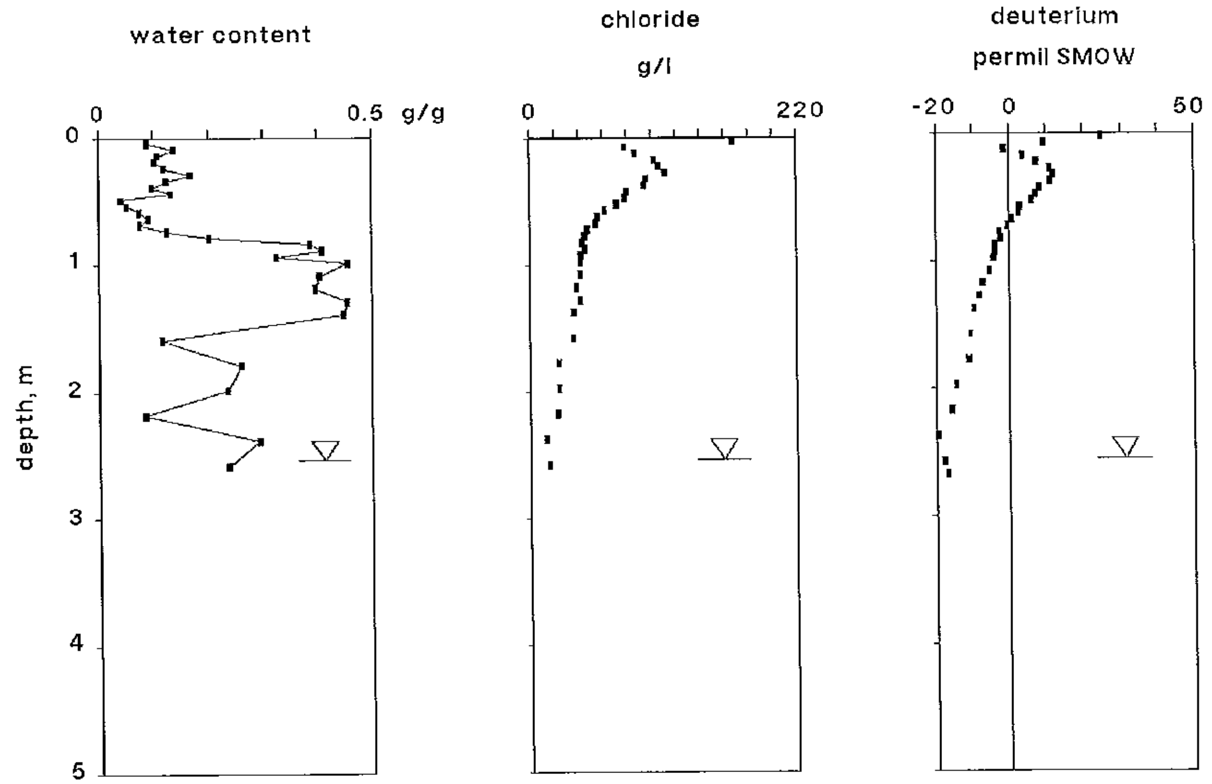

FIGURE 4.4.4 Water, Chloride and Deuterium Profiles,Hole 4 Flood Plain at Hamilton Hill 9-9-86

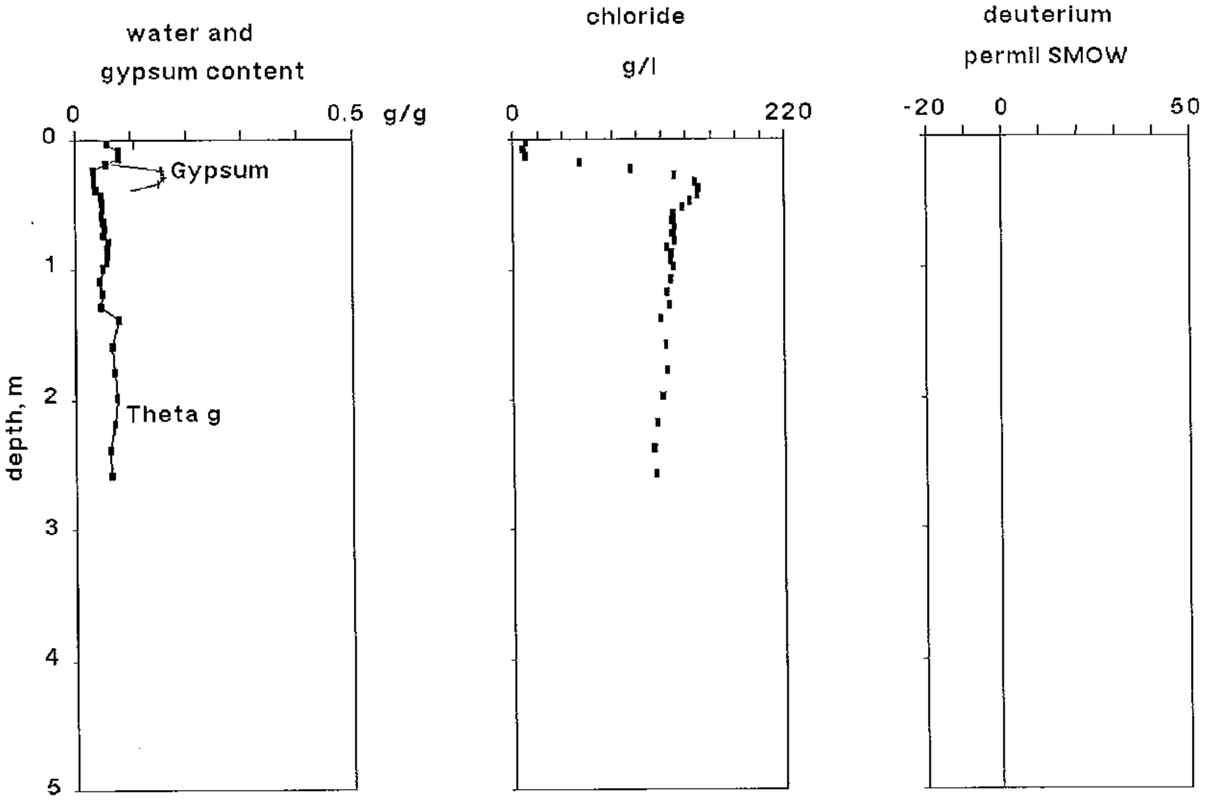

FIGURE 4.4.5 Water and Chloride Profiles,Hole 5 Interdune Flat, west of William Creek

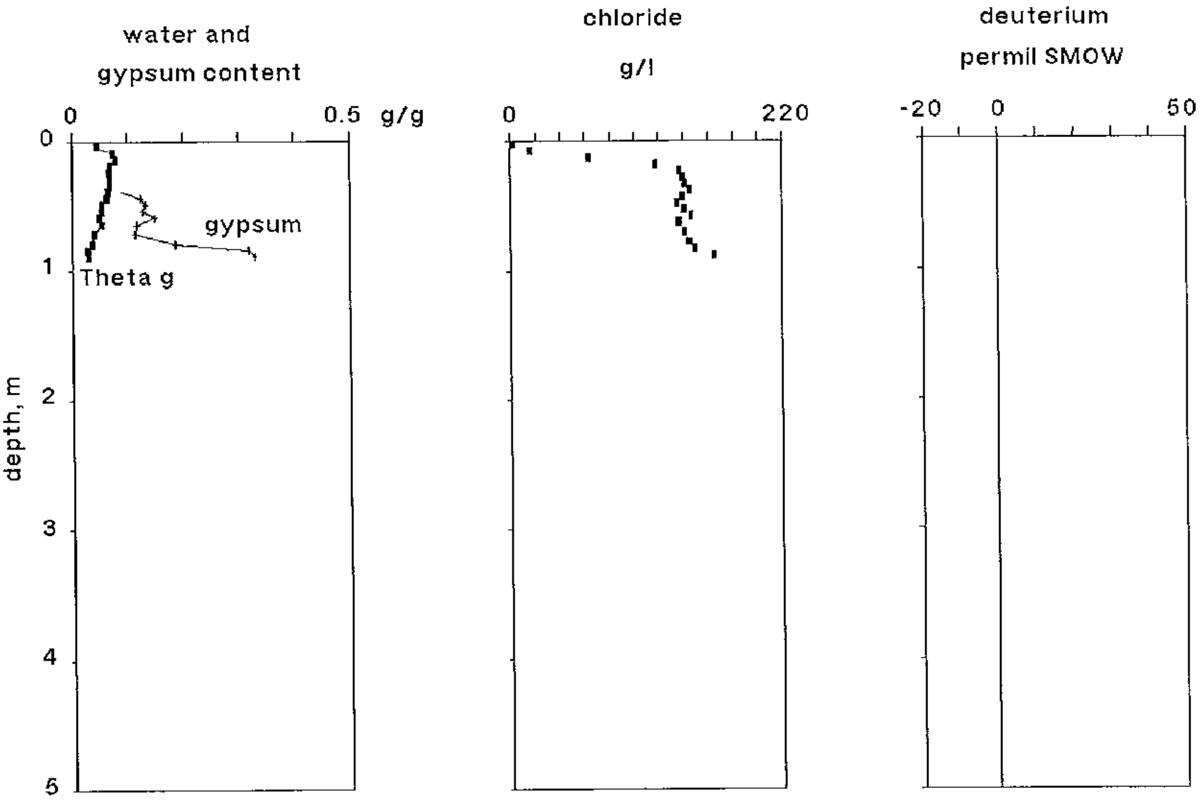

FIGURE 4.4.6 Water and Chloride Profiles, Hole 6 Gibber Plain, east of Coober Pedy

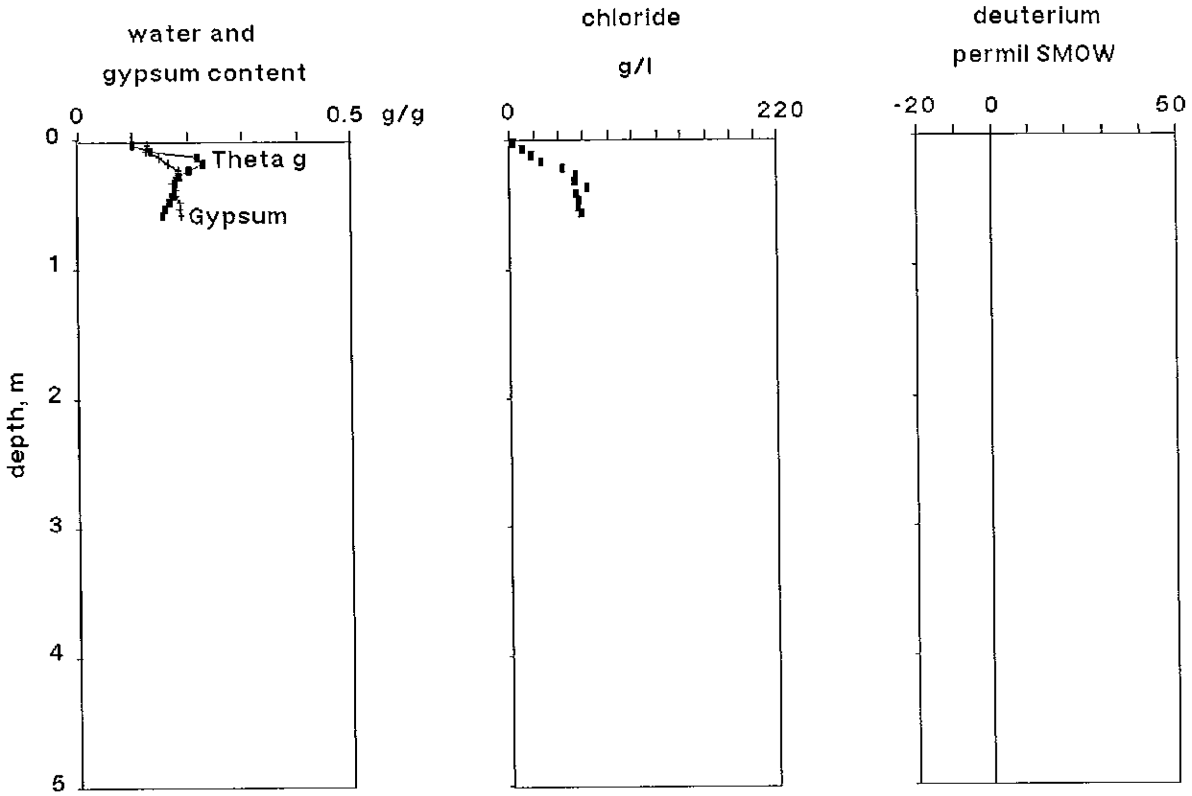

FIGURE 4.4.7 Water and Chloride Profiles, Hole 7 Gibber Plain at Coober Pedy Borefield

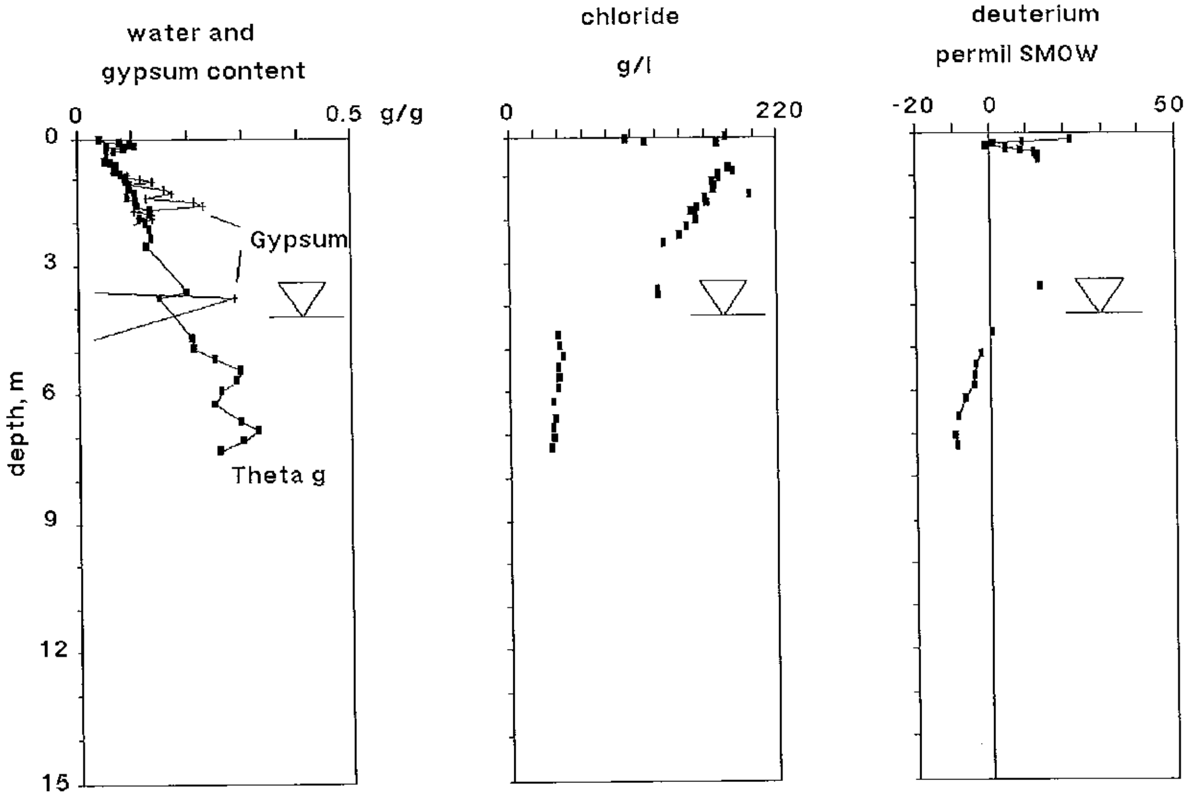

FIGURE 4.4.8 Water, Chloride and Deuterium Profiles, Hole 8 Gibber Plain near GAB 7

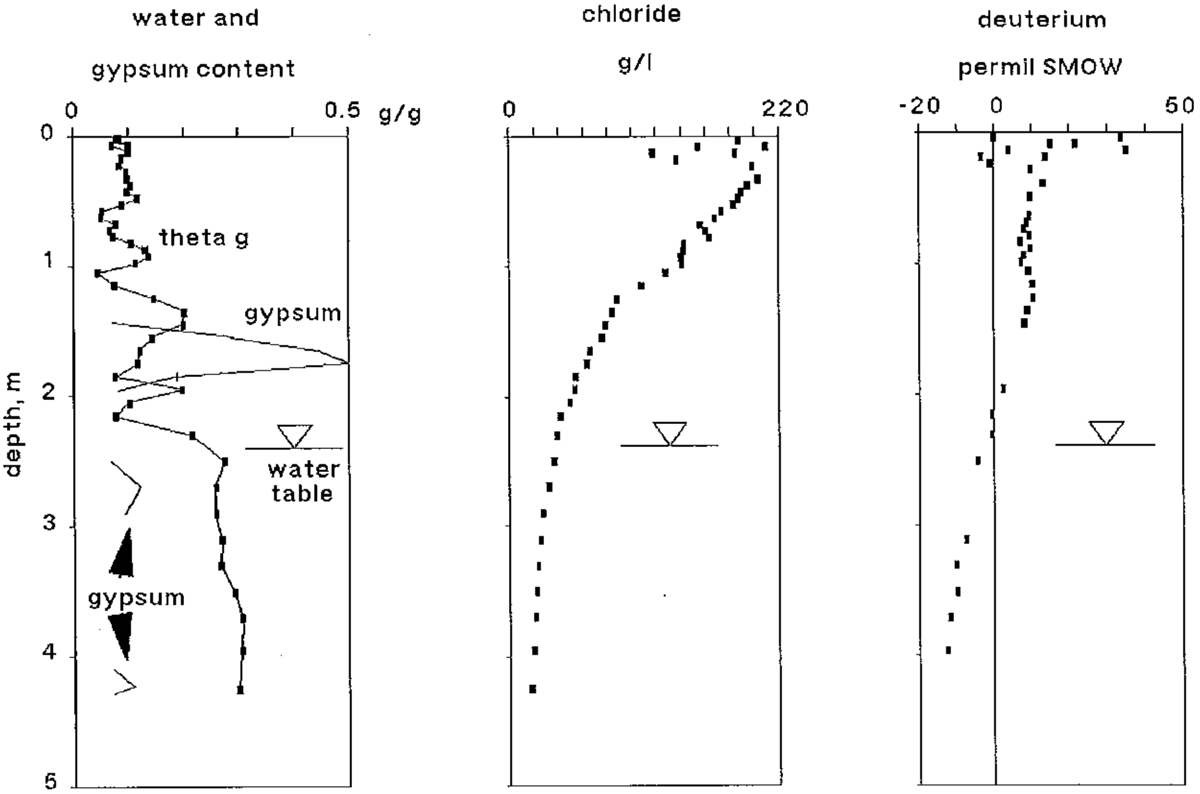

FIGURE 4.4.10 Water, Chloride and Deuterium Profiles, Hole 10 Gibber Plain near bore GAB 6

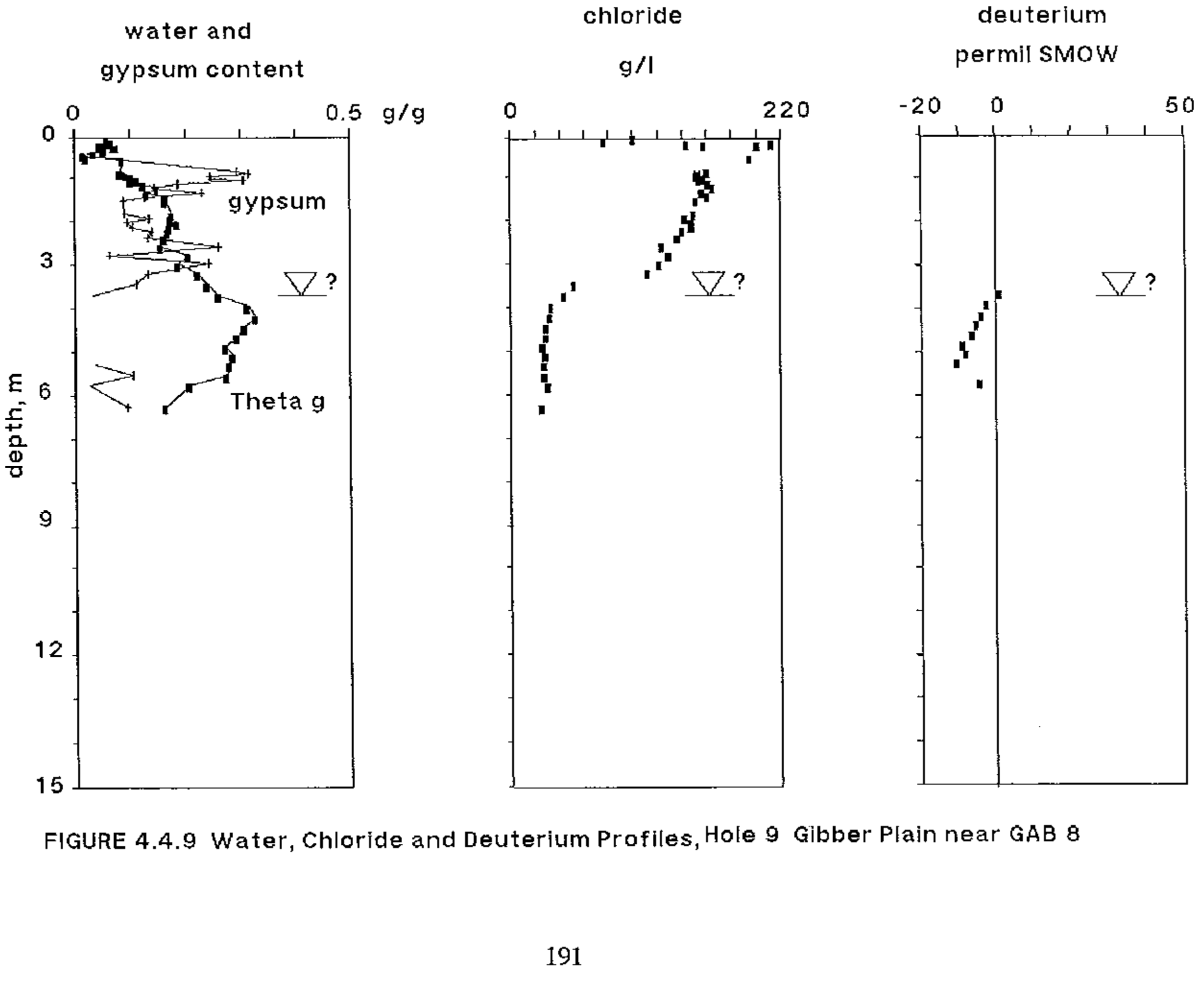

FIGURE 4.4.9 Water, Chloride and Deuterium Profiles, Hole 9 Gibber Plain near GAB 8

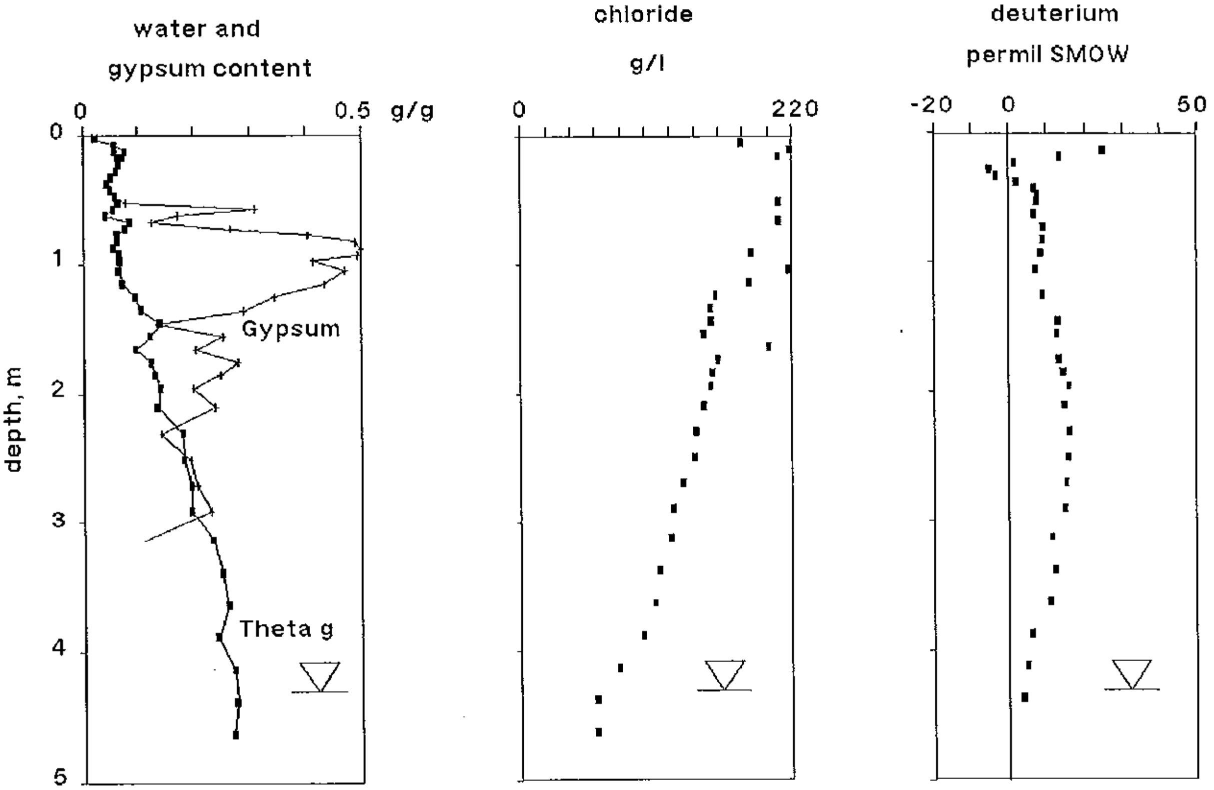

FIGURE 4.4.11 Water, Chloride and Deuterium Profiles, Hole 11 Gibber Plain near Fred Springs

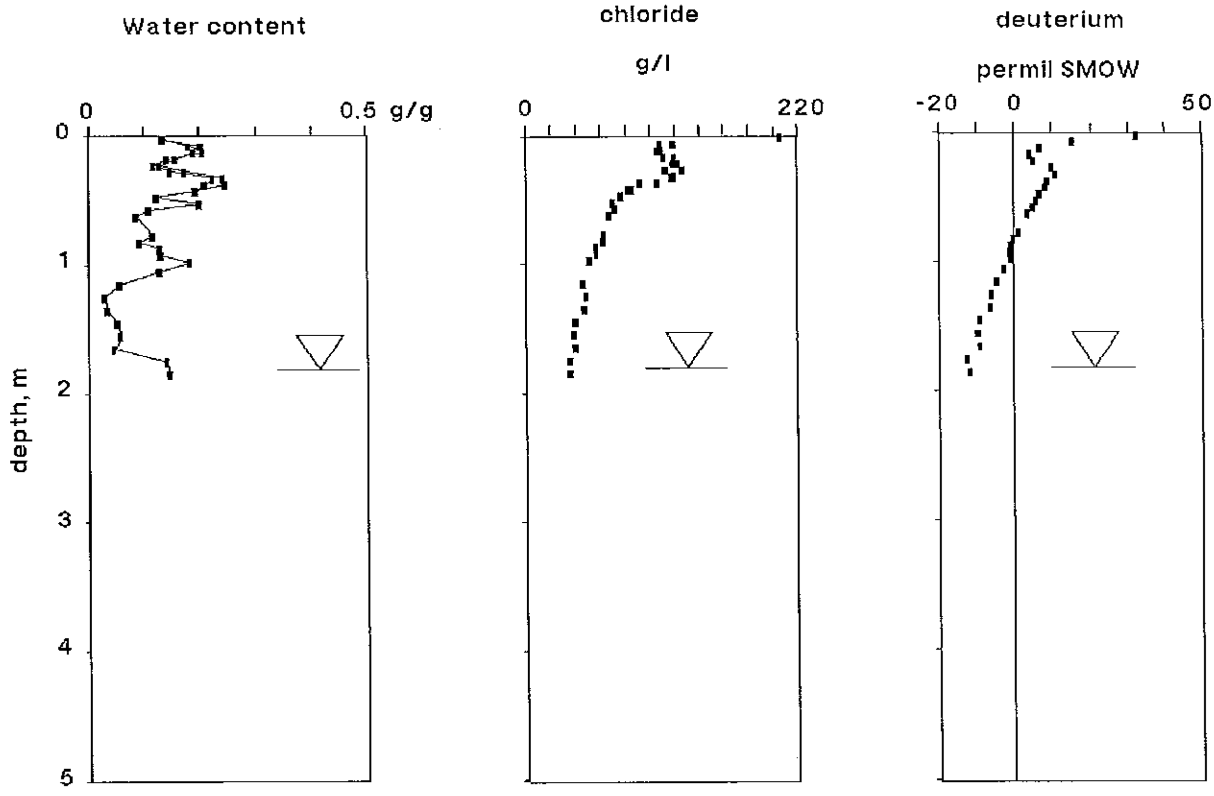

FIGURE 4.4.12 Water, Chloride and Deuterium Profiles, Hole 12 Flood Plain, Hamilton Hill

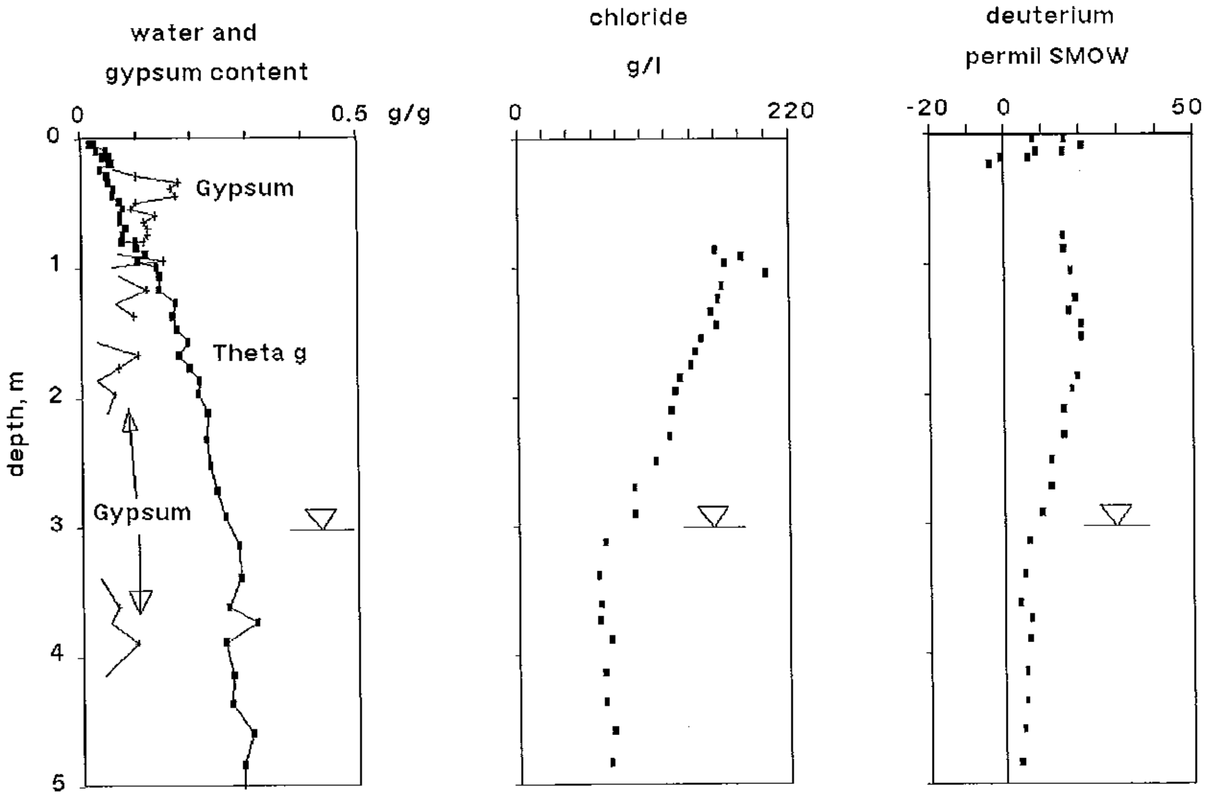

FIGURE 4.4.13 Water, Chloride and Deuterium Profiles, Hole 13 Gibber Plain near L. Eyre South

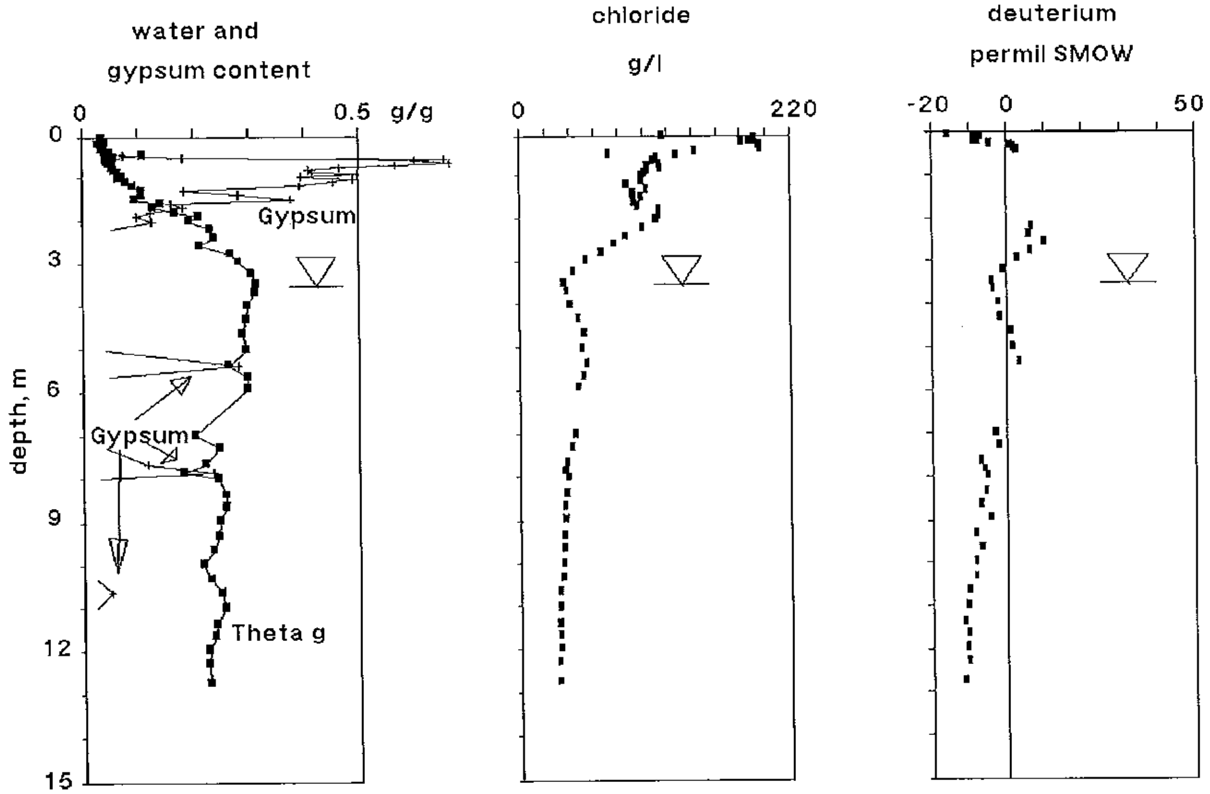

FIGURE 4.4.14 Water, Chloride and Deuterium Profiles, Hole 14 Gibber Slope near GAB 9

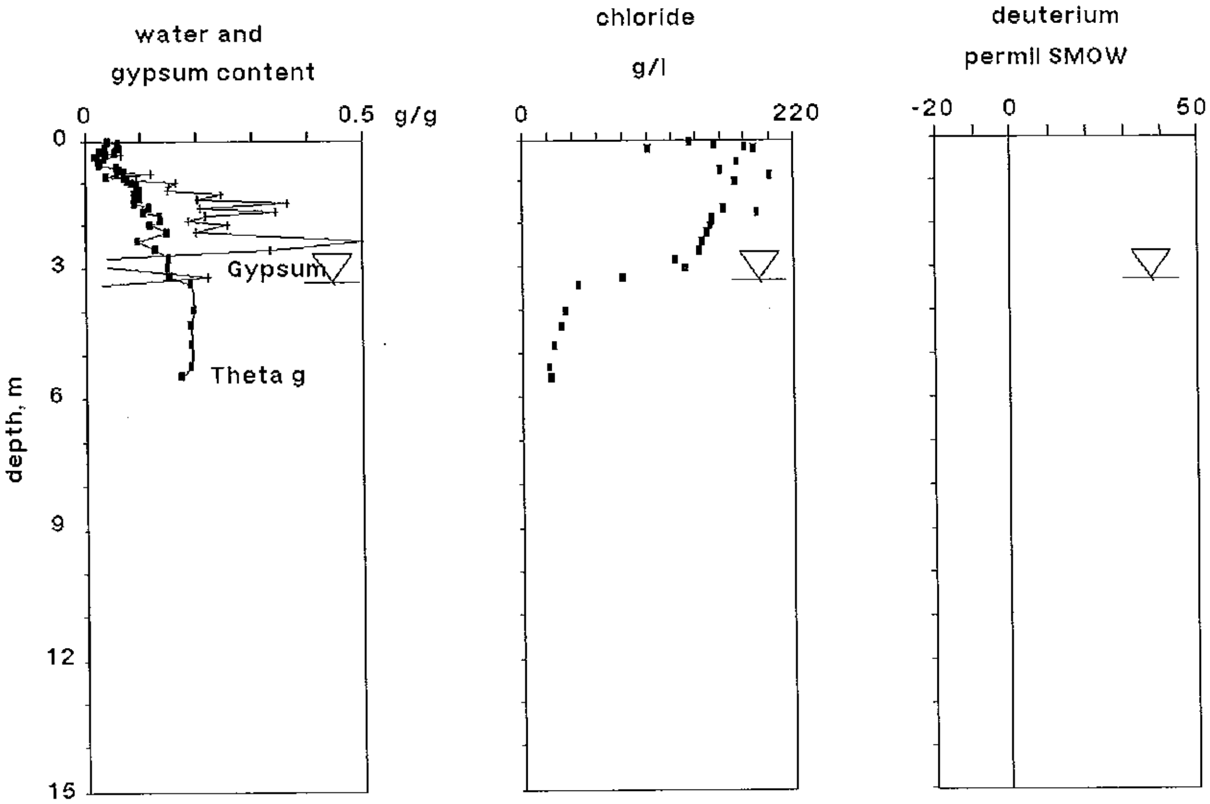

FIGURE 4.4.15 Water, Chloride and Deuterium Profiles, Hole 15 Gibber Plain near GAB 8

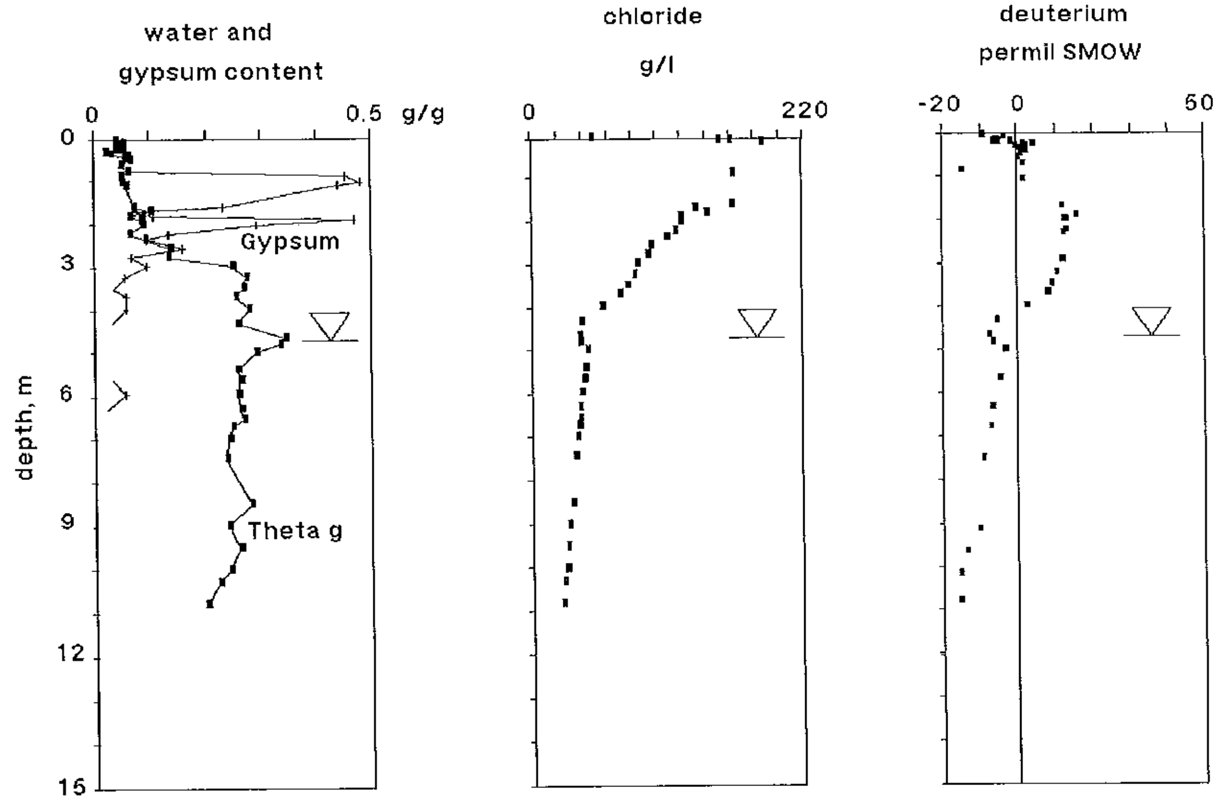

FIGURE 4.4.16 Water, Chloride and Deuterium Profiles, Hole 16 Gibber Plain near GAB 12

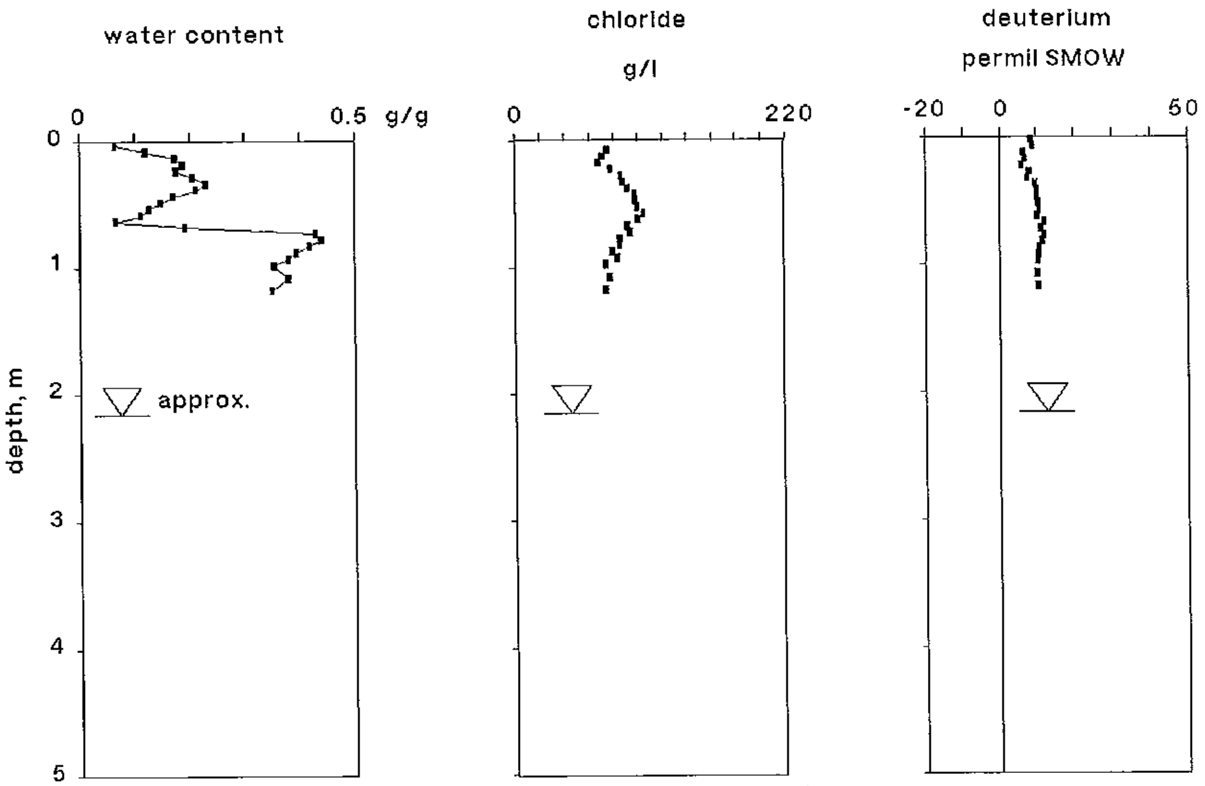

FIGURE 4.4.17 Water, Chloride and Deuterium Profiles, Hole 17 Flood Plain at Hermit Hill 23-7-87

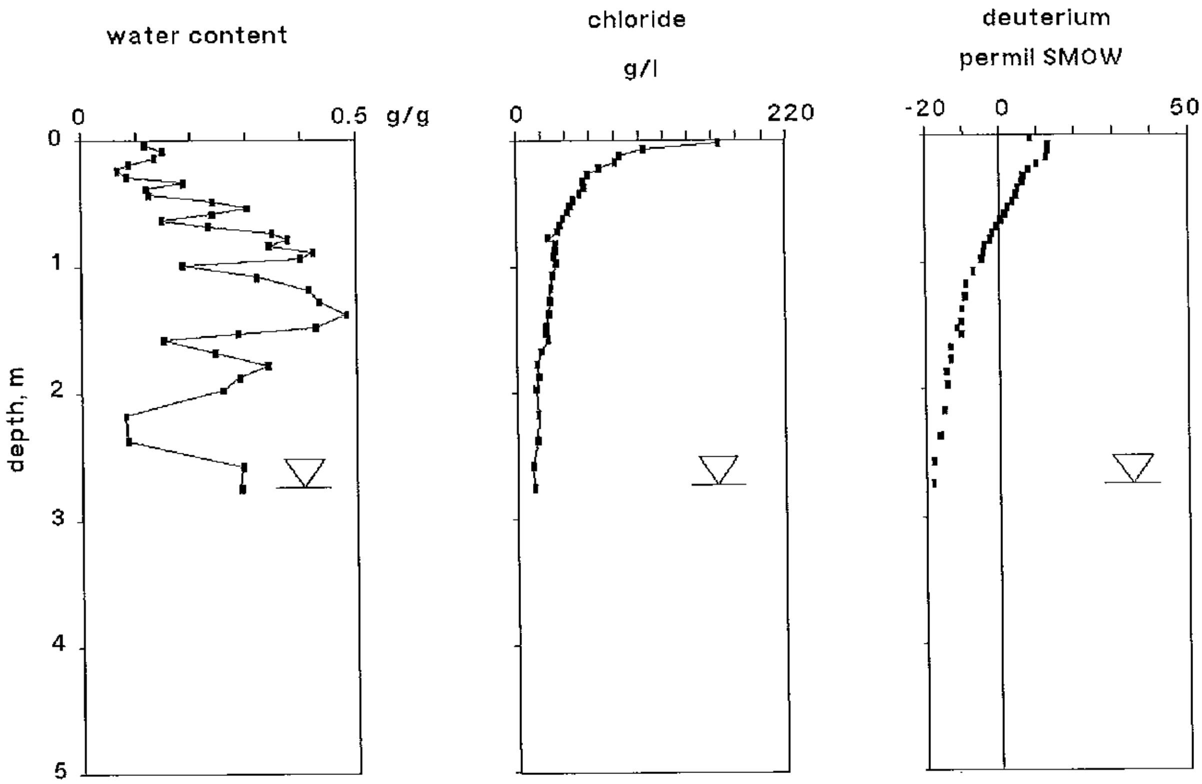

FIGURE 4.4.18 Water, Chloride and Deuterium Profiles, Hole 18 Flood Plain at Hamilton Hill 24-3-87

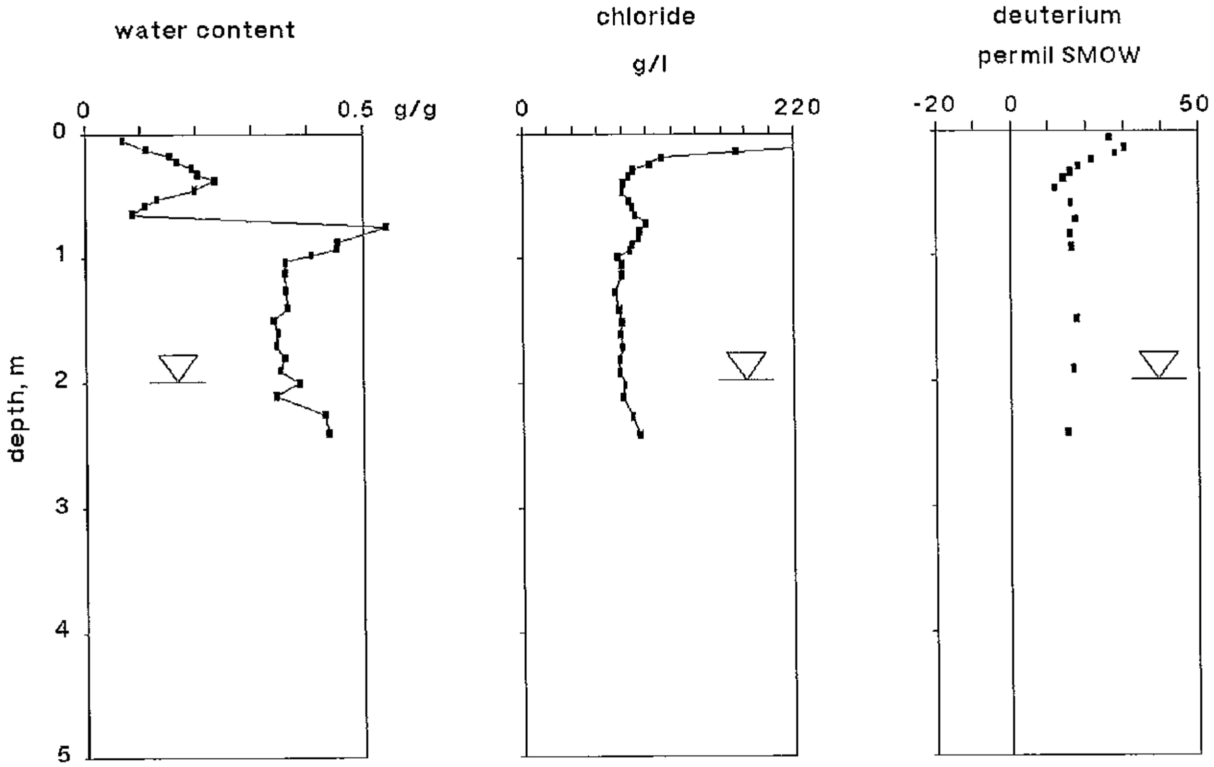

FIGURE 4.4.19 Water, Chloride and Deuterium Profiles, Hole 19 Flood Plain at Hermit Hill, March 1988

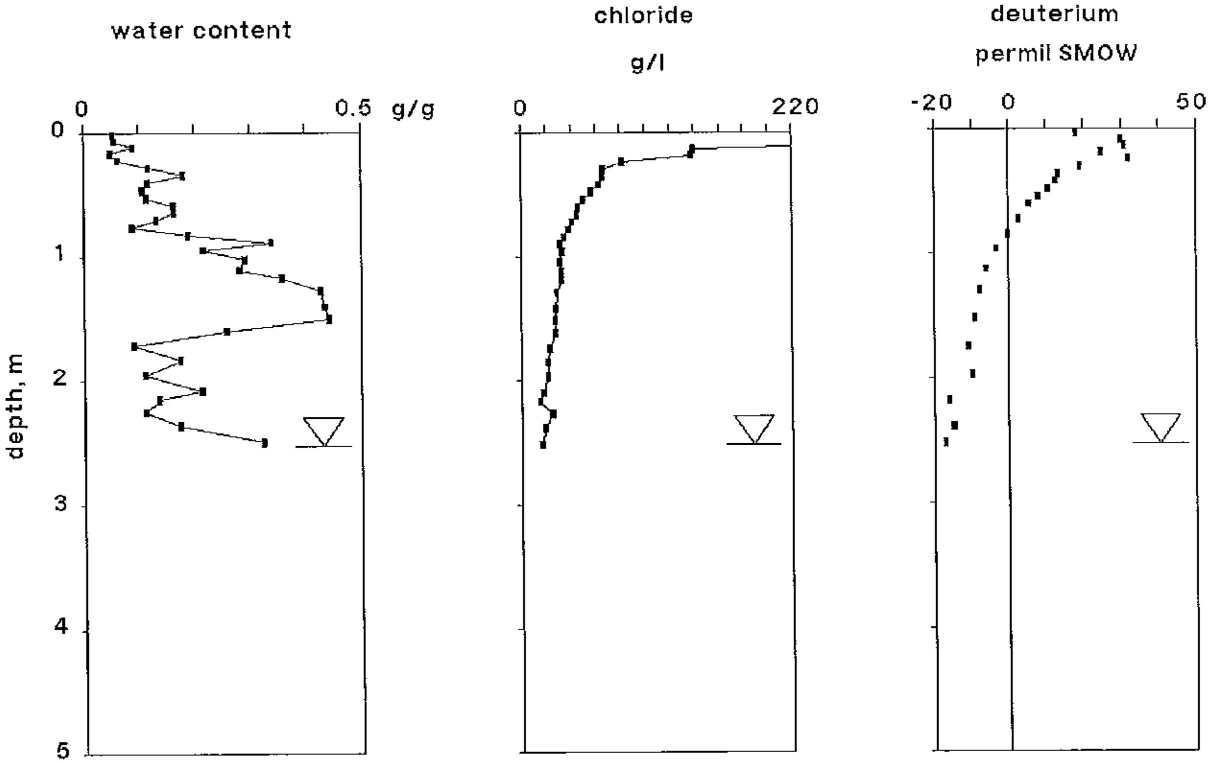

FIGURE 4.4.20 Water, Chloride and Deuterium Profiles, Hole 20 Flood Plain at Hamilton Hill, March 1988

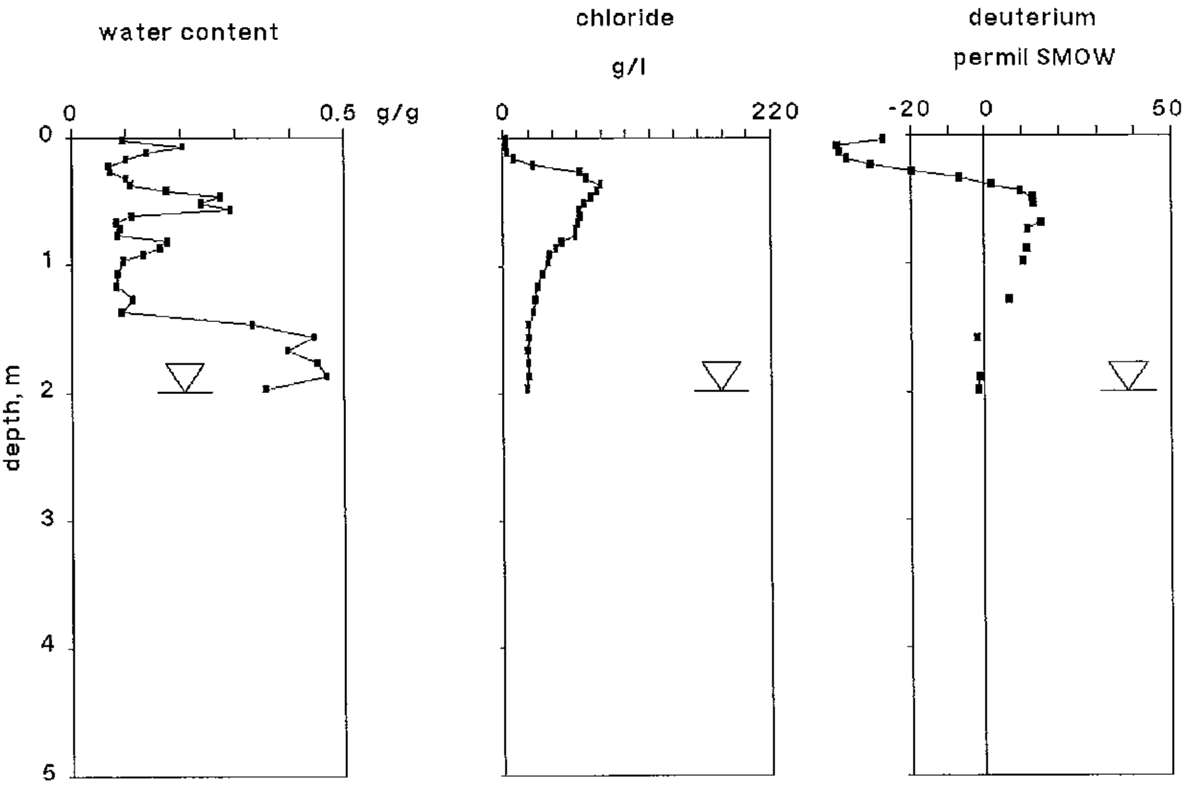

FIGURE 4.4.21 Water, Chloride and Deuterium Profiles, Hole 21 Floodplain at Hamilton Hill, April 1986

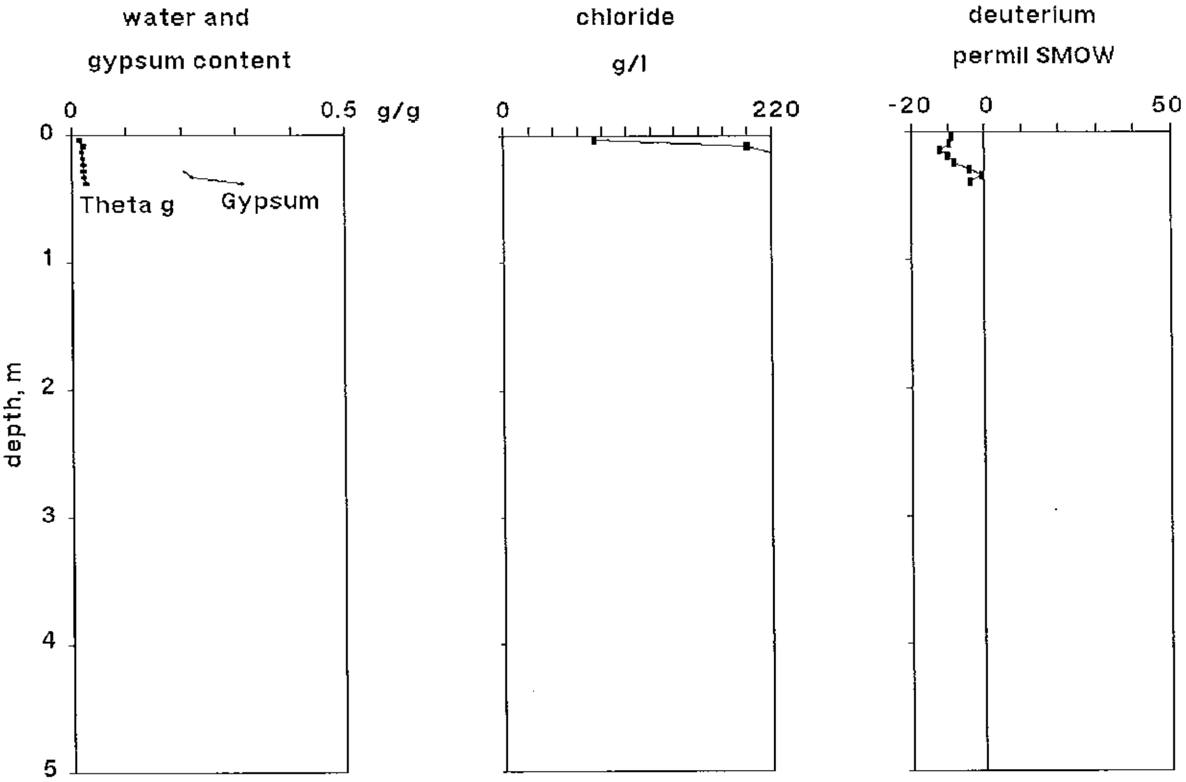

FIGURE 4.4.22 Water, Chloride and Deuterium Contents, Hole 22 Gibber Plain near GAB 11, April 1989

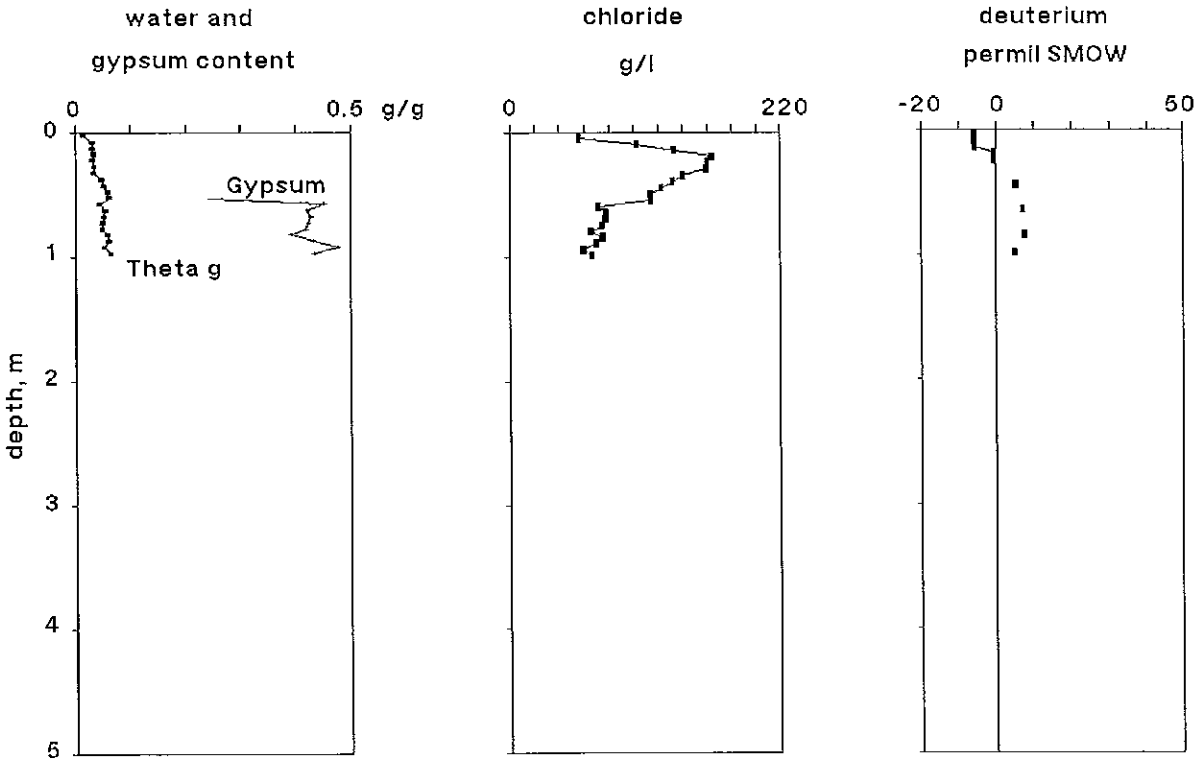

FIGURE 4.4.23 Water, Chloride and Deuterium Profiles, Hole 23 Gibber Plain near GAB 6, slight rise, April 1989

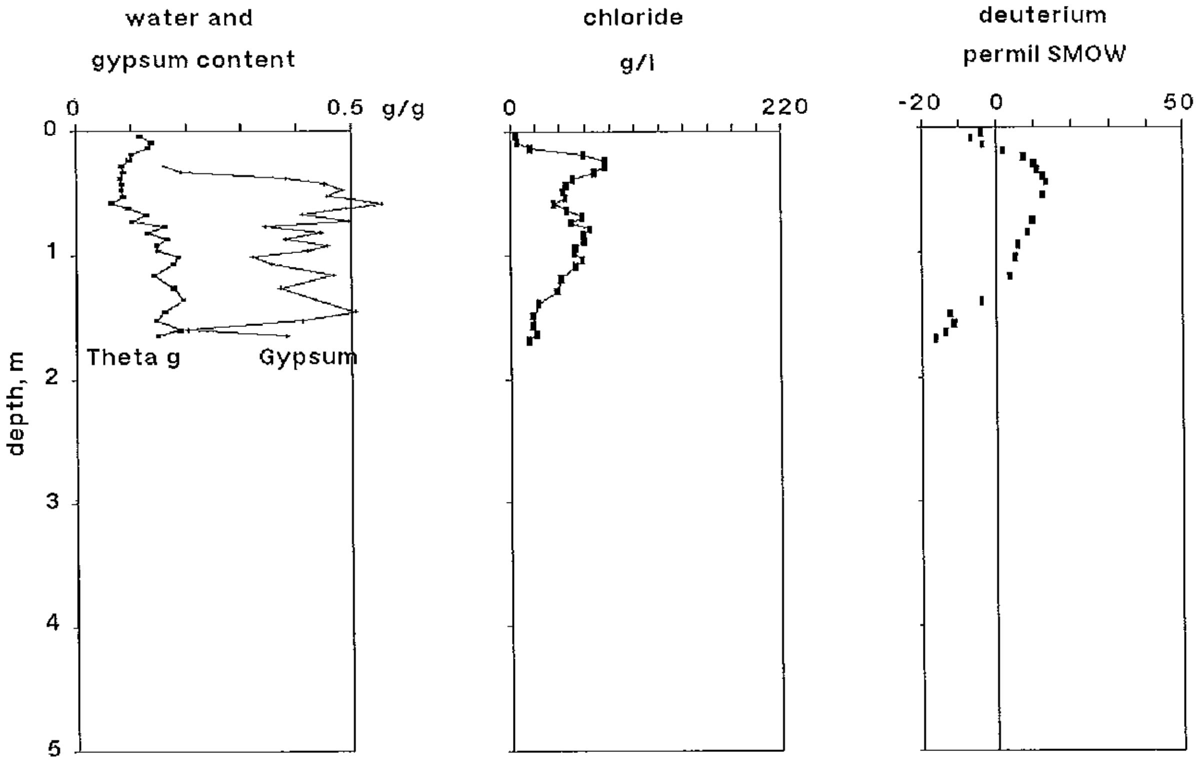

FIGURE 4.4.24 Water, Chloride and Deuterium Profiles, Hole 24 Gibber Plain near GAB 6, slight hollow, March 1989

during the several years' evaporation between floods. Gypsum contents often reached 50% or more by mass at intermediate depths in holes, usually between about 0.4 and 2.0 m depth. This gypsum exists as dirty crystals that appear to have grown in place, disrupting the surrounding soil and weathered rock. They sometime interlock to the extent of forming a hard gypcrete layer, that prevented deeper penetration of some holes, both by hand (e.g. holes 6, 7, 22) or even the drilling rig on one occasion (hole 16A).

Further down the profiles, gypsum was often found as clear, crystalline veins occupying fractures in the shale, from less than one to more than 10mm thick. These appear as small peaks in some profiles (e.g. holes 10, 14).

Halite was present at or near the surface in most holes, and the total amount of halite generally ranged up to about 3% by mass, except for hole 13 nearest Lake Eyre South, where it reaches 35% at 0.2-0.25 m (appendix 2). It would seem possible that at this site, halite deposited by the upward movement and evaporation of groundwater is supplemented by wind-blown salt from the lake that is leached below the surface, but not to the groundwater, by occasional large rain events.

Where both gypsum and halite were present in the same profile, the halite was always found above or conjointly with the upper part of the gypsum occurrence. This is consistent with an upward movement and concentration (by evaporation) of the parent brine (from the water table) with the progressive precipitation of these minerals in reverse order of solubility.

4.4.2 PORE WATER PROPERTIES

The chloride and stable isotope profiles obtained on field samples are displayed graphically in figures 4.4.1 to 4.4.24, and full data is found in appendix 2. Some general features will be highlighted here, and detailed interpretation set out in chapter 5.

4.4.2.1 Chloride

The soils around Lake Eyre are naturally saline (Working Party on Dryland Salting in Australia, 1982; Jolly, 1988) and this is reflected in the high chloride values present in the soil water. Although only checked in one location (hole 14, Cation Exchange Capacity, CEC, table 3.1.2) the predominant balancing cation may be safely assumed to be sodium at least for all gibber plain sites. The evaporating groundwaters contain between 75 and 99 % sodium (out of total cations, in equivalents), and 66 to 91 % chloride, with the next most common components usually magnesium (0 to 19%, also the second most abundant ion in the CEC measurements) and sulphate (5 to 20%). Halite was the most common evaporite mineral other than gypsum identified by XRD analysis of the surface sediments.

The chloride profiles are plotted in g l^{-1} up to 220 g l^{-1}, that corresponding to the solubility of NaCl at surface temperatures. Most profiles show a maximum at or near the surface where the mineral halite is often present (section 4.4.1.2). There is often a surface freshening of pore water, due to recent rainfall: this is particularly apparent for holes 1 to 7 of September 1986, and holes 21 to 24 of April 1989, after moderately and extremely wet periods. In some of these, very recent evaporation has lead to higher chloride in the top one or two samples only, i.e. down to 0.05 or 0.10 m (e.g. holes 1, 2, 4, 12).

The general chloride profile in the main project area (i.e. except holes 5, 6, and 7) is for an increased concentration from the water table (or deeper) towards the surface. This is altered to shallow depth by recent rainfall that usually penetrates only to 0.1 to 0.3 m, after which the surface soil dries out and the chloride concentration rises to similar or greater levels than the more stable concentration below. The wetting and drying of surface soil will be discussed in more detail in the following chapter, and is also apparent in the matric suction profiles to be discussed shortly. The penetration of water at different times to different depths, perhaps along fracture lines at up to several metres depth, and the subsequent return to the general, monotonically increasing with height above the water table, is proposed as an explanation for the "kinks" in some chloride profiles, notably hole 14.

A prominent feature of some chloride profiles is a large jump in chlorinity immediately above the water table, most evident in holes 8, 9, and 15, and to a lesser extent in holes 11, 13, and 16. This is thought due to lateral movement of water, the shale being permeable enough in some areas to be considered a legitimate aquifer. Where the chloride concentration is constant below the water table (holes 8, 9, 13, and possibly 11), the shale is probably most permeable due to fractures, and the water is well mixed. In other holes the chlorinity continues to decrease below the water table, so that the shale is less permeable and not well mixed. Water movement may be in a discrete layer; fractured horizons a few centimetres thick containing free water were encountered in holes 9 and 16, with hard, visuallyly "dry" shale above and below.

The continuity of chlorinity above and below the water table in other holes, notably hole 10 and to a lesser extent holes 3 and 14, is taken as an indication of very little horizontal movement of water in highly impermeable shale. The only water movement is vertical, and the water table is strictly defined as the plane where the pore pressure of water is atmospheric, not as the place where water is encountered in a hole or would quickly rise to (although this would happen eventually if evaporation from the sides of the hole were eliminated). The convection-diffusion process that is modelled to estimate evaporation (chapters 2 and 5) is continuous across that plane. Where the water-table aquifer is active and the water well-mixed, this may set a different boundary condition for the process, and the simple theory may only be applied with less confidence, or not at all.

4.4.2.2 Stable Isotopes

Deuterium analyses were carried out for most holes, and oxygen-18 for several, according to the time available and quality of information available from each hole. A small number of holes have deuterium data, and some of those oxygen-18 as well, for the water of crystallisation of gypsum hand-picked from the samples.

On the whole, except near the surface, the stable isotope profiles reflect the shape of the chloride profiles. This is expected as the same convection-diffusion process is a major control on them both. Deuterium shows the same "kinks" as chloride in holes such as 8, 14, and 16. Closer to the surface deuterium (and oxygen-18 when done) is affected by exchange with soil air and atmospheric water vapour, and often deviates from the pattern of chloride. This point will be pursued in the next chapter.

Oxygen-18 profiles mirror the equivalent deuterium profiles with a lesser absolute amplitude in permil. The nature of the δD - $\delta^{18}O$ relationship is examined in chapter 5.

The stable isotope composition of gypsum crystal water reflects that in the pore water at the same depth with an offset related to the fractionation between the two. Deuterium in gypsum crystal water is lighter than the pore water by about 4 to 63‰, with most between 30 and 50‰. This difference is greater than the equilibrium fractionation of -20‰ (Sofer, 1978). Oxygen-18 is also lighter, by about 7 or 8‰, on the limited set of data, rather than heavier by about 4‰ (ibid.). Again, the nature of the $\delta D - \delta^{18}O$ relationship is examined in the next chapter.

4.5 HYDROCHEMISTRY

Major ions, some minor ions on some samples, and stable isotopes were determined on a range of surface and deep and shallow groundwaters in the project area. Full analyses appear in Appendix 3, and representative analyses are presented here. The water types and relationships will be discussed, but a detailed study and modelling of the chemical evolution of the groundwater as it reaches the very margin of the basin and is concentrated by evaporation is unfortunately beyond the scope of this investigation.

4.5.1 SURFACE WATERS

The chemistry of the surface water samples taken is summarised in table 4.5.1, and shown as a Schoeller diagram in figure 4.5.1.

The waters are all dominated by sodium chloride despite their range in total salinity. Calcium is the next most common cation in some samples: Lake Eyre South, Stuart Creek on October 1986, and the fresh water sample from Screechowl Creek (April 1989). Magnesium is slightly more common than calcium in most other samples, the April 1989 saline samples from Margaret River and Stuarts and Screechowl Creeks and the Margaret River in October 1986, and much more common in the Margaret

TABLE 4.5.1A

Surface Water Chemistry

isotope no.	Location	Short name	Date
7488	Margaret R. Pool, Curdimurka	Marg.R.1	30/10/86
13430	Margaret R. Pool, Curdimurka	Marg.R.2	19/4/89
9804	Margaret R. Pool, Hamilton Hill	Marg.R.3	24/7/87
7489	Stuart's Creek pool, Curdimurka	Stu.Ck 1	30/10/86
13429	Stuart's Creek pool, Curdimurka	Stu.Ck 2	19/4/89
13427	Screechowl Creek, Bopeechee	SO.Ck 1	19/4/89
13428	Screechowl Creek, at Railway	SO.Ck 2	19/4/89
13431	Lake Eyre South	L.Eyre S.	19/4/89

TABLE 4.5.1b

Surface Water Chemistry

Short Name	Lab. pH	Field EC µS/cm	Lab. EC uS/cm	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
Marg.R.1	8.1	-	7470	1430	19	72	45
Marg.R.2	8.5	33500	34400	7437	99	590	456
Marg.R.3	9.3	43000	39500	11400	243	6	25
Stu.Ck 1	9.3	-	2640	430	6	44	17
Stu.Ck 2	7.8	25300	25000	5125	6	455	335
SO.Ck 1	8.3	50000	47000	10362	65	830	635
SO.Ck 2	7.6	940	900	122	5	63	11.1
L.Eyre S.	7.7	21300	19100	4598	21	189	28.2

	SO_4 mg/l	Cl mg/l	HCO_3 mg/l	TSS mg/l	δD ‰	$\delta^{18}O$ ‰
Marg.R.1	449	2120	290	4425	+51.2	+9.19
Marg.R.2	2480	12460	165	23687	-40.2	-4.64
Marg.R.3	1580	14300	4880	32444	+12.5	+3.8
Stu.Ck 1	138	720	27	1382	+59.1	+9.83
Stu.Ck 2	1820	8540	165	16446	-38.6	-4.61
SO.Ck 1	3070	17890	185	33037	-35.9	-3.82
SO.Ck 2	134	167	130	632	-58.6	-8.54
L.Eyre S.	620	6980	56	12492	-59.1	-8.54

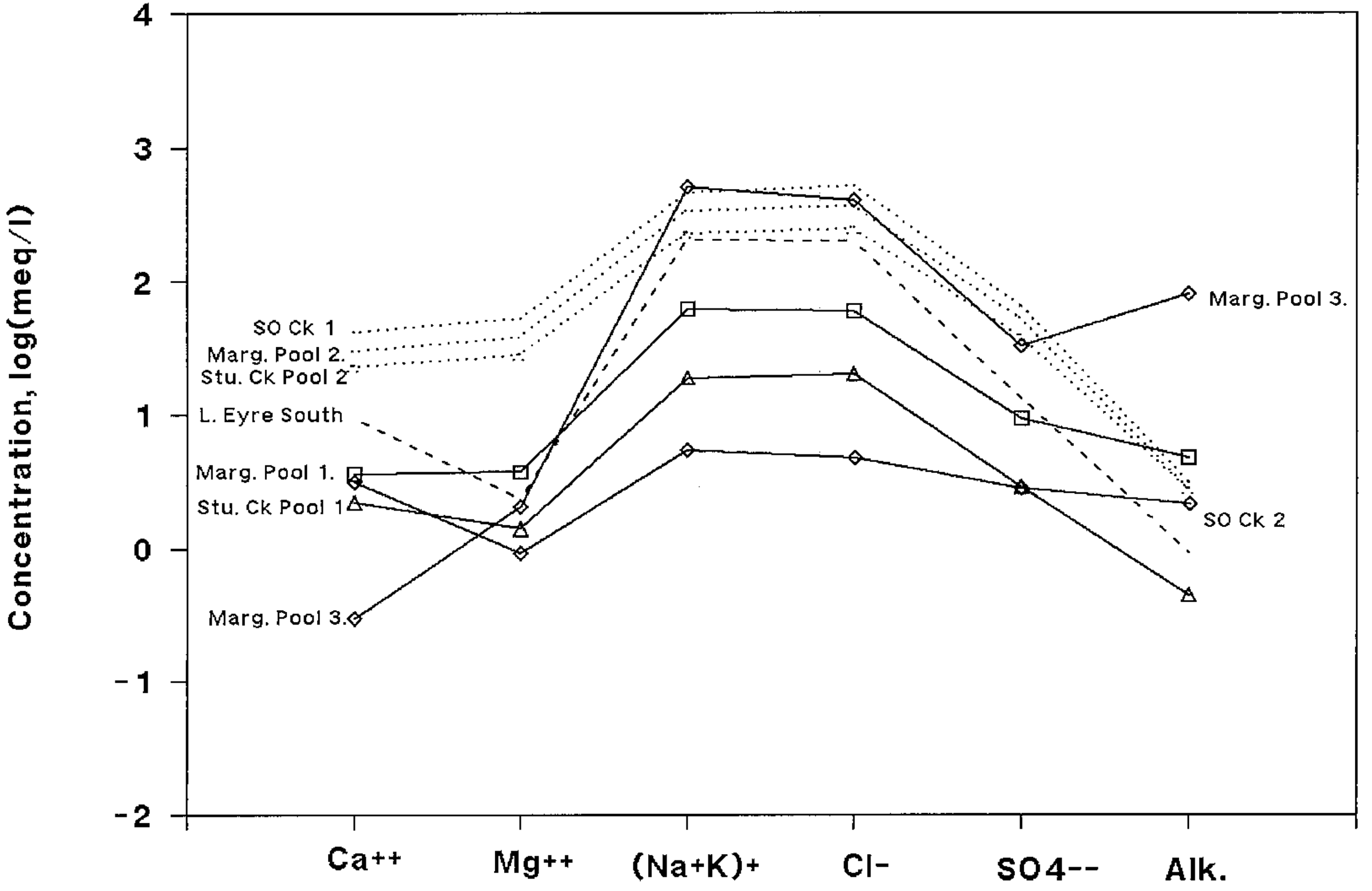

FIGURE 4.5.1 Schoeller diagram, surface waters

River sample from Hamilton Hill (July 1987). In that same sample bicarbonate is the sub-dominant anion to chloride, but sulphate exceeds it in all other samples. This dominance is less pronounced in the fresh sample from Screechowl Creek (SO.Ck 2) and October 1986 sample from Margaret River (no. 2).

The chemistry of those waters that were flowing (trip 5, April 1989) or from creeks that had recently flowed (trip 2, October 1986) appears to be largely controlled by the ions that would be dissolved by flow of runoff over the surface soil and previously dry creek beds, where the two most soluble minerals present are halite, NaCl, very common, and the less common epsomite, $MgSO_4.7H_2O$, with contributions from sparingly soluble gypsum $CaSO_4.2H_2O$ and calcite, $CaCO_3$, and local shallow groundwaters (next section). The dominance of Ca over Mg in Lake Eyre South may be due to the dissolution of gypsum in the lake where standing water has time to dissolve significant quantities of the mineral, or interaction with the pre-existing shallow brines. The fresh sample from Screech Owl Creek is obviously less affected by the dissolution of evaporite minerals, and has a Ca content similar to the less saline of the remaining samples, but is much lower in all other ions. With regard to anions, the one exception is the lower bicarbonate of Lake Eyre South; this may be explained by the large amount of Ca in the lake waters that cause nearly all of the alkalinity to be precipitated out as $CaCO_3$.

The sample taken from the Margaret River in July 1987, when the river had not flowed for a considerable time, is more closely related to the local shallow groundwater, as typified by hole 18 (Fig 4.5.5). The most striking difference is magnesium, which is very much lower in the pool, and to a lesser extent calcium. Both are high in pH and alkalinity, because of low calcium contents that prevent the continued consumption of the carbonate/bicarbonate to form calcite, a mineral very common in that area encrusting the flanks of the mound springs and the edge of the pool. The lower magnesium in the pool is more difficult to explain, unless perhaps dolomite, $CaMg(CO_3)_2$ or magnesite, $MgCO_3$ is forming because of the high alkalinity, or by reaction with calcite, in a way not occurring in the shallow aquifer, where the main mineral constituent is quartz and clay minerals.

4.5.2 DEEP GROUNDWATERS

The chemistry of representative deep groundwater sampled in the project area is summarised in table 4.5.2, and shown as a Schoeller diagram in figure 4.5.2. The chemistry is typical for this part of the basin, and reflects its location near the point where the waters recharged in the east, rich in Na, HCO_3 and Cl, meet those recharged in the west, rich in Na, Cl and SO_4 and generally of higher salinity. This is clear on the Schoeller diagram in the sulphate column, with HH4 and GAB 7 in the east have low sulphate (3 and 6 mg l^{-1}), those from the borefield a bit further west about 80 to 120 mg l^{-1} (GAB 6, 12A, 16), and Blanche Cup Spring in the west about 280 mg l^{-1}. This last value may, however, be partly due to dissolution of minerals or evaporative concentration in the pool of the spring, since the more strongly flowing The Bubbler spring in the same group has a sulphate content of about 110 mg l^{-1} and salinity of about 3600 mg l^{-1}, compared to Blanche Cup's 4300. This salinity is still much higher than those of about 2500 mg l^{-1} in the borefield. Those bores and springs sampled more than once showed small, non-systematic variations in chemistry and isotopic composition over the period of the project.

TABLE 4.5.2

Deep Groundwater Chemistry

Isotope No.	Identity	date taken
11239	GAB 6	30/3/88
7493	GAB 7	28/10/86
9793	GAB 12A	23/7/87
11241	GAB 16	30/3/88
11242	HH 4 Hermit Hill	29/3/88
9799	Curdimurka Bore	24/7/87
11247	HOF 081 spring	29/3/88
9802	Blanche Cup Spring	24/7/87
9803	The Bubbler Spring	24/7/87

TABLE 4.5.2b

Deep Groundwater Chemistry

Short Name	Lab. pH	Field EC µS/cm	Lab. EC uS/cm	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
GAB 6	7.9		3400	750	19	14	19
GAB 7	8.0		3230	620	14	11	5
GAB 12A	8.3		3570	750	30	6	9
GAB 16	7.9		3350	760	20	14	20
HH 4	8.1		2890	690	9	4	3
Curdi.	7.8		4330	920	19	19	14
HOF 081	8.0		3960	970	14	9	5
Bl.Cup	7.4		6980	1390	40	69	38
Bubbler	7.2		5400	1110	32	34	26

	S04 mg/l	Cl mg/l	HC03 mg/l	TSS mg/l
GAB 6	99	650	915	2489
GAB 7	6	610	670	1936
GAB 12A	81	609	1070	2602
GAB 16	96	640	940	2518
HH 4	3	550	1025	2311
Curdi.	51	836	1040	2923
HOF 081	1	750	1380	3153
Bl. Cup	285	1700	740	4288
Bubbler	114	1200	910	3451

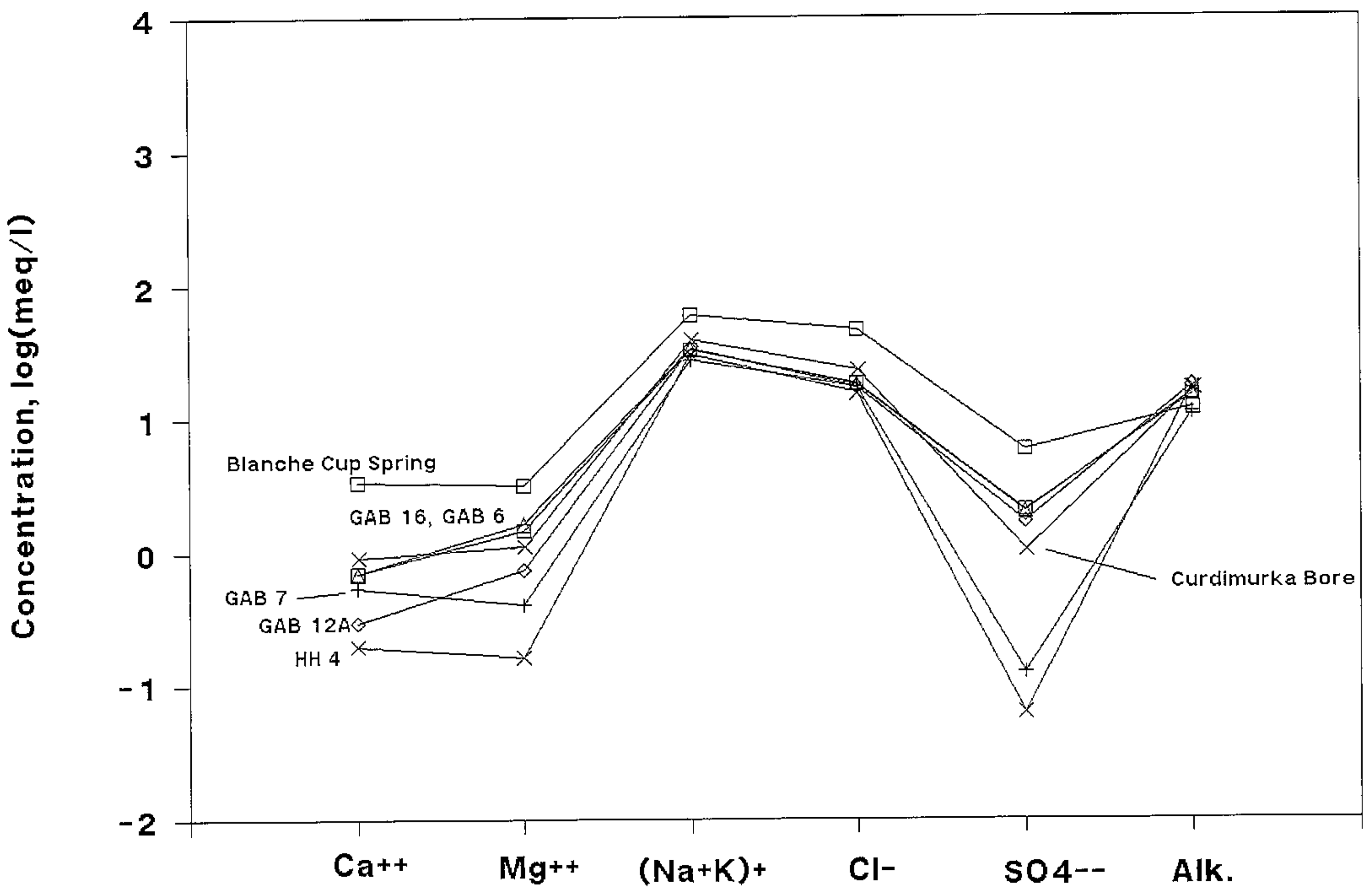

FIGURE 4.5.2 Schoeller diagram, deep groundwaters

4.5.3 SHALLOW GROUNDWATERS AND RELATIONSHIPS BETWEEN WATERS

The chemistry of representative shallow waters is given in table 4.5.3, but for discussion will be presented in three Schoeller diagrams with local deep groundwaters.

4.5.3.1 Eastern Waters

The analyses of bores GAB 7 and HH 4, and spring HOF 081 at Hermit Hill are shown with that from hole 19 in figure 4.5.3. The bore waters are very similar to the spring water, of the Na-HCO_3-Cl type typical of most of the GAB. The brine from hole 19, the saltiest of all shallow groundwaters sampled, shows a quite different pattern. Calcium and magnesium are lower, and all other major ions much higher. This is explained as due to the high initial alkalinity, 11 to 22 meq l^{-1}, which greatly exceeds the combined total equivalence of Ca and Mg, about 0.1 to 0.5 meq l^{-1}. As the water became concentrated by evaporation, Ca and Mg were precipitated out as carbonates, and then perhaps as sulphates. Excess alkalinity and sulphate continued to build up as evaporative concentration of the brine continued, resulting in a Na-Cl-CO_3-SO_4 brine (this argument for the evolution of brines is laid out in detail in such texts as Drever, 1982, following early work known as the Hardie-Eugster model.)

4.5.3.2 Central Waters

Analyses from several bores of the main Olympic Dam Project borefield A and shallow groundwaters from their monitoring bores (GAB 12S and GAB 16S) and hole 16B near GAB 12 are shown in figure 4.5.4. The

TABLE 4.5.3a

Shallow Groundwater Chemistry (Representative samples)

Isotope No.	Identity	Date taken
10055	GAB 12S	Sept'87
10058	GAB 16S	Sept'87
9797	Hole 16B	23/7/87
9798	Hole 18	24/7/87
11248	Hole 19	29/3/88

TABLE 4.5.3b

Shallow Groundwater Chemistry

Short Name	Lab. pH	Field EC µS/cm	Lab. EC uS/cm	Na mg/l	K mg/l	Ca mg/l	Mg mg/l
GAB 12S	6.9		78100	23300	212	1120	1400
GAB 16S	6.8		44100	11700	101	990	700
Hole 16B	7.2	100000	87500	31600	273	910	1580
Hole 18	8.5	52000	50000	14000	735	16	1340
Hole 19	9.4	148000	162700	103900	130	1	1

	SO4 mg/l	Cl mg/l	HCO3 mg/l	TSS mg/l
GAB 12S	6830	36400	220	69482
GAB 16S	3920	20100	110	37621
Hole 16B	12100	46200	90	92775
Hole 18	1760	21500	3900	43258
Hole 19	27900	68500	19200	219700#

\# There is a large excess of cations in this sample if all ions are considered fully dissociated; no allowance has been made for the formation of ion complexes.

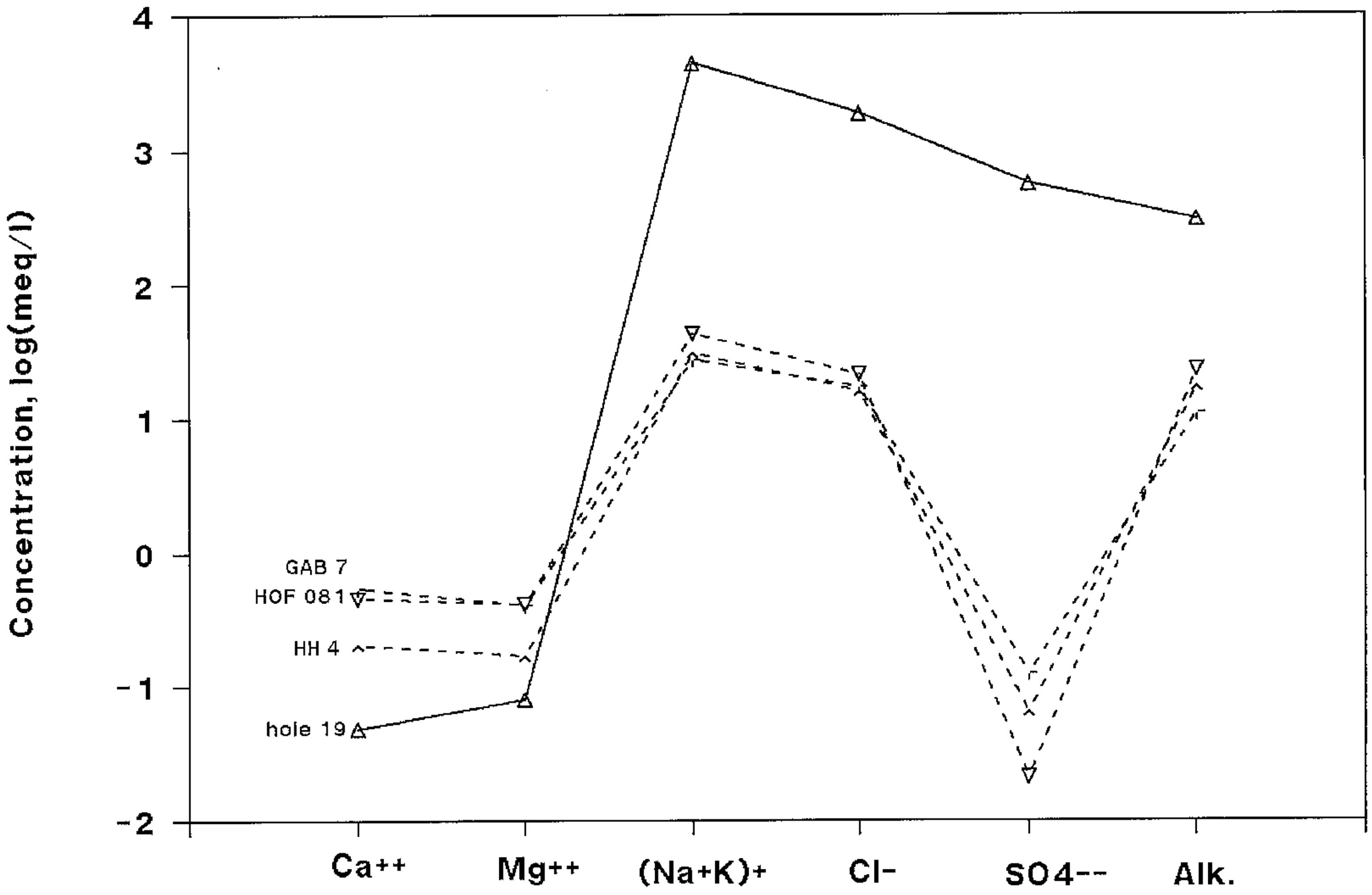

FIGURE 4.5.3 Schoeller diagram, eastern waters

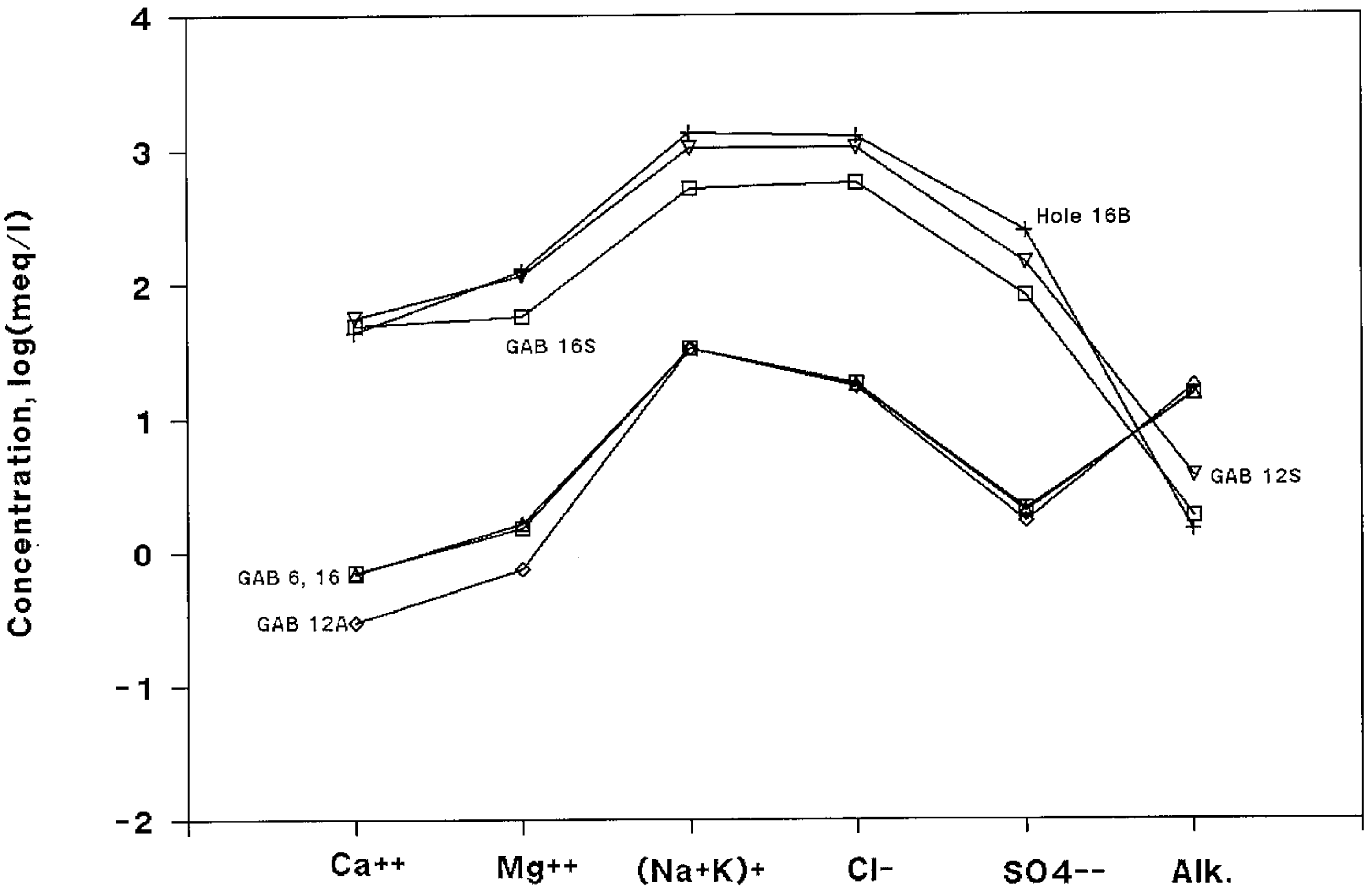

FIGURE 4.5.4 Schoeller diagram, central (borefield) waters

deep bores show a sightly western influence as mentioned in section 4.5.2. The shallow bores show waters concentrated in all ions except bicarbonate, which has dropped. In the the initial waters Ca+Mg was about 2.1 meq l^{-1}, still greatly exceeded by HCO_3^{2-} at about 16 meq l^{-1}, so cannot be explained by the same process as the eastern site. Extra Ca and Mg may have been dissolved from dolomite and calcite lenses known to be common in the Bulldog Shale during the passage through that aquitard (although this should also generate HCO_3), or perhaps cation exchange with, or alteration of the clay minerals, with Na being consumed (Na has been reduced relative to chloride in the shallow groundwaters). In any case the resultant brines contain nearly all Na Cl, with minor sulphate and very little else.

4.5.3.3 Western Waters

A short analysis of water from one of the western holes, hole 18 at Hamilton Hill was given in table 4.5.3, and it is shown with local deep waters (springs) and, in this case, surface waters in figure 4.5.5 The shallow water is very depleted in Ca, high in Mg, and has high alkalinity and sulphate. Sodium and chloride dominate in almost exact balance (609 and 606 eq l^{-1}), making up about 83% of ions. Except for the low calcium, the water shows similar relative amounts of major ions to the deep water exemplified by Blanche Cup Spring.

4.5.3.4 Comments

The dominance of Na Cl in all the brines of the shallow aquifers systems of the project area is partly due to the large amounts of these ions in the originating deep groundwaters, which continues to be

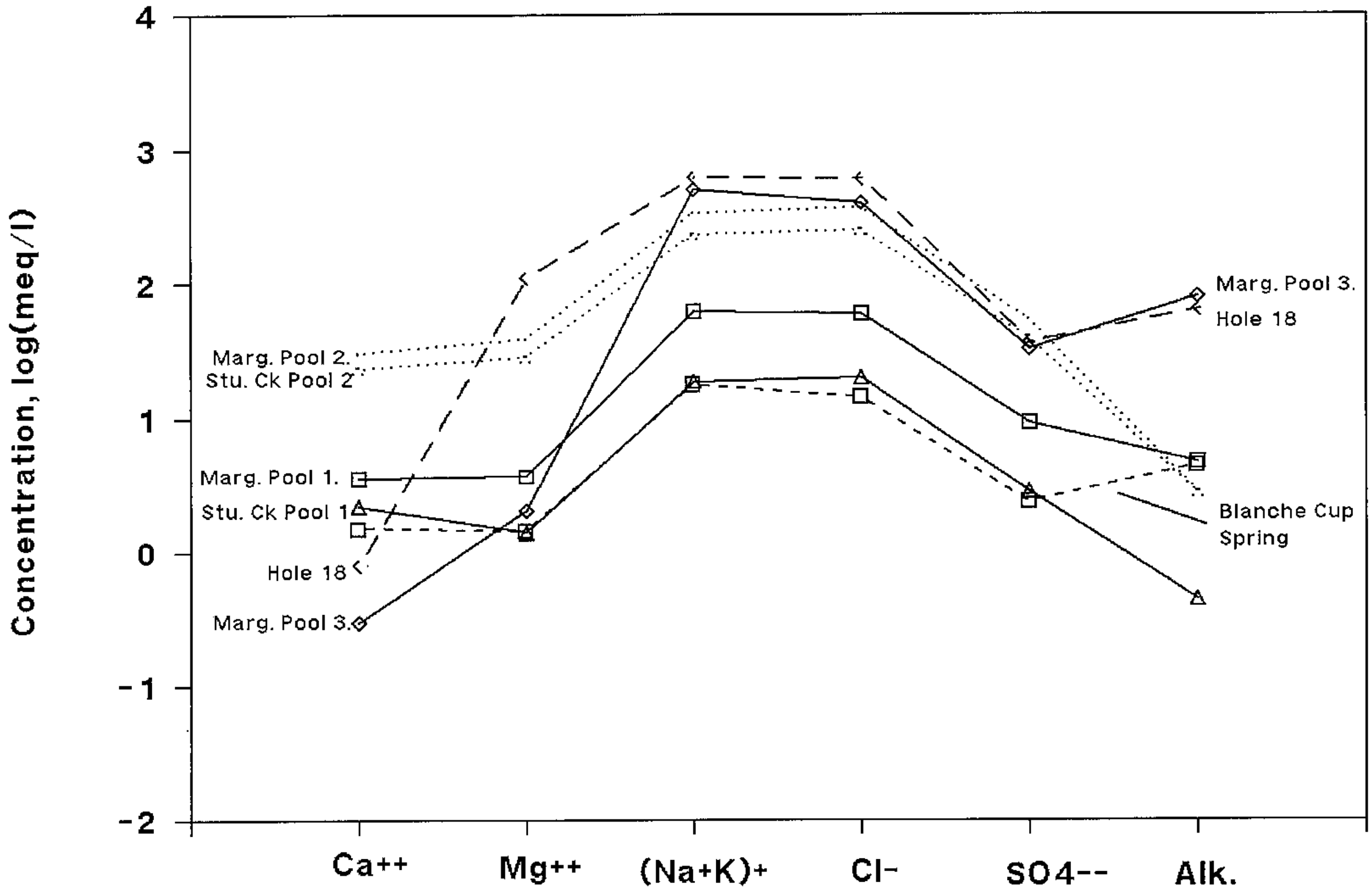

FIGURE 4.5.5 Schoeller diagram, western waters

concentrated while some other ions precipitate out as evaporite minerals. The recycling of halite is also likely to be important. Halite is precipitated in the unsaturated zone near the surface, as is gypsum and other minerals, although gypsum and calcite were both also noted beneath the water table in the Gibber Plain environment. When the rare rains occur that cause recharge of the shallow aquifer from above, adding to the continuous but slow additions from below, significant halite is dissolved by the percolating rainwater and added to the groundwater, and only small amounts of the other, less soluble main evaporite minerals, gypsum and calcite. This kinetic effect (due to the rates of dissolution) and recycling is one of the modifications needed to Hardie-Eugster models of chemical evolution of waters (Drever, 1982) and is likely to be important in the project area, contributing to the dominance of sodium chloride.

4.5.4 STABLE ISOTOPE RELATIONSHIPS

The stable isotope compositions (δD and $\delta^{18}O$) for surface and ground water samples are given in table 4.5.4, and plotted in figure 4.5.6.

The deep waters from bores fall on or close to the meteoric line at about $\delta D, \delta^{18}O$ of -50,-7.2‰, a little lighter than the GAB average of -41.8,-6.6‰ given by Airey *et al.* (1978). Shallow groundwaters fall on a line leading from the deep groundwater value at a slope of about 3.8, up to a maximum at hole 19 of +14,+11.6‰. Water from Blanche Cup Spring lies a little along this line, representing probably slight contamination of deep water with shallow, or simply evaporative enrichment in the pool of the spring. The equation of the line is

$$\delta D = 3.8\ \delta^{18}O - 22.6 \qquad (4.2)$$

TABLE 4.5.4

Isotope Analyses of Surface and Groundwater Samples

iso#	i.d.	δD	$\delta^{18}O$	iso#	i.d.	δD	$\delta^{18}O$
Shallow Groundwaters							
7491	Hole 9	-7.3	4.72	7492	Hole 12	-10.9	2.72
9797	Hole 16B	-5.9	5.08	9798	Hole 18	-17.3	0.85
10055	GAB 12S	-15.6	2.24	10056	GAB 14S	-17.1	1.90
10057	GAB 15S	-14.9	2.10	10058	GAB 16S	-9.8	1.28
10059	GAB 18S	-22.0	0.70	11248	Hole 19	+14.0	11.60
13432	Hole 21	-4.3	2.76				
Deep Groundwaters and Surface Waters							
7344	Bl. Cup	-46.4	-6.12	7486	NewYearGift	-49.6	-7.12
7487	Bl. Cup	-44.6	-5.99	7488	Marg.R.1	+51.2	+9.19
7489	Stu. Ck 1	+59.1	+9.83	7490	GAB6 ('86)	-50.6	-7.20
7492	GAB 11	-50.1	-7.20	7493	GAB 7	-48.9	-7.09
9788	GAB 1	-48.8	-7.14	9789	GAB 2	-48.3	-7.17
9790	GAB 5	-50.0	-7.37	9791	GAB6 ('87)	-49.1	-7.35
9792	GAB 8	-49.0	-7.28	9793	GAB 12A	-49.6	-7.48
9794	GAB15A('87)	-49.4	-7.37	9795	GAB 18	-49.8	-7.59
9796	HH 4 ('87)	-50.0		9799	Curdimurka	-47.9	
9800	HOF081 ('87)	-47.1	-6.98	9801	Fred Spr.	-50.6	-7.55

TABLE 4.5.4 (continued)

Isotope Analyses of Surface and Groundwater Samples

iso#	i.d.	δD	$\delta^{18}O$	iso#	i.d.	δD	$\delta^{18}O$
9802	Bl.Cup ('87)	-46.0	-7.20	9803	TheBub.('87)	-48.7	-6.65
9804	Marg.R.3	+12.5	+3.80	11239	GAB6 ('88)	-53.7	-7.66
11240	GAB15A('88)	-54.0	-7.99	11241	GAB 16	-53.5	-7.29
11242	HH 4 ('88)	-54.8	-7.93	11243	Ven.B.('88)	-52.3	-9.06
11244	Ven.Sp.('88)	-52.8	-7.43	11245	Bl.Cup('88)	-48.4	-7.21
11246	TheBub.('88)	-52.6	-7.21	11247	HOF081('88)	-49.3	-7.47
13422	GAB6('89)	-47.8	-7.67	13423	HH 1	-49.1	-7.72
13424	HOF081('89)	-45.1	-7.01	13425	Ven.B.('89)	-47.2	-7.14
13426	Ven.Sp('89)	-46.1	-6.98	13427	SOwl Ck 1	-35.9	-3.82
13428	SOwl Ck 2	-58.6	-8.54	13429	Stu. Ck 2	-38.6	-4.61
13430	Marg. R. 2	-40.2	-4.64	13431	L.Eyre S.	-59.1	-8.54

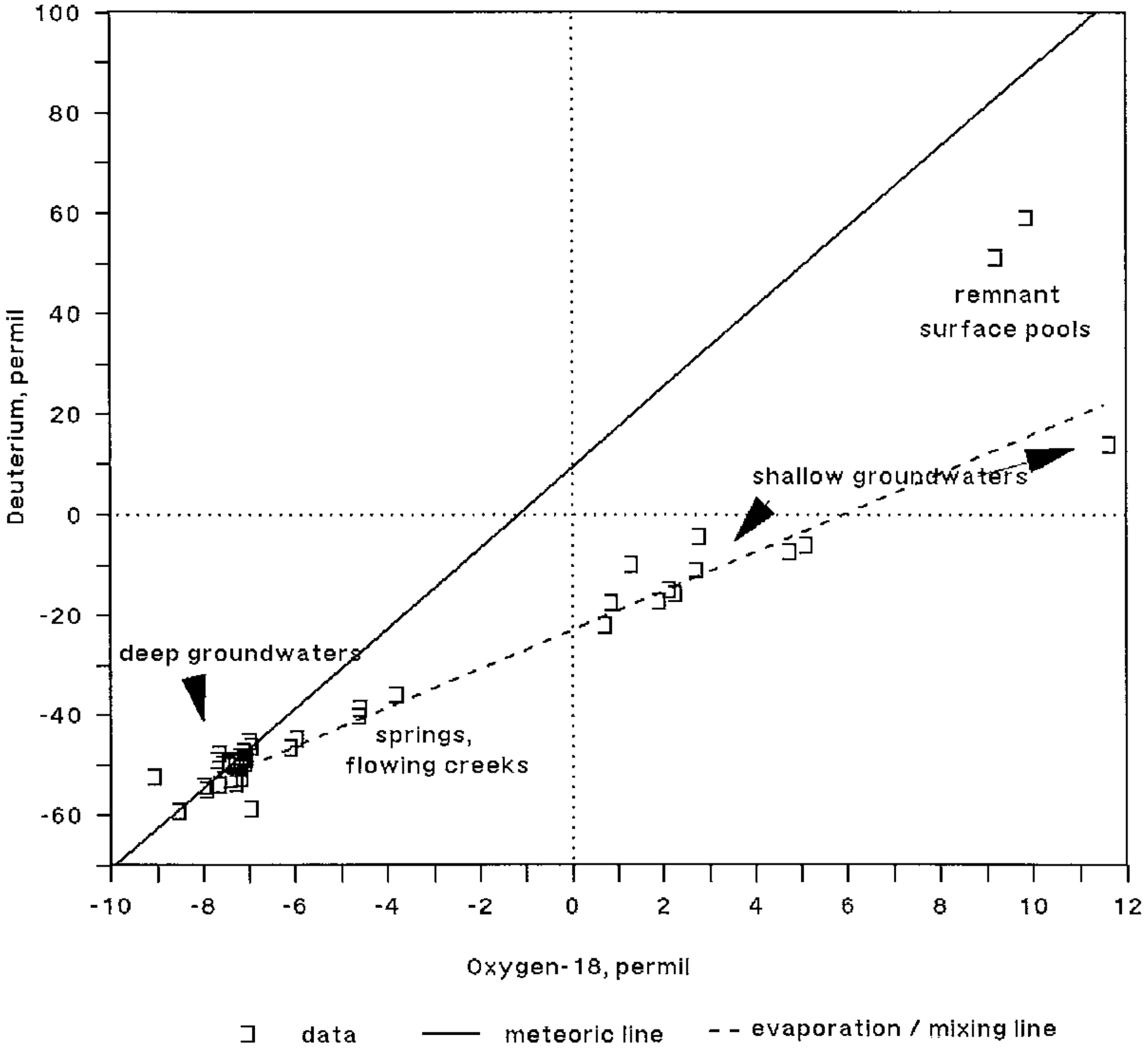

FIGURE 4.5.6 Surface and groundwaters near Lake Eyre South, O-18 - D plot

The waters from the fresh water-hole in Screechowl Creek and Lake Eyre South in April 1989 both fall on the meteoric line at about -59, -8.6‰. These values probably represent a weighted average of the rain that fell in March 1989, as they do not appear to have been enriched by evaporation. The flowing saline creeks of that time lie off the meteoric line, almost on the "evaporation line" of the shallow groundwaters.
If the Lake Eyre South and Screechowl Creek fresh water-hole data is indeed representative of the rain that fell, and having an isotopic composition close to the average deep groundwater, it is considered more likely that the saline creek waters are a mixture of rain (as recent recharge) and pre-existing shallow groundwater, rather than a mixture of deep and shallow groundwater. However, it is also possible that they represent pure pre-existing groundwater from zones that had not been enriched by evaporation as much as those sampled.

The standing surface water from pools in Margaret River and Stuarts Creek in October 1986 are quite distinct from the rest of the waters. Although nothing firm may be concluded from these values, the waters may be evaporated rainwater with some groundwater influence. The sample of July 1987 from Margaret River at Hamilton Hill was thought to be largely groundwater based on its chemistry, but is isotopically distinct from the local shallow groundwater. This may be because of some mixing with rainwater, and/or modification by exchange with atmospheric water vapour during the preceding autumn and winter months, when relative humidities are considerably higher, and evaporation rates lower, than in spring. Again, no firm conclusion can be drawn without additional information.

The evaporation line for waters evaporating through a soil may be predicted by the formulation of Barnes and Allison (1983) given in section 2.1.3. Using the parameters $h_a = 0.4$, the "average" relative humidity of the air (from figure 1.2.3), reservoir isotope values of δD = −50‰, $\delta^{18}O$ = −7.5‰, and atmospheric values of δD = −80‰, $\delta^{18}O$ = −11‰ (close to those noted by Walker *et al.*, 1988 as "reasonable long-term atmospheric delta values for Southern Australia", there being very few available measurements), the equation is predicted to be

$$\delta D = 3.4\ \delta^{18}O - 25, \tag{4.3}$$

quite similar to that observed.