CHAPTER ONE

INTRODUCTION

1.1 LOCATION AND HISTORY OF THE STUDY AREA

The Thirlmere Lakes are situated in a valley 9.6 km southwest of Picton, N.S.W., and 112 km southwest of Sydney, N.S.W. (Fig. 1.1). The topographic map (Fig. 1.2 - rear pocket) shows that the lakes' surfaces are approximately 305 metres (1,000 ft) above sea level, with the surrounding ridges rising to 378 metres in the west, 350 metres in the east and 408 metres in the north; the ridge which forms the central axis of the valley rises to 335 metres above sea level.

There are four freshwater lakes in the system, separated one from the other by stands of sedges and paperbarks, numbered according to the system shown on Fig. 1.2; Lake IA is merely a northern extension of Lake I which has become separated from it since about 1960. Dry Lake, to the north of the main lakes, is a freshwater swamp which may, in the past, have been connected to the lakes. The relationship of the lakes to the surrounding area is best seen in Plate 1.1.

According to a local historian, Mr. F. B. Knox of Tahmoor, the first recorded discovery of the lakes was by the members of the Wilson expedition on 14th March, 1798. In 1802, George Caley visited the area and named the largest lake "Scirpus mere" (reedy lake); he was of the erroneous opinion that the lakes were the source of the Bargo River. The lakes, then called "Couridjah Lagoons" after the local aboriginal name for the area, were investigated as a source of water for Sydney in 1867, and a pumping station was established on the shores of Lake II to supply water for the southern railway; at this time water courses were cut through the reeds to connect the various lakes. The name of the lakes was changed to "Picton Lakes" in the late nineteenth century, and to "Thirlmere Lakes" in 1960, and in an effort to

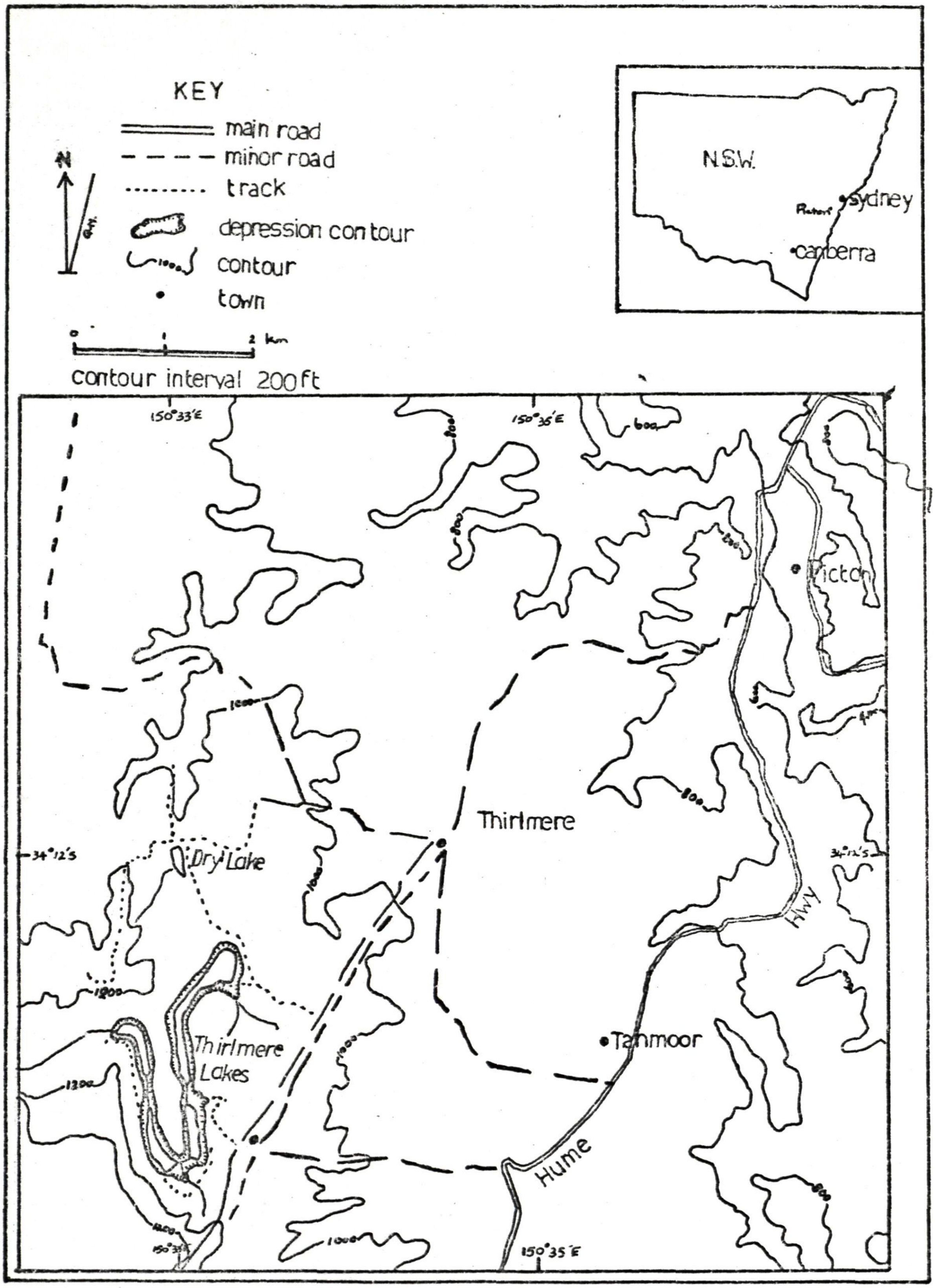


Fig. 1.1 : LOCATION OF THE STUDY AREA

Plate 1.1 Aerial Photograph of Study Area and Environs

establish a tourist trade for the local village of Thirlmere, the W. E. Middleton Memorial Drive was constructed around the perimeter of the lakes. At the present time the area is a State Park, under the management of the N.S.W. National Parks and Wildlife Service.

1.2 SCOPE OF THE STUDY

At the outset, it must be stated that research on the Thirlmere Lakes was undertaken in order to gain an understanding of geomorphic processes operating within and around a lacustrine environment. Thus, the research is not based on one specific problem, but on a whole host of problems related to the influence of land-surface form and process on lake basin evolution. Nor are the lakes the sole centre of attention; while they form the local base level for tributary streams, and therefore influence the behaviour of these streams, the processes operating on the subaerial land forms are equally important as they provide some of the sediment which is deposited in the lakes.

While the origin of the lake basin is interesting in itself because of its possible relationship to a former river valley, lack of time and resources has limited research in this area. However, a whole chapter has been devoted to it because it raises some questions about the geomorphology of the whole Sydney region and how present stream patterns relate to past ones. This subject has received little of the attention it deserves since the pioneering work of Edgeworth David, Griffith Taylor and others at the beginning of this century.

Because a lake basin can in many ways be considered a closed system, a study of the total environment, both physical and biological, is important to an understanding of lake basin dynamics. With this thought in mind, floral and faunal evidence, as well as sedimentological evidence, has been used to identify and interpret such phenomena as lake level changes, and depositional sedimentary environments as portrayed in the valley fill.

Thus, the aims of the research as reported in this thesis may be stated as follows :

1. to describe the land surface features of the area and the processes operating on them;

2. to describe the stratigraphy of the valley fill, with a view to interpreting depositional environments in the light of geomorphic processes currently operating in the area; and

3. to formulate hypotheses about the origin and evolution of the Thirlmere Lakes and the valley in which they are found.

1.3 PREVIOUS WORK

Lake basins tend to occupy a wide variety of environments and have very diverse origins; Hutchinson (1957) recognises seventy-six different types, grouped into eleven major categories which define the dominant process responsible for the building, excavating, and/or damming of the lake basin.

Because of the diverse locations of lakes, literature on lake basins is not directly pertinent to Thirlmere Lakes, other than in terms of increasing an understanding of lacustrine sedimentary processes. This is particularly so when one considers that sedimentation in lacustrine environments is influenced by such factors as the origin of the basin, the size and depth of the basin, relief of the catchment area, extent of vegetal protection over the catchment area, characteristics of the rock and soil of the catchment area, extent of shallow water adjacent to the shore, the bottom topography of the lake, the circulation of the water, the characteristics of the water, and climatic conditions (Twenhofel and McElvey, 1941). A review of such literature showed that, in keeping with the classical model of lake sedimentation purported by Twenhofel (in Picard and High, 1972), in most lakes sediment size tends to decrease with depth of water in response to a change in the energy of the depositional medium; that it also decreased with distance from the shore was not as well supported (see, for example, Kindle, 1925; Hough, 1935; Moore, 1961; Nelson, 1967). According to this classical model "ageing", i.e. infilling, of a lake basin commences almost as soon as the basin originates and the sedimentary sequence so generated is an upward coarsening one, as the water depth becomes less.

Studies of lakes in Australia have mainly concentrated on their faunal content; in a bibliography in the Australian Society for Liminology Bulletin (1970), only two articles, i.e. those by Galloway (1967) and Hope (1970) pertained to physiography, and the latter related to a coastal lagoon. Until the work of Bowler (1970) on lake sediments in southeastern Australia and Coventry (1973; in press) on the sediments and shoreline features of Lake George, little work had been done on the reconstruction of Late Quaternary climates from lake sediments in Australia.

The research reported in this thesis is the first on the physiography of Thirlmere Lakes. Stanisic (1972) undertook a survey of the faunal content of Lake I, with particular reference to the freshwater sponge *Radiospongilla sceptroides*, and, as will be shown later, this work has proved to be of assistance to the present author in the reconstruction of past depositional environments in the area. Moreover, Stanisic found that the faunal assemblage in the lakes was fairly unique and seemed to indicate that stable conditions had prevailed for some considerable period.

1.4 METHODS OF STUDY

Field work was undertaken from January 1974, to July 1974, with laboratory analyses being conducted concurrently. The following procedures were employed.

1.4.1 Surveying: The shallow bore hole transects were surveyed using a dumpy level and a staff. The slope profiles were measured with an Abney Level, ranging poles and tape measure. As there was no Standard Datum point, all profiles are drawn to an arbitrary datum.

1.4.2 Sediment Sample Collection: The lack of natural exposures, the moist nature of the sediment, and the thick vegetation cover made sample collection difficult. The deep bore holes were drilled using a Gemcodril rig, and samples were collected from the tip of the cleaned drilling bit; however, sample contamination was unavoidable. A Jarrett auger and extensions was used for the short bore holes. The few cores able to be extracted from the Dry Lake sediments were obtained by driving a length of steel tubing, lined with plastic, into the sediment with a sledge hammer. A marine corer was used for some of the lake sediment cores and a piece of steel tubing welded onto an auger handle for others; both methods proved unsatisfactory due to the cohesionless nature of the sediment. Bulk samples of the lake surface sediment were obtained with a clamshell snapper device. The alluvial fan surface sediments were also obtained with an auger; the top 10 cm of sediment were sampled at each location. pH and colour of some samples were determined in the field using a C.S.I.R.O. Field pH Kit and a Munsell Colour Book.

1.4.3 Water Depth Determination: Spot depths of the lakes were obtained using a leadweight on the end of a calibrated line, while the bottom profiling was undertaken using a Furuno FG200 Echosounder, which produces a continuous paper trace. Given that the speed of the boat was constant for the duration of each traverse, the trace was then fitted to the known length of the traverse calculated from the topographic map. Possible sources of error include the following:

1. The boat may have been pushed off course due to the variable force of the wind.
2. Because the reed margin could not be penetrated, the traces finish before the shoreline is reached; an estimate of the width of the margin had to be made during the construction of the bathymetric profiles.

1.4.4 Grain Size Analysis: This was undertaken according to the procedures outlined in the Australian Standards Association Handbook (1971). All samples were dispersed using a dispersal solution of sodium hexametaphosphate and sodium carbonate; the alluvial fan samples were also pretreated with hydrogen peroxide to remove the organic matter.

Samples of 50 g dry weight were washed through a 4ϕ sieve with distilled water, the fines were placed in a measuring cylinder and the solution was made up to 1000 ml. The coarse fraction was dried at 80^{o}C for 24 hours, then sieved on a sieve shaker for 15 minutes each sample, using a nest of stainless steel sieves at $\frac{1}{2}\phi$ intervals from -2ϕ to 4ϕ plus pan. The cumulative percentage weights retained on each sieve were calculated and tabled. The fine fraction was analysed using the hydrometer method as outlined in the Australian Standards Association Handbook (1971). Hydrometer readings were taken at 1 min., 2 mins., 4 mins., 8 mins., 16 mins., 30 mins., 1 hour, 2 hours, 4 hours, and 24 hours and the equivalent particle sizes (ϕ) were determined along with their cumulative percentage weights.

The combined results were plotted on arithmetic probability paper and the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles were fed into a computer program which determined the following grain size parameters of Folk and Ward (1957):

$$\text{Mean (Mz)} = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Inclusive Graphic Standard Deviation (σ)

$$= \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Inclusive Graphic Skewness (Sk)

$$= \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

$$\text{Graphic Kurtosis (Kg)} = \frac{\phi95 - \phi5}{2.44\ (\phi75 - \phi25)}$$

1.4.5 Organic Content: The loss of dry weight on ignition of the material is taken as an indication of the organic matter content. However, with this method some water loss from alteration of clay minerals also occurs, but it was sufficient for the purposes for which the results were required. A sample of known weight was placed in a weighed porcelain crucible in a muffle furnace set at 600^oC and was burned for two hours. The crucibles and their contents were cooled in a dessicator, then weighed, and the percentage loss in weight was taken as an estimate of organic matter content.

1.4.6 X-Ray Photographs: Some X-ray photographs of peat sections were taken using a Philips Radiographic-Fluoroscopic inspection system (Radifluor 360) and Kodak X-ray film. The sections were exposed for times ranging from 2 minutes to 4.25 minutes, and the negatives were compared with the sections in order to identify the structures contained.

1.4.7 Microscopic Studies: Samples of sediment were placed on a microscope slide, moistened with water, a cover slip placed over them, and viewed under various magnifications with a trinocular microscope. For sponge spicule abundance estimates, six slides of each sample were studied and the estimates for each slide were averaged.

The plant tissue for transverse sections was treated in the following manner (method by courtesy of Mr. K. Bamber, Div. of Wood Technology, Forestry Commission of N.S.W.):

1. Sections were bleached by heating (80^o - 100^oC) for about ½ hour in solution of 1 part glacial acetic acid plus 1 part conc. hydrogen peroxide and 1 part water.

2. Sections were placed on microscope slides, excess

bleaching solution was quickly removed and several crystals of phenol were placed beside the sections and melted by warming the slide (this removes water from sections).

3. Excess phenol was then drained off and the sections were covered by oil of cloves. This mountant makes silica bodies in the tissue clearly visible because of the refractive index difference between the silica and the oil.

4. Photographs of untreated sections were taken using an Olympus microscope, Olympus automatic exposure photographic head and Olympus 35 mm camera body. The magnification on the film negative was 100 X (objective 40 X eyepiece 2.5).

CHAPTER TWO

PHYSIOGRAPHY OF THE STUDY AREA

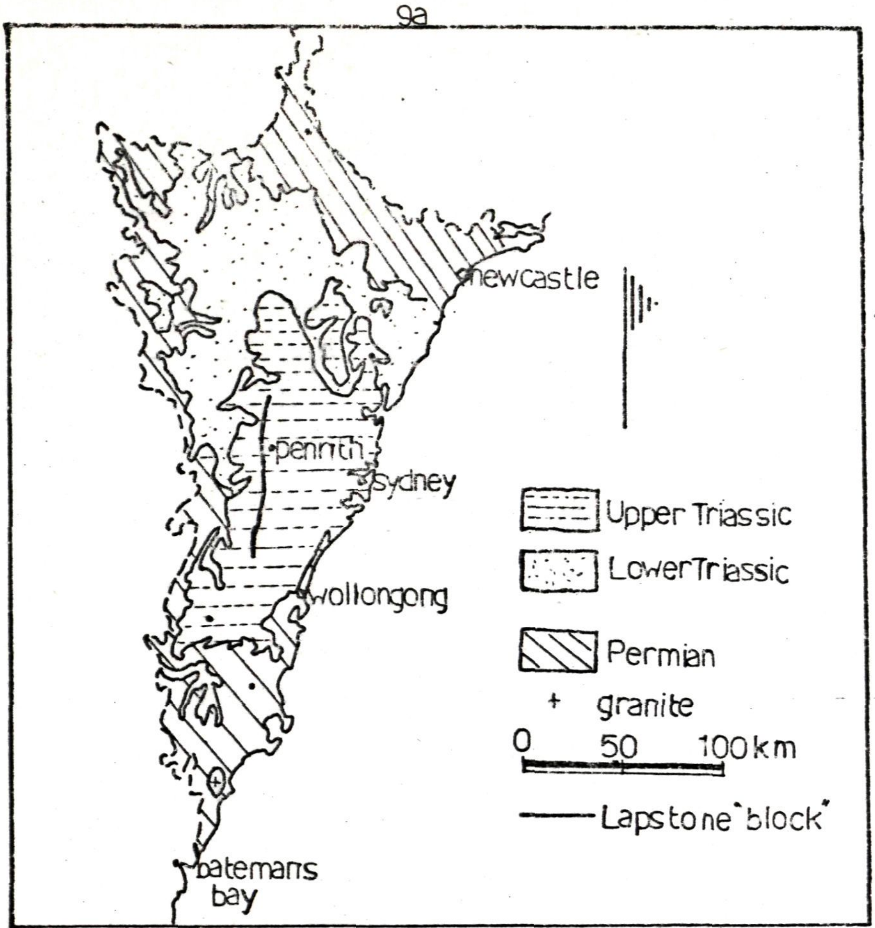
2.1 GEOLOGY

The valley in which Thirlmere Lakes are located is incised into Hawkesbury Sandstone which is part of the sequence of sedimentary rocks known as the Sydney Basin (Fig. 2.1). This consists of alternating marine and non-marine rocks of Triassic age, with a thickness of about 4,800 metres and covering an area of 36,000 km^2 onshore and about 16,000 km^2 offshore to the edge of the continental shelf (Mayne et. al., 1974). The basin shape is largely due to deformation during the Cainozoic Era and is only partly related to the structure of the area during the time of deposition of the sediments (Packham, 1969). Table 2.1 shows the location of the Hawkesbury Sandstone within the sequence.

2.1.1 The Nature of Hawkesbury Sandstone: The Hawkesbury Sandstone has an area of 12,500 km^2, from Kiama and Bundanoon in the south to Mt. Yango and Mt. Warrawalong in the north; its western boundary is near Woodford, and it extends as far as Mt. Tomah in the northwest and the present coastline in the east, except between Dee Why and Royal National Park, where it extends seaward for a few kilometres (Standard, 1969). Its thickness ranges from 30 metres to 240 metres, and in the Picton area is approximately 160 metres (Standard, 1969, Fig. 5.35).

It consists of highly lenticular beds of quartz - rich sandstone, mainly cross-bedded with a northeast dip direction, but with some massive units. Beds of shale and conglomerate also occur. The sandstone has an argillaceous matrix and a secondary quartz - siderite cement. The detrital grains are moderately to poorly sorted, with a modal grain size of medium to coarse sand (0.25 - 1.00 mm), and are sub-angular to sub-rounded in shape (Standard, 1969).

The environment of deposition of the Hawkesbury Sandstone has been a source of conflict since the formation was first defined:



source: Packham (1969)

Fig. 2.1 : GEOLOGY OF THE SYDNEY BASIN

			interval	WESTERN AREA	NORTHERN AREA	CENTRAL AREA	SOUTHERN AREA: ILLAWARRA DISTRICT	SOUTHERN AREA: CLYDE RIVER COALFIELD
TRIASSIC	LOWER AND MIDDLE		14	WIANAMATTA GROUP		WIANAMATTA GROUP	WIANAMATTA GROUP	
			13	Hawkesbury Sandstone		Hawkesbury Sandstone	Hawkesbury Sandstone	
			12	NARRABEEN GROUP: GROSE SUB-GROUP; CALEY SUB-GROUP		NARRABEEN GROUP: GOSFORD FORMATION; CLIFTON SUB-GROUP	NARRABEEN GROUP: GOSFORD FORMATION; CLIFTON SUB-GROUP	
PERMIAN	UPPER	TATARIAN	7 – 11	SHOALHAVEN GROUP: ILLAWARRA COAL MEASURES (Western and Southwestern Coalfields)	SINGLETON COAL MEASURES: WOLLOMBI COAL MEASURES (UPPER HUNTER); NEWCASTLE COAL MEASURES (LOWER HUNTER); WITTINGHAM COAL MEASURES (UPPER HUNTER); TOMAGO COAL MEASURES (LOWER HUNTER)	ILLAWARRA COAL MEASURES (Central Coalfield); SHOALHAVEN GROUP: Budgong Sandstone	ILLAWARRA COAL MEASURES (Southern Coalfield); SHOALHAVEN GROUP: Budgong Sandstone	
		KAZANIAN	6	Berry Formation	MAITLAND GROUP: Mulbring Siltstone	Berry Formation	Berry Formation	Berry Formation
			5		Muree Sandstone Member	Nowra Sandstone	Nowra Sandstone	Nowra Sandstone
	LOWER	[illegible]	4	Megalong Conglomerate ? ? ?	Branxton Formation	Wandrawandian Siltstone	Wandrawandian Siltstone	Wandrawandian Siltstone
		ARTINSKIAN	3		GRETA COAL MEASURES	CONJOLA SUB-GROUP: Snapper Point Formation	CONJOLA SUB-GROUP: Snapper Point Formation	Snapper Point Formation
			2		DALWOOD GROUP: Farley Formation; Rutherford Formation; Seaham Formation and Gyarran Volcanics	Pebbley Beach Formation	Pebbley Beach Formation	Pebbley Beach Formation
		SAKMARIAN			Allandale Formation; Lochinvar Formation	Wasp Head ? Formation	Wasp Head Formation	? Clyde Coal Measures ?; Wasp Head Formation

source: Mayne et al. (1974)

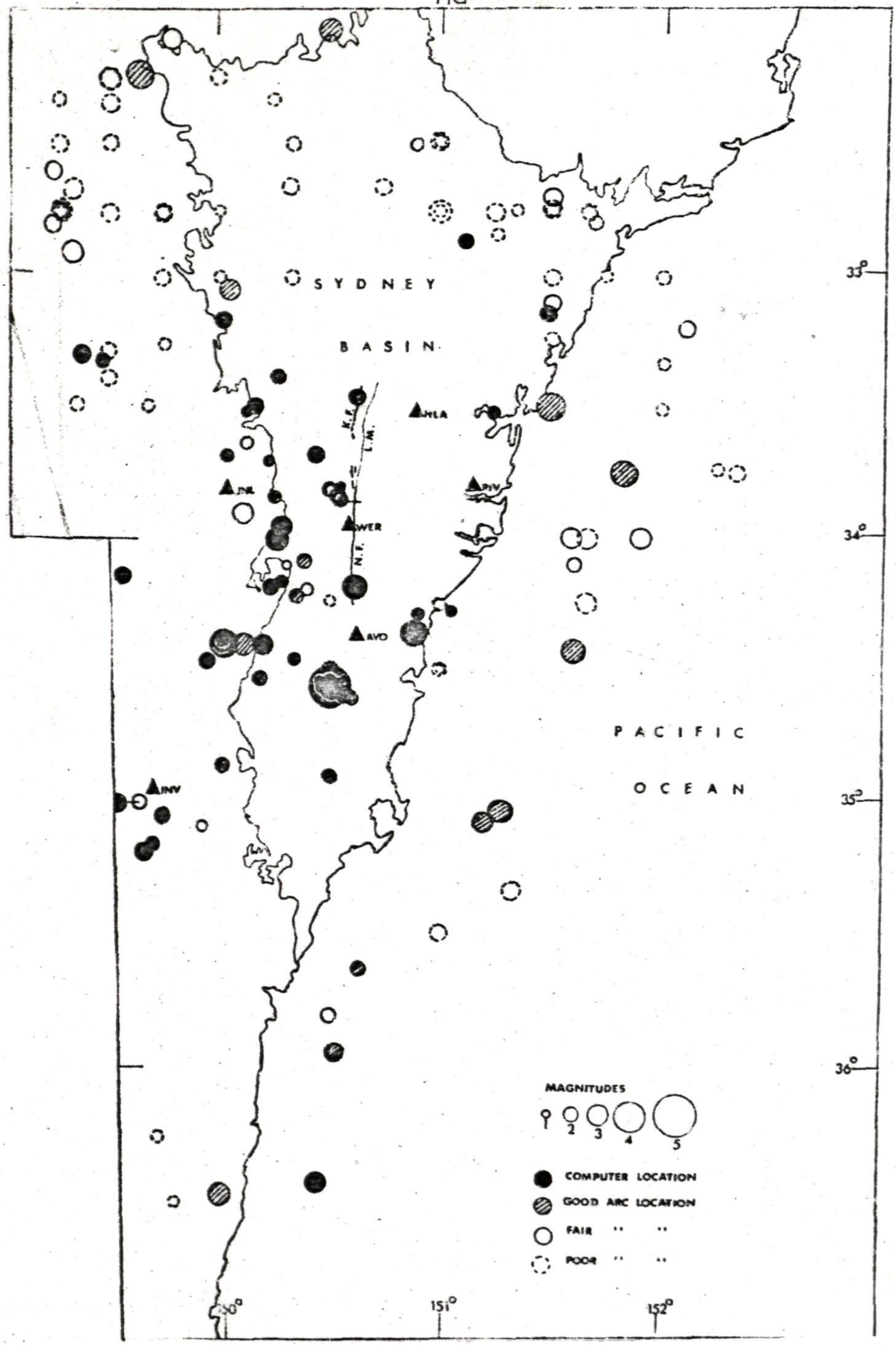
Table 2.1 : SEQUENCE OF PERMO-TRIASSIC ROCKS IN THE SYDNEY BASIN

Charles Darwin (1844, in David, 1896) considered it to be of marine origin, while Tennison - Woods (1883) thought that the steep ridges of sandstone in the Blue Mountains to the west of Sydney (now defined as part of the Narrabeen Group - Standard, 1961) could only have been formed by the action of the wind. More recently, Standard (1969) considered it to have been deposited by a fluvial system on a stable coastal plain, and this view is supported in part by Conaghan and Jones (in Hare, 1973), who point out that features such as the high ratio of sandstone to mudstone and the low variance of cross-bedding inclination and textural characteristics are considered diagnostic of low sinuosity fluvial regimes. On the other hand, Connolly (1969) interpreted the blanket-type deposit as being indicative of a barrier bar/tidal delta complex, and his view is supported by Mayne et. al. (1974) in their recent publication.

2.1.2 Structure and Seismicity: The major structural feature of the Sydney Basin is a line of major folding and faulting commonly referred to as the Lapstone Monocline (Fig. 2.1). It was first noted by Darwin (1844, in David, 1896) who considered it to be a primary depositional structure. To the south of Wallacia, the feature is largely a fault and is referred to as the Nepean Fault; its total extent is over 160 km (Branagan, 1969). The change in elevation across the feature is approximately 640 metres, but in places to the west it is paralleled by a fault which results in a drop in elevation of approximately 160 metres. This fault, extending from Mountain Lagoon to Glenbrook Creek, is known as the Kurrajong Fault, and has a southern extension known as the Glenbrook Fault which can be traced on the Wollongong 1:250,000 geological sheet as far as Lakesland. However, Branagan (1969) is doubtful if much faulting has occurred in the latter region and the structure appears to him to be a hinge fault merging into a monocline downwarped to the west. Its surface appearance along its length (see Chapter Five) resembles an uplifted block (Dr. J. G. Jones, pers. comm.), and in this thesis, for the sake of simplicity, the monoclinal fold and associated faults will be referred to as the "Lapstone Block".

The age of the "block" is generally considered to be Late Tertiary, with activity occurring during the time referred to as the Kosciusko Period. This name was given it by Andrews (1910) who considered that, before this time, peniplanation had been extensive on the east coast of Australia; at the close of the Tertiary Period, warping and faulting took place, carrying the Blue Mountains and Snowy Mountains areas up to heights varying from 1,500 to 7,300 feet. However, there is no direct evidence of age, other than the fact that it occurred after deposition of the Wianamatta Group sediments, which are often found to occur in isolated areas to the west of the fold (David, 1896; Osborne, 1948). Most of the early writers (eg Andrews, 1910; Craft, 1928a and b; Osborne, 1948) consider that there has been at least two stages of uplift, or that movement has been relatively continuous and may still be occurring.

That the zone is still active is evidenced by the seismic record for the Sydney Basin. Fig. 2.2 shows that several earth tremors were experienced in the area between 1959 and 1967 alone. Jaeger and Browne (1958) and Doyle et. al. (1968) consider this to be evidence of the continuing subsidence of the Cumberland Basin, to the east of the "Lapstone Block". The most recent earth tremor experienced in the Sydney area occurred on 9th March, 1973, and its epicentre was located under the southern end of Lake Burragorang, to the west of Picton. Drake (1974) considers that its cause may have been the weight of water in the lake, but also points out that the area around Picton could be considered to be of high seismic risk because of the presence of the Nepean Fault dipping westward towards the more seismically active region near the western edge of the Sydney Basin, the presence of alluvial ground with poor bearing capacity, and slopes with a high landslide potential; these features have all been considered by Steinbrugge (1968, in Drake, 1974) to deserve added consideration when calculating the seismic risk of any area.



Seismic Stations: AVO—Avon; HLA—Halls Lagoon; INV—Inveralochy; JNL—Jenolan; RIV—Riverview; WER—Werombi.

Structures: KF—Kurrajong Fault; LM—Lapstone Monocline; NF—Nepean Fault.

source: Doyle et al (1968)

Fig. 2.2 : SEISMICITY OF THE SYDNEY BASIN AREA, 1959-67

2.1.3 Hawkesbury Sandstone in the Study Area: The Hawkesbury Sandstone forms a plateau-type surface in the study area, which is deeply dissected by numerous streams. Incision tends to follow the dominant joint directions in the rock, i.e. northwest and northeast, and it is possible that this influences the northwest - southeast orientation of the long axis of the valley in which the lakes are found. The rocks tend to break up into large blocks due to weathering along the joint planes and sub-horizontal bedding planes.

In fresh exposures the bedrock is red to orange in colour and contains abundant quartz pebbles throughout; the dominant particle size is in the medium to coarse sand range (0.25 - 1.00 mm).

The geological features in the study area are shown on Fig. 2.3, which is a portion of the 1:50,000 geological sheet for the Camden area at present being compiled by the N.S.W. Geological Survey. The present of the fault running in a northwest - southeast direction to the northeast of the lake has not been confirmed in the field. There are few outcrop exposures in this area, and mapping of the possible fault would require correlation of marker beds between bore holes or in exposures.

2.2 SOILS

The soils in the study area may be differentiated in terms of the parent material from which they are derived. On the one hand are the residual soils on the sandstone ridge-tops and on the other are the weakly developed soils in the colluvial[1] material of the debris slopes and the colluvial/alluvial[1] material of the fan surfaces (see Section 2.3).

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1 Alluvium and colluvium are distinguished in terms of their transportational processes : the former is deposited by essentially channelled flow, while the latter is derived from slope processes such as sheetwash and debris flows.

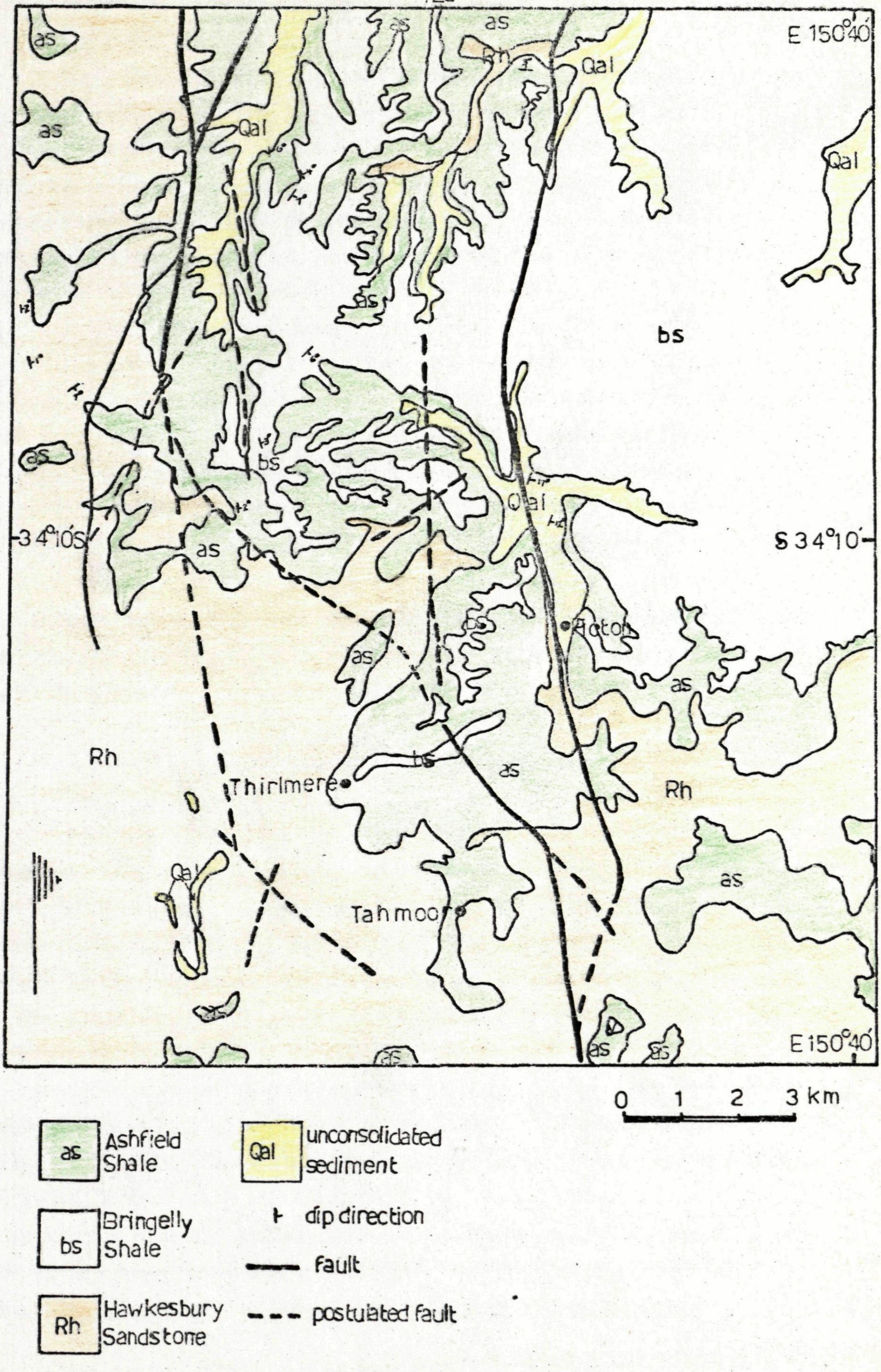


Fig. 2.3 : GEOLOGY OF THE STUDY AREA

The ridge-top soils are shallow (2 - 30 cm) and undifferentiated into horizons, except for the accumulation of organic matter at the surface. Their colour is generally a dark yellow brown (Munsell 10YR2/2) to black, depending on the amount of organic matter they contain, and they exhibit an acid reaction (pH 5.0). Their texture is essentially a sandy loam, and they may be classified as lithosols according to the definition of Stace et. al. (1968).

The soils of the debris slopes and fans are weakly developed, and are distinguished from freshly deposited sediment by an organic rich surface horizon and some development of a crumb structure, whereby the sand particles are aggregated within an earthy matrix. Texture is generally a sandy loam with clay content increasing with depth. pH is generally acidic (pH range 5.0 - 6.0), with the organic topsoil sometimes having a pH as low as 4.0. The colour of the subsoil is reddish brown (Munsell 5YR4/6). As the surface of the soil is often buried beneath a deposit of fresh sediment, they are best classified as alluvial or colluvial soils.

2.3 VALLEY FORM AND PROCESS

Fig. 2.4 shows that the study area is composed of three landform features, namely the hillslopes, comprising both a cliff or free face and a debris slope, the alluvial fans, and the lakes themselves. For reasons already given in Chapter One, the lakes will be discussed at length in Chapter Three, and discussion in this section will centre on the hillslopes and fans and the processes operating on them.

It must be pointed out at this stage that the land forms have been distinguished on the basis of form alone; it has been shown (Section 2.2) that the material on the surfaces of the fans and debris slopes is essentially the same. The fans and debris slopes merge imperceptibly on the ground, but can be distinguished by the fact that the former bulges out beyond the limits of the latter (see Plate 1.1 and Fig. 2.4) at the mouths of the tributary stream valleys.

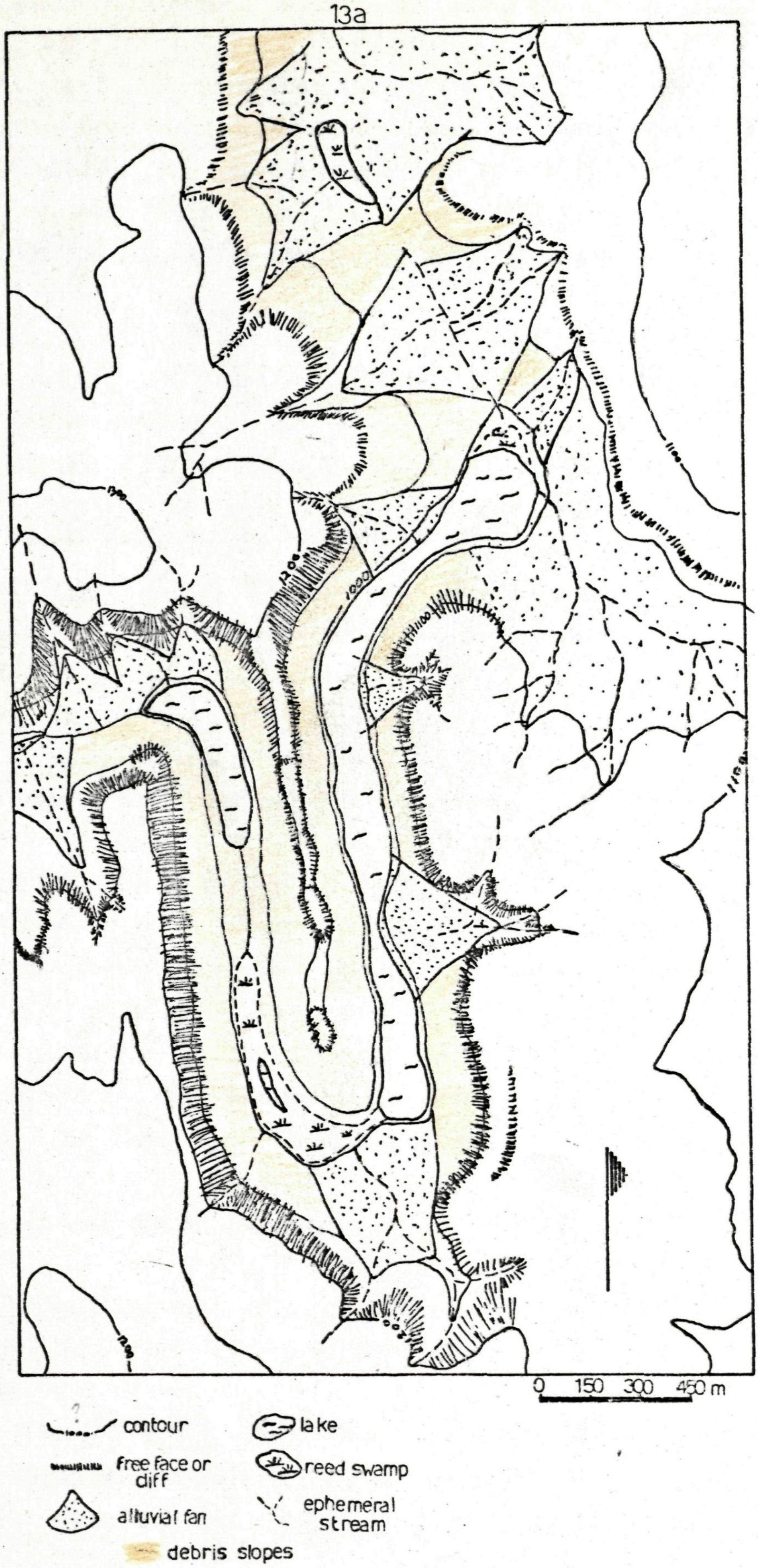


Fig. 2.4 : LANDFORMS IN THE STUDY AREA

2.3.1 Hillslopes: As mentioned above, the hillslopes exhibit both a cliff or free face, composed of Hawkesbury Sandstone, and a colluvial debris slope, separated one from the other by a sharp break in slope (see Plate 2.1). The former reclines at angles of between 45^{o} and 70^{o}, while the latter exhibits angles of less than 15^{o}.

Seismic evidence, outlined in Chapter Five, shows that the bedrock cliffs extend beneath the debris slopes at approximately the same angle as above the junction and that, therefore, the debris slopes must be comprised of transported, as opposed to in situ, material. The mode of deposition at present operating on the debris slopes and on the fans will be discussed later.

The vertical and lateral extent of the free face is shown in Fig. 2.4. In some places, it consists of a nearly vertical bedrock face, with an angular junction with the ridge top. Elsewhere, for example on the eastern side of Lake II, the cliff has a stepped appearance, due to the removal of joint blocks from the uppermost layers. Elsewhere again, there are caves and overhangs where less resistant bands of sandstone have eroded away. On the central ridge (see Plate 1.1) the debris slope extends almost to the top of the sandstone at the southern end, with more and more bedrock exposure occurring in a series of steps towards the northern end. Mechanical weathering and erosion under the influence of running water is the chief process operating on the cliffs, and the rate of retreat of the cliffs is weathering - controlled, as opposed to transport - controlled (Carson and Kirkby, 1972), in that there is no impediment to the transport of material down the free face other than that imposed by the rate of supply by the weathering of the rock.

The material on the debris slopes is described in Section 2.2 above. Some representative profiles are shown in Fig. 2.5, and it can be seen that they exhibit an upper concave element,

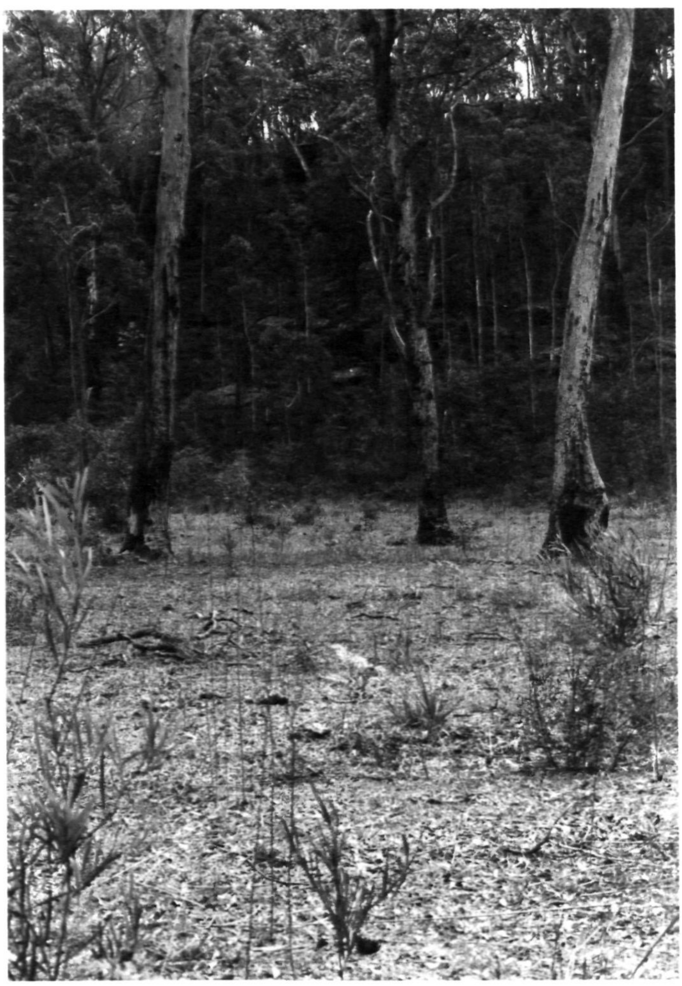


Plate 2.1 : Cliff (Freeface) and Debris Slope
(Note sharp break in slope between the two hillslope elements)

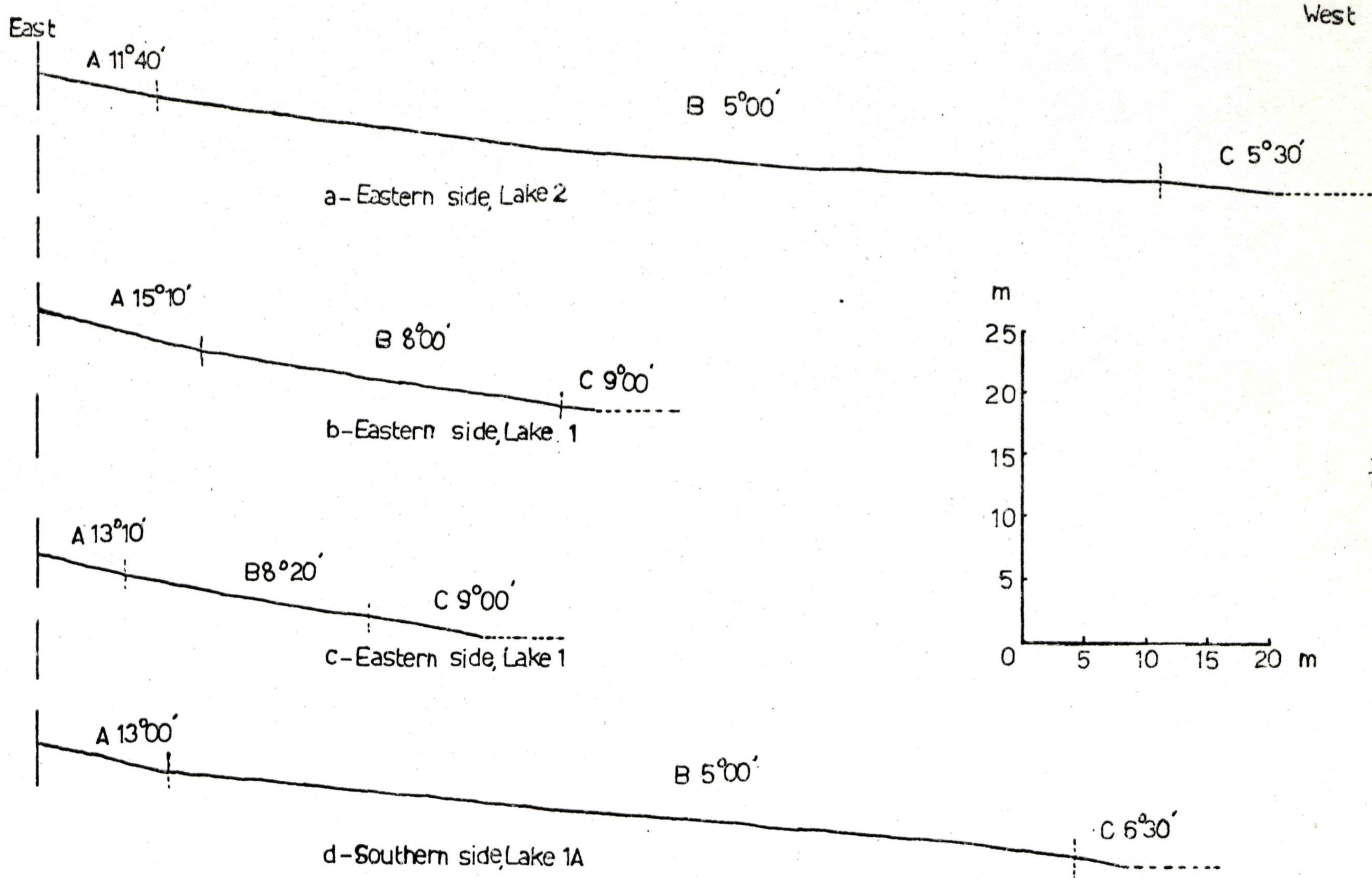
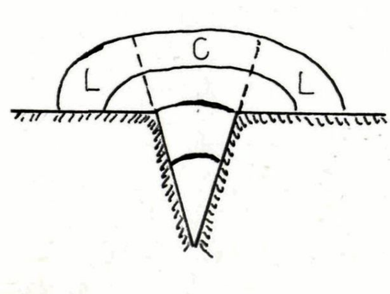


Fig. 2.5 : REPRESENTATIVE DEBRIS SLOPE PROFILES

a middle straight element, and a lower convex element. This latter feature was originally thought to indicate the presence of a higher lake shoreline; however, there were no shoreline deposits exhibited on the surface (though they may have been obliterated by vegetation growth), and augering revealed that sandycolluvial material was underlain by bleached grey to white sand typical of the material found in the present littoral zone of the lakes. These littoral sands rapidly lense out upslope from the lake margin. While not a legacy of a former higher shoreline, the lower convexity in the slope profiles may be related to the present water levels in the lakes, in that the oscillatory motion of the water due to the passage of the wind across the surface causes oversteepening of the adjacent slope; but for the presence of the reed margin (see Chapter Three) and the shortness of the fetch across the lakes, a clifted shoreline may have formed.

2.3.2 Alluvial Fans: The alluvial fans in the study area (Fig. 2.4 and Plate 2.2) are found emanating from the mouths of the valleys which are tributaries of both the lakes and Blue Gum Creek. The tributary streams are at present ephemeral, and flow only after heavy rainfall. During the research period, the streams were seen to be flowing for several weeks after the torrential rainfall of 25th May, 1974, but there was no channel erosion, and very little deposition of fresh sediment on the fans; upon drying up, the only evidence to show that they had existed was in the form of swathes cut through the very thick grass and herb cover.

Most of the fans extend back into the bedrock ridge in the form of a wedge. Both Davis (1954) and Murata (1966) have distinguished these from fans which extend from a linear mountain front, in terms of their composition as a number of lateral cones, as illustrated schematically below.



L: lateral cone

C: central cone

Plate 2.2 : Alluvial Fan at Western End of Lake IV, Viewed from Apex.
Lake IV is to the east, in left background of photograph.

Each of the cones of which the fan is composed has a uniform slope, which corresponds to the slope at the same height on the central cone, and in this way the fan theoretically has a continuous smooth surface.

Slope angles near the apices of the fans in the study area range from 5^{o} to 15^{o}, and most of the profiles exhibit an upper straight segment and a lower convex segment. This is contrary to the general view in the literature that alluvial fans are concave upward along a radial profile (Blissenbach; 1954; Denny, 1967). However, those writers who hold this view attribute it to an abrupt decrease in stream gradient where it debouches onto the fan; this is cited as the mechanism responsible for fan deposition. If this were so, then the stream should rapidly aggrade its bed upstream of the apex, whereas Bull (1964; 1968) has found that the area of deposition and the stream upslope from it tend to maintain a common and uniform gradient. Deposition in the form of the fan, where fluvial processes are the dominant transporting mechanism, is merely the result of a change in hydraulic conditions, whereby a formerly constricted stream is able to widen its bed, resulting in decreased competence and hence deposition of part, or all, of its load. The lower convexity in the fan profiles has been discussed in Section 2.3.1 above.

The surfaces of the fans are heavily vegetated, but a hummocky microrelief can still be seen. This is in the form of mounds of sediment, usually built up behind some obstruction such as a burnt log or behind tree trunks, and have diameters of anything up to 0.5 metres, the average height above the surrounding swale being about 0.3 metres. There appears to be no pattern in their distribution.

Alluvial fans have in the past been considered to be indicative of a semi-arid to arid climatic environment; fans found in regions of humid or tropical climate were cited as relict features, evident of a climatic change from dry to more moist conditions. This view has probably arisen because of their inclusion in the desert environment of W. M. Davis, and because most studies of alluvial fans have been undertaken in semi-arid regions. However, the idea of an arid environment of deposition has extended to studies of fans in humid temperate regions. For example, Hopley (1973) and Hopley and Murtha (in press) considered alluvial fans along the coast of northeastern Queensland to be fossil features related to a drier phase during the Pleistocene Period, when dessication of the land surface allowed erosion in the mountain ranges and deposition in the form of alluvial fans on the coastal plain. Incision into the fan surfaces occurred during more humid phases. However, Bird (1970), working in the same area, noted that material deposited on the fans after a severe storm on 12th January, 1951, in which 40 inches (102.8 cm) of rain fell in five hours at Buchan Point, could hardly be distinguished from the older deposits beneath, and from this he concluded that catastrophic phenomena such as the sheetwash after this storm were valid fan-building mechanisms, and drastic landscape dessication accompanying climatic change need not be implied.

To test whether this hypothesis also applies in the Thirlmere Lakes area, samples of sediment from the surface of the fan between Lakes I and II (Fig. 2.4) were analysed for grain size distribution and were compared with samples similarly analysed from the catchment area (i.e. the sediment source area) of the fan. It was thought that if the processes responsible for the deposition of sediment on the fans were no longer operating then this should be reflected in the grain size distributions, whereby those of the fans sediments would differ from those of the catchment sediments. Fig. 1.2 shows the sampling points for the fan and catchment sediments, and laboratory procedures utilised are described in Chapter One. The formulae of Folk and Ward (1957) were employed to obtain mean size, sorting, skewness and kurtosis, and the results are shown in Table 2.2. The grain size distributions were plotted on arithmetic probability paper and the example presented in Appendix A shows that the distributions were non-normal.

The mean particle size in the catchment area is 2.94ϕ (i.e. in the fine sand range) and on the fan surface is 3.02ϕ (i.e. in the very fine sand range). A Mann-Whitney U-test (Siegel, 1956) showed that there was no significant difference (at the 0.001 significance level) between the mean grain sizes of the fan and catchment sediments. The particle size frequency histograms (Fig. 2.6) show that, in both areas, there is a bimodal grain size distribution with peaks in the medium to fine sand and in the silt-clay ranges. This reflects the grain size of the source rock (Hawkesbury Sandstone), which consists of medium sand particles embedded in a clay-sized cement. Table 2.1 shows that the sediment in both areas is generally very poorly sorted, positively skewed and very leptokurtic (based on definition of these parameters by Fold and Ward, 1957), possibly indicating a very low energy transporting mechanism operating between the source area of the sediment and the fan. The one obviously fluvially deposited sample (CIO), obtained from a dry stream channel where it left the catchment area, was well-sorted, symmetrical and mesokurtic.

Bearing in mind that the number of samples analysed was small, the results seem to indicate that a low-energy transporting mechanism may be responsible for fan deposition in this environment, and the hummocky microrelief described above points to sheetwash[1] as being the dominant process. It can also be said that there is no sediment-ological evidence to indicate that the processes responsible for the build-up of the fan are not operating in the present environment, as there was no difference in the grain size distributions of the fan and source area sediments. Thus, evidence from Thirlmere Lakes tends to support Bird's (1970) view. However, sampling at depth

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[1] This mechanism is largely the result of overland flow, whereby particles are entrained by the movement of sheets of water over the land surface, and is characterized by rapid changes in discharge and sediment carrying capacity.

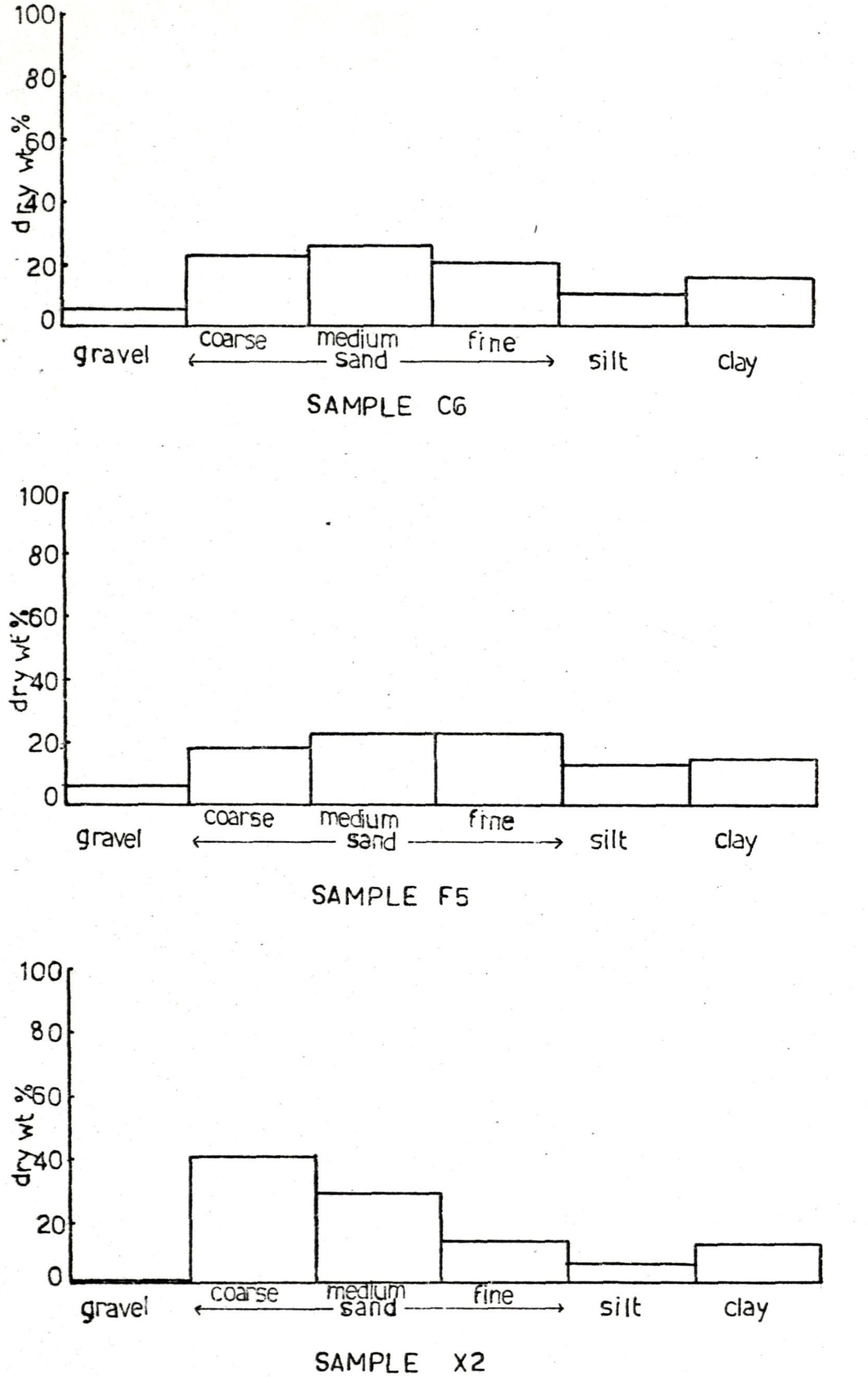

Fig. 2.6 : REPRESENTATIVE PARTICLE SIZE FREQUENCY HISTOGRAMS OF ALLUVIAL FAN SEDIMENTS

A. <u>CATCHMENT AREA</u>

SAMPLE NUMBER	% GRAVEL ($>-1\phi$)	% COARSE SAND ($-1.0-1.0\phi$)	% MEDIUM SAND ($1.0-2.0\phi$)	% FINE SAND ($2.0-4.0\phi$)	% SILT ($4.0-9.0\phi$)	% CLAY ($<9.0\phi$)	MEAN SIZE (ϕ)	σ (SORTING; ϕ)		SKEWNESS (ϕ)		KURTOSIS (ϕ)	
C1A	4.09	25.87	28.09	19.88	12.14	8.93	2.42	3.26	vps	0.60	v + s	2.54	vl
C1B	5.92	17.40	31.21	25.23	11.56	10.68	2.37	3.04	vps	0.47	v + s	2.93	vl
C2	10.75	6.66	15.09	30.44	13.03	24.03	4.95	5.49	eps	0.47	v + s	1.16	l
C4	38.18	7.83	19.66	20.75	8.63	4.95	0.12	8.83	vps	-0.16	ns	0.89	pl
C6	5.81	23.04	25.19	21.70	10.24	14.02	3.33	4.20	eps	0.61	v + s	2.29	vl
C8	0.22	10.19	30.66	25.38	14.96	18.59	4.43	3.88	vps	0.70	v + s	1.03	m

B. <u>FAN SURFACE</u>

C10	0.45	26.59	48.74	21.41	0.22	2.59	1.47	0.80	ms	0.00	s	1.04	m
F1	1.56	17.29	21.70	31.07	14.87	14.51	3.73	4.08	eps	0.66	v + s	2.01	vl
F3	0.07	13.19	15.26	27.68	21.75	22.05	4.63	4.40	eps	0.55	v + s	1.14	l
F5	6.33	18.75	23.81	23.08	13.25	14.81	3.68	4.74	eps	0.55	v + s	2.22	vl
F7	1.11	20.82	33.50	22.69	11.62	10.26	2.60	3.05	vps	0.64	v + s	4.41	el
F9	0.04	28.05	28.84	18.56	14.12	10.39	2.67	3.20	vps	0.71	v + s	1.76	vl
F11	0.03	27.46	23.67	19.78	19.62	9.44	2.62	3.27	vps	0.58	v + s	1.29	l
F13	0.01	21.52	29.65	14.87	15.13	8.82	2.72	2.83	vps	0.61	v + s	1.71	vl
F15	0	25.09	29.25	23.54	13.91	8.31	2.60	2.89	vps	0.62	v + s	1.96	vl
F17	0	23.38	29.90	23.06	16.52	7.14	2.58	2.73	vps	0.59	v + s	1.64	vl
F19	0	12.04	20.54	19.06	31.37	18.19	4.60	3.73	vps	0.39	v + s	0.99	m
X1	2.78	21.03	32.09	18.36	13.46	12.18	2.87	3.69	vps	0.69	v + s	2.31	vl
X2	0.69	40.61	28.73	12.94	5.82	11.21	2.00	3.31	vps	0.65	v + s	3.64	el
X3	0.15	17.26	27.17	22.69	15.92	16.84	4.03	4.15	eps	0.69	v + s	1.54	vl
X4	0.12	17.81	27.52	26.12	14.51	13.92	3.60	3.79	vps	0.68	v + s	1.77	vl
X5	0.09	36.57	24.38	13.86	10.21	14.89	3.33	4.25	eps	0.79	v + s	1.92	vl
X6	1.29	22.57	32.44	26.44	6.78	9.48	2.33	3.42	vps	0.61	v + s	3.87	el
X7	2.67	23.91	30.99	26.25	8.28	7.90	2.22	3.25	vps	0.54	v + s	3.65	el

TABLE 2.2 : Summary of grain size analysis of alluvial fan and catchment sediments (vps - very poorly sorted; eps - extremely poorly sorted; ms - moderately sorted; v + s - very positively skewed; ns - negatively skewed; s - symmetrical; el - extremely leptokurtic; vl - very leptokurtic; l - leptokurtic; m - mesokurtic; pl - platykurtic)

on the fans would be required to confirm this. It must be remembered that the fan itself is, in part, its own source-area, in that material at the apex may be remobilised by subsequent sheet floods and redeposited downfan; this mechanism will continue to operate until the material is finally deposited at the water's edge. Thus, the surface sediment may reflect a number of transportational and depositional phases.

It has generally been found that median grain sizes decreases and sorting increases with distance from the apex of an alluvial fan (Blissenbach, 1954; Bluck, 1964; Bull, 1972; Hopley and Murtha, in press). Fig. 2.7 shows that there was no pattern in the median size and sorting values in the downfan direction in the study area; however, this was not expected because of the very short distance of transport from apex to toe, and the limited number of samples analysed.

2.3.3 Initiation of Sediment Transport on Hillslopes and Alluvial Fans: At the present time, the hillslopes and alluvial fans are stabilised by a thick vegetation cover. This may be considered to be relatively undisturbed by human interference; the main agent of association evolution is bushfire, which "leads to the elimination of types not possessing powers of rapid regeneration ...(and) an increase in the density and purity of components" (Pidgeon, 1938). However, this would mainly influence the shrubs understory and grass and herbs groundcover, as most *Eucalyptus sp* are capable of regeneration by epicormic buds[1]. The nature of the vegetative cover in the study area will be more fully described in Chapter Three. Sediment movement downslope and downfan through sheetwash would require the removal of a substantial portion of at least the ground cover so that the surface sediments could be exposed to the erosive action of raindrops and overland flow. As mentioned above, a decrease in vegetation cover through a change to a more arid environment has in the past been thought to be the prime mechanism

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1 Epicormic buds: these remain dormant beneath the phallem (cork) until the plant is defoliated, e.g. by fire or insect attack.

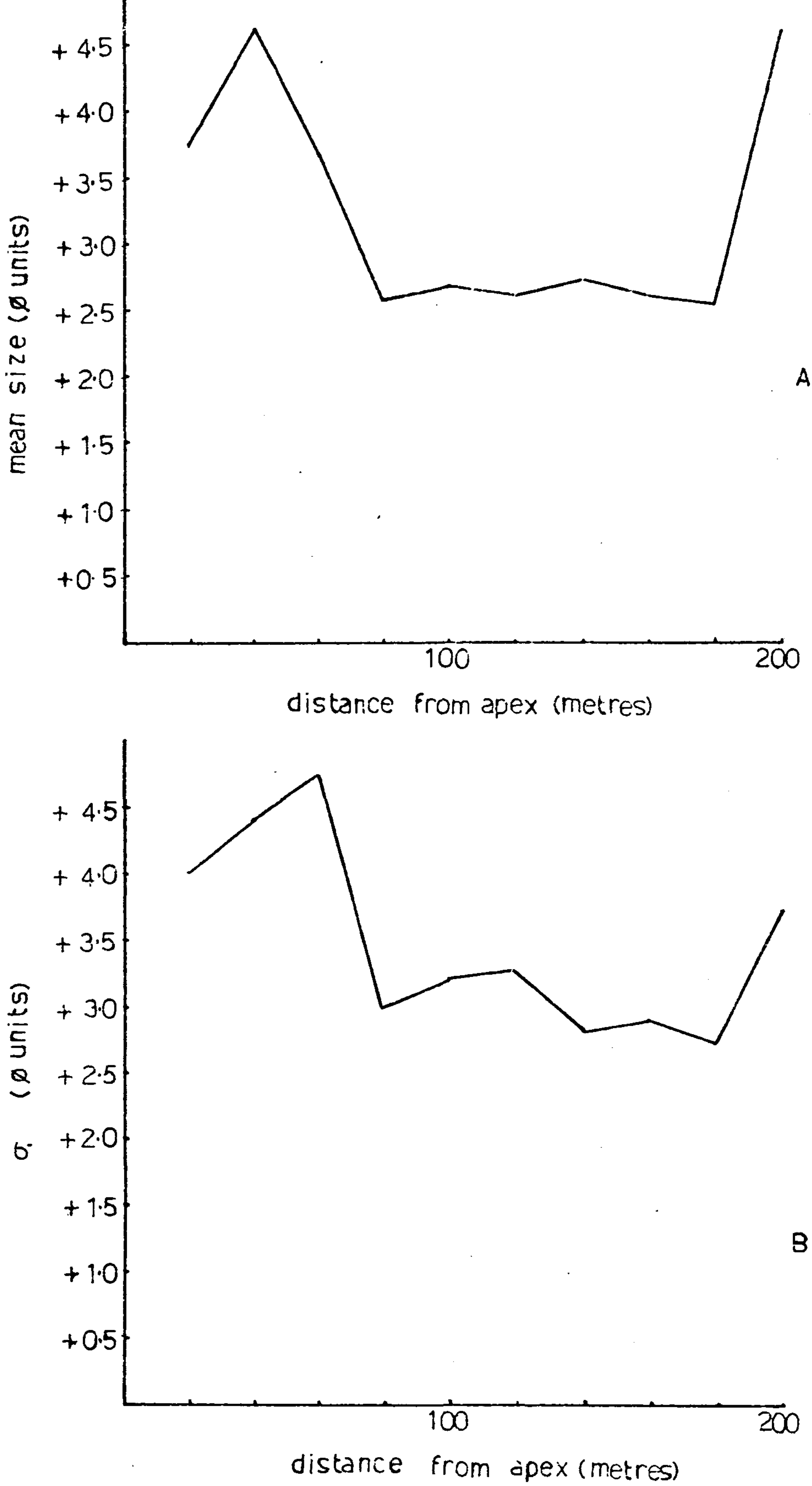

Fig. 2.7 : RELATIONSHIP BETWEEN MEAN SIZE AND SORTING (σ) OF SEDIMENTS WITH DISTANCE FROM APEX OF ALLUVIAL FAN (samples F1 to F19)

for the initiation of sediment transport on fans. However, reduction in the vegetation cover can be brought about by other events, such as fire and insect attack, and it is the repeated occurrence of bushfires which is thought to be the agent responsible for the initiation of sediment transport on the hillslopes and fans in the study area.

The structure of the vegetation cover (see Chapter Three) and the abundance of charcoal on the surface of the hillslopes and fans and in the lake deposits indicates that bushfire is prevalent here, as it is in most heavily timbered areas in Australia. A severe fire in the Wallace and Yarrangobilly Creeks catchment areas in Kosciusko National Park, N.S.W., in 1965 (Brown, 1972) resulted in severe sheet erosion and denudation of the topsoil, mainly because of high intensity storms which occurred immediately after the fire. Brown found that there was a significant change in the shape of the flood hydrograph for the Yarrangobilly Creek catchment, with the occurrence of pronounced secondary peaks on the rising limb; the amount of runoff from each catchment was significantly greater for four years after the fire, and the sediment loads and concentrations of both creeks were very much higher. At Wallace Creek, at a discharge of 334 cu secs, sediment concentration was 143,000 p.p.m. or the equivalent of 116,000 tons per day for a reading taken six months after the fire. After fires in the Grey Mare Range and Jacobs River catchment in the Park in November and December, 1972, and January, 1973 (Good, 1973), the sediment loads in the Geehi River increased from 14 p.p.m. or 30 tons per day at a discharge of 1,000 cusecs to 54 p.p.m. or 141 tons per day at a discharge of 1,010 cusecs; that of the Swampy Plains River increased from 182 p.p.m. or 119 tons per day at 800 cusecs to 1,031 tons per day at 2,350 cusecs.

Increased sediment yields after fires such as these arise from three causes (Brown, 1972) :

1. The burning off of all leaves and undergrowth

exposes soil thus allowing raindrop impact to increase;

2. The destruction of litter allows higher overland flow velocities which in turn permit entrainment of a greater quantity of sediment;

3. For a given rainfall, stream discharges are higher because of decreased time of concentration in the catchment resulting from increased overland flow velocity and higher channel velocity, both of which result directly from burning of undergrowth and litter which greatly decrease catchment roughness (i.e. that due to the presence of a vegetation groundcover).

In extreme cases, the topsoil may be stripped by the updraughts created by the intense heat of a fire. According to Professor Jackson, Dept. of Botany, University of Tasmania (R. J. Wasson, pers. comm.), the fires which raged in southeastern Tasmania in February, 1967, resulted in the total removal of the A horizon and the baking of the B horizon in some areas. Debris from this fire was being flooded out of the catchment as late as 1973. In a Public Works Department memorandum on damage to the Lyell Highway, Tasmania, after a storm on 21st March, 1968, H. van Hulst stated that, because of the removal of the vegetation after the 1967 fires, the immediate run-off after a storm could be twice as much as previously anticipated, and that, therefore, a computed 100 year flood would occur once in five years!

Thus it can be seen that the removal of vegetation after fire has a dramatic effect on runoff and erosion; the recurrence of fire at regular intervals could easily initiate each phase of deposition on the debris slopes and alluvial fans in the study area, and has been postulated to be an important factor in the deposition of recent inset fills on some alluvial fans in Tasmania (R. J. Wasson, pers. comm.). At Thirlmere Lakes, where the last major fire, resulting in complete destruction of the undergrowth occurred on 28th November to 2nd December, 1968, the piling up of sediment behind burnt logs and other obstructions and the abundance of charcoal associated with this sediment indicates that fire was a factor in the deposition of the surface sediments. Fire has probably been important since at least the beginning of Aboriginal occupation of the area. Extensive drilling through the fan and slope sediments would determine, through the presence/absence of abundant charcoal, whether fire has been an important factor throughout the depositional history of the area.