STRATIGRAPHIC BACKGROUND OF GULLY DEVELOPMENT OF THE PEKINA CATCHMENT IN THE MT. LOFTY RANGES, SOUTH AUSTRALIA

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Abstract The Pekina catchment is a high-level headwater basin of 139 km^2 in area. Mean annual rainfall is about 350 mm. The most common landform pattern type is undulating rises. Steeper land is mainly rolling low hills, and gentler land mainly pediments. The main streams are incised about 5 m below pediments and fans. Before settlement, most areas of the catchment were dominated by *Eucalyptus* trees, except for the steep hills near major drainage divides, where *Casuarina cristata* open scrub is still found. Most vegetation was cleared for agriculture in the late 19th Century, resulting in the initiation of serious sheet erosion and gully erosion, mainly on gentler lands. Almost all newly developed gullies have a marked nick point with a vertical wall at their heads. The stratigraphy of subsurface material of pediments observed on the walls of gullies shows cycles of alternating deposition and erosion. Gullies inherit buried old channels, suggesting that ground water concentrated in such channels plays a more important role for gully development than surface water flow.

1. Introduction

Gullying is one of the most obvious forms of erosion and causes problems in many agricultural lands. Gully erosion has occurred in semi-arid regions of the southern part of Australia, particularly in hilly lands with pediments and fans, since European settlement. It is said that gully erosion was recognized in South Australia before the 1930's, but there was not much concern about its consequences until serious and extensive water erosion occurred in 1941 when torrential storms moved across the State following a major drought in the previous year (Matheson, 1978). Vegetation clearance for agriculture, bushfires, overgrazing by stock, rabbit infestation and deterioration of soil structure by wheel traffic and stock trampling cause increased runoff or concentration

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of runoff, resulting in gully development (Twidale, 1976; Laybutt and Willcox, 1980; Gillespie, 1981; Atkinson, 1984; Graham, 1984). Some gullies were initiated by ploughing itself. Shallow furrows are ready to be eroded to form gullies (Twidale, 1976; Twidale and Bourne, 1978).

Gullies have been morphometrically and pedologically investigated by many researchers (Welch, 1978; Tennie, 1978; Veness, 1980; Gillespie, 1981; Watkins, 1981; Crouch, 1983; Hannam, 1983; Harte, 1984; Crouch *et al.*, 1984), who discuss causes of gully initiation, processes occurring in present gullies, mechanisms of progression of head wall and of extension of side wall, and methods of gully erosion control. On the basis of their descriptions, most gully heads have a vertical wall, sometimes an overhanging one. Tunnel erosion that accelerates gully head retreat is observed in many gullies (Crouch, 1983). Chains of small pools or depressions, and small discontinuous gullies observed upstream of a gully head have developed into a big gully by coalescence (Graham, 1984).

These facts suggest that the concentration of ground water (subsurface water) is more significant than surface water flow for gully development, particularly for the head progression. Large gullies are developed in pediments and fans where the sediments overlying bedrock are relatively thick in comparison with those in hills and rises. The original surface of pediments and fans is flat and even, but the subsurface material consisting of gravel, sand and clay are divided into layers, and the buried old surfaces recognized by unconformities show undulating shapes. Ground water is presumed to concentrate according to the stratigraphy of the subsurface materials. But investigation of gully development has not yet been done from the stratigraphic point of view.

The field survey was carried out in 1983 and the data obtained were reported with brief summary in 1985 (Ohmori *et al.*, 1985). In the present paper, the stratigraphic characteristics of subsurface material observed on gully walls, and their effect on gully development are examined and discussed.

2. Geological and Geomorphological Setting

Broad-scale landform features

The Pekina catcment is located in South Australia, east of Spencer Gulf, as shown in Fig. 1. Mean annual rainfall is 480 mm at Jamestown, 350 mm at Peterborough and Orroroo, decreasing from south to north (Fig. 1). This region includes parts of the Mt. Lofty Ranges and the Flinders Ranges and is the boundary between the northern summer rainfall region and the southern winter rainfall one (Bureau of Meteorology of Australia, 1977; Iwasaki, 1985). The rocks are Proterozoic sedments, includng tillite, sandstone, siltstone and shale. They are folded into northerly-trending anticlines and synclines with a wavelength of 20 km and a vertical amplitude of 7 km. Structural ridges are formed on the more resistant beds, which dip at about 25°. The area has been tectonically stable since the Cambrian, except near some fault zones. Denudation may have been continuous for 500 million years.

The relief and the average slope vary from place to place as shown in Figs. 2-**a** and 2-**b**. These maps are taken from data in "Environments of South Australia" (Laut *et al.*,

1977) and the accompanying "Planners Atlas" (Scott, 1982). From Fig. 2-**a** one may see that the Pekina catchment is in the northern part of a narrow zone of rather low hills having less than 180 m relief. Surroundng land is typically either higher hills, or plains and rises with relief less than 30 m. Altitudes are all below 1,000 m. Figure 2-**b** shows that it is also in the northern part of a very broad zone of gentle or moderate slopes. To the north there are alternating ares of steeper (≧ 18%) and gentler (≦ 3%) slopes. This different pattern may relate to the more arid climate in the north and north-east.

The Orroroo basin

The Pekina catchment is a part of a 2,000 km² basin extending north and south from

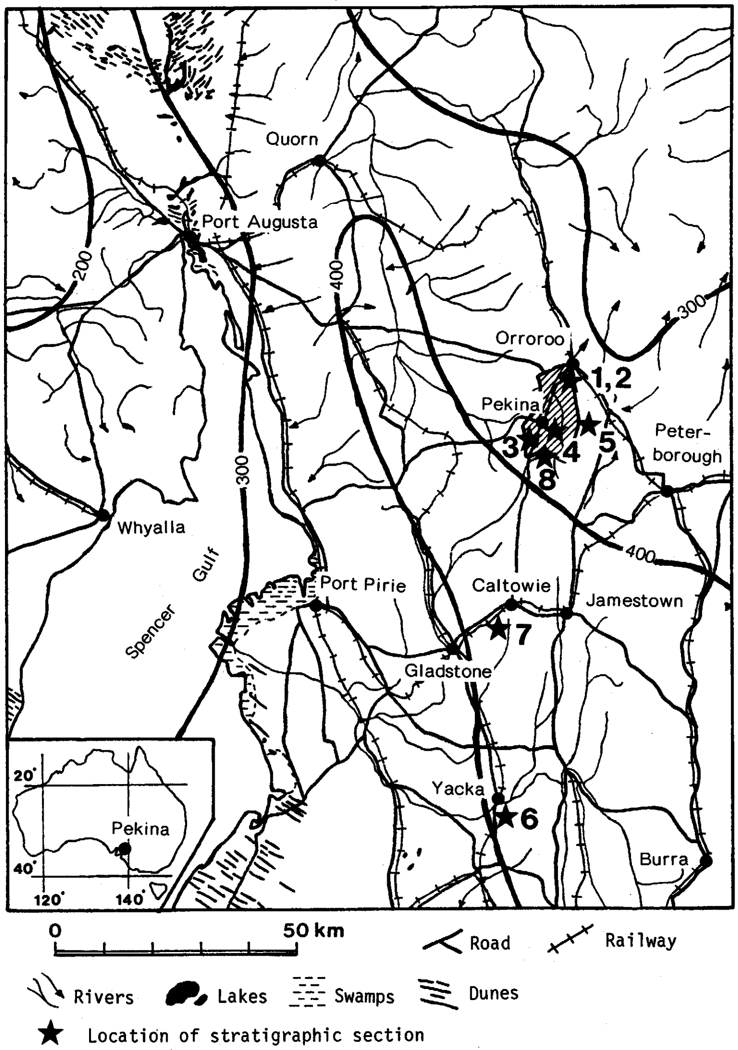

Fig. 1 Locality map of study areas near Pekina, South Australia, showing distribution of mean annual rainfall (mm, Burean of Meteorology, Australia, 1977).

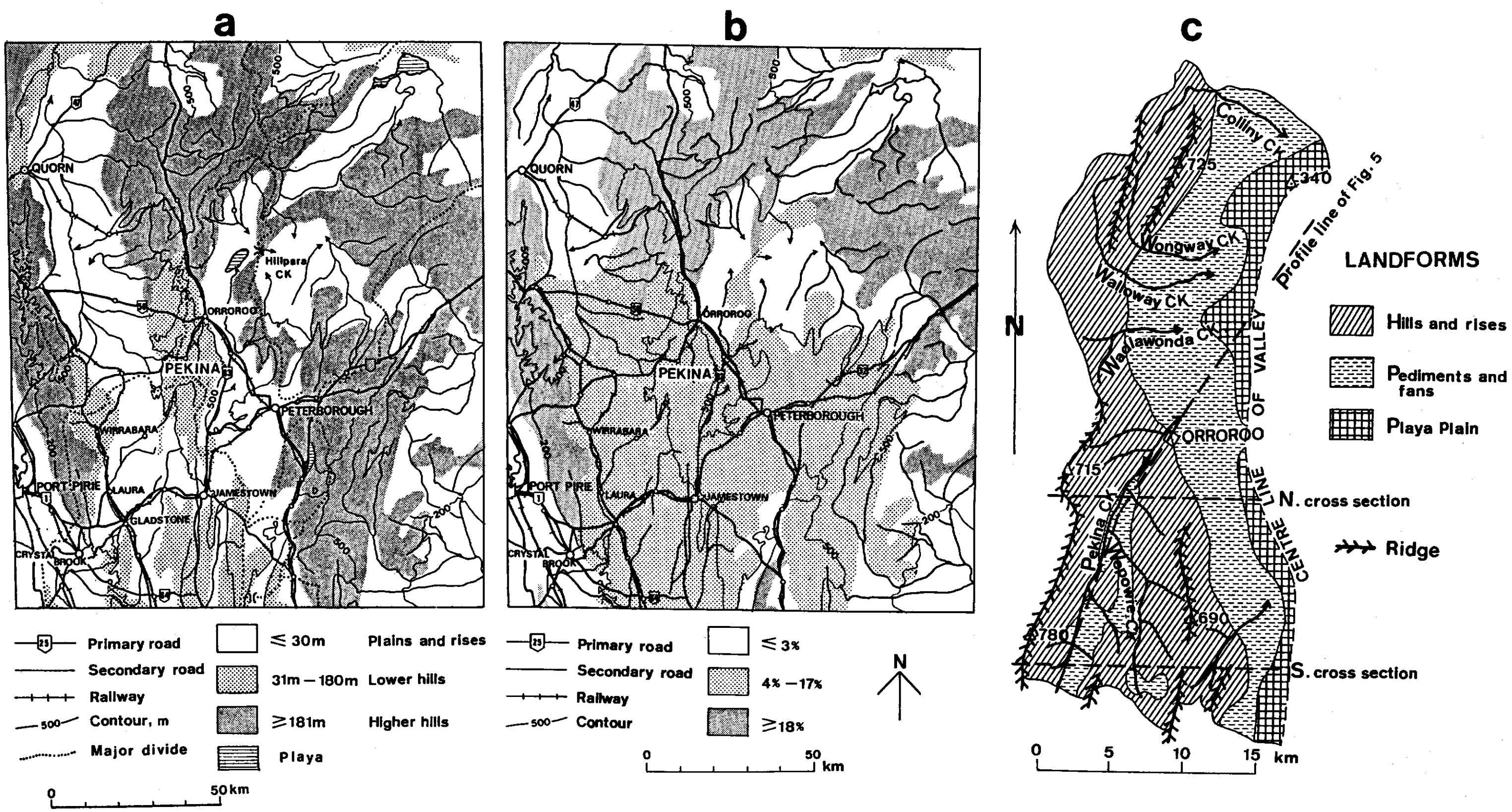

Fig. 2 Relief class map **(a)** and slope class map **(b)** of the region surrounding the Pekina catchment, and main landform pattern type map **(c)** for part of the Orroroo basin including the Pekina catchment. Section lines of Fig. 4 and profile lines of Fig. 5 are shown on **(c)**.

Orroroo. This basin is almost closed, but the central playa can drain eastwards through the gorge of Hillpara Creek (Figs. 2-**a** and 5). The part of the Orroroo basin shown in the map, Fig. 2-**c**, is representative of the landforms of the basin. Erosional hills and rises make up half of the area. Of the remainder, three-quarters is pediments and fans and one quarter is playa plain.

Streams rise in the hills and form fans as they enter the zone of pediments and fans. No stream channels reaches as far as the playa plain. Only the six streams shown on the map attain 10 km^2 of catchment area before their channels are lost. Pekina Creek has by far the largest catchment: 153 km^2. There are hundreds of other very small drainage nets. More than half of the total area either drains to channel networks having catchments smaler than 10 km^2, or has no channels at all. In the playa plain there are practically no stream channels. This very flat plain has not been called a floodplain because there is no landform evidence of either vertical or lateral accretion from streams.

Pediments

Pediments are a characteristic feature of this area. By definition, pediments differ from fans in being eroded rather than aggraded. They should not be formed of deposited material but of planed-off bedrock, with only a veneer of debris in transit over the surface. It may be difficult to tell the difference by morphology alone. Fans usually have

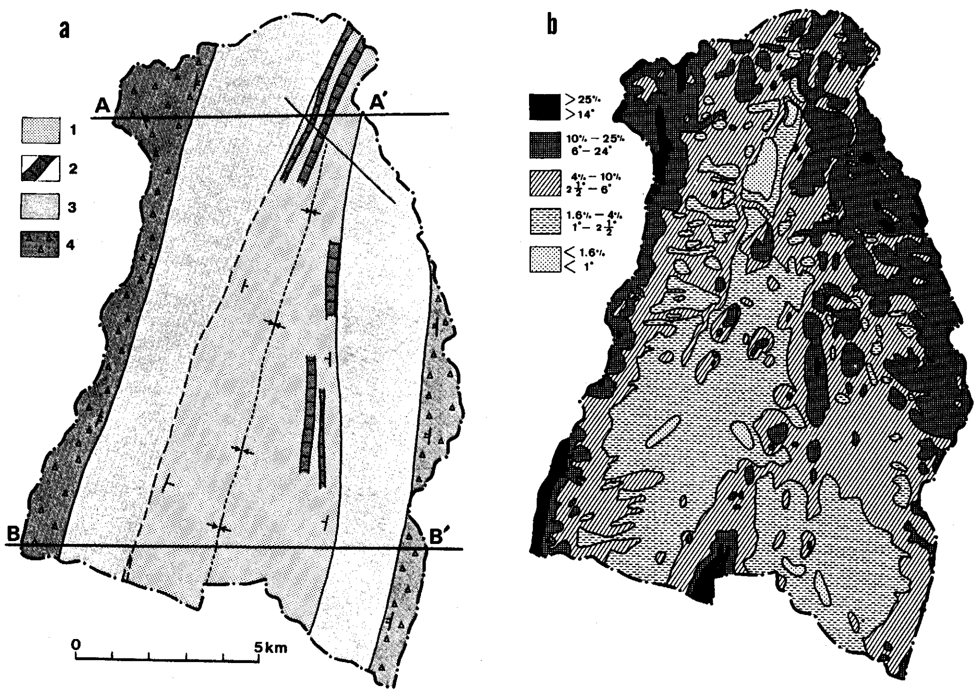

Fig. 3 The Pekina catchment : **(a)** Geology (Proterozoic rocks ; after Geological Survey of South Australia, 1968): 1 Tarcowie Siltstone ; 2 dolomite member ; 3 Tapley Hill Formation (flaggy siltstone); 4 Appila Tillite. **(b)** Slope class map.

more convex contour lines and radiate from the point where a large stream flows out of the hills.

In the area mapped in Fig. 2-**c**, pediments seem to be more extensive than fans. In the larger zone of pediments and fans, they are from 2 km to 5 km long and their slopes decrease downslope from about 6% to 1.5%. Contour lines are almost straight. There are numerous shallow stream channels, which seldom form a tributary network, but

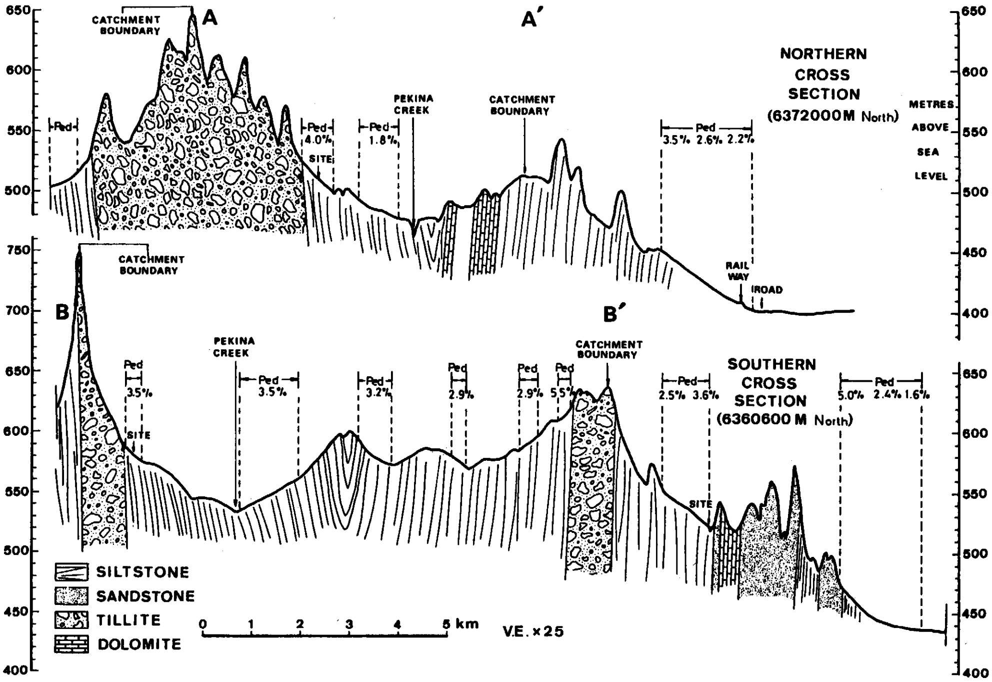

Fig. 4 Cross sections of the Pekina catchment, showing the extent of pediments. Location shown on Figs. 2-**c** and 3-**a**.

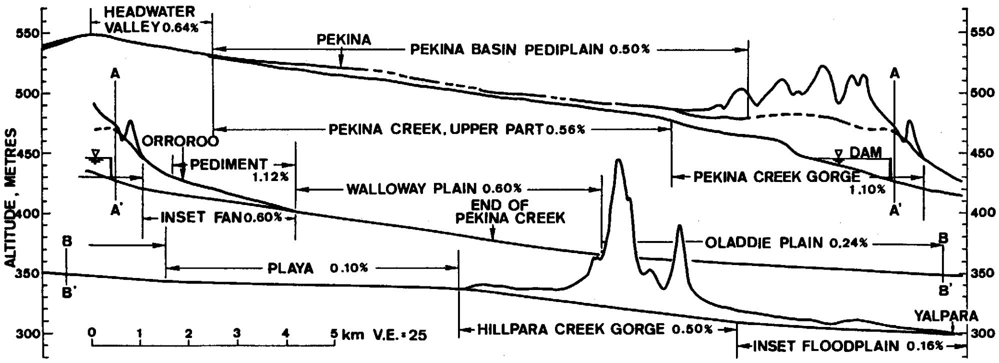

Fig. 5 Topographic profile down the slope-line including Pekina Creek and Hillpara Creek. Profiles of adjacent plains and hills are projected to the main profile line. Location shown on Fig. 2-**c**.

generally flow parallel down the slope. The surface between the channels seldom slopes towards them. It appears that denudation of the land surface by sheetwash, creep, and perhaps by wind are the dominant geomorphic processes. Smaller zones of pediments and fans occur in the Pekina catchment. Here the pediment slopes are about 1 km long.

Where there are pediments, stream channels tend to disappear before they can link up with others to form high-order drainage networks. Using Strahler's stream-ordering for stream segments identified on 1/50,000 topographic maps, channel networks in the zone of hills and rises typically reach the 4th order when their catchment areas reach 4 km^2. Pekina Creek and Wepowie Creek do not become 4th order channels until their catchment areas, which contain extensive pediments, exceed 25 km^2. None of the streams in the area ever becomes a 6th-order channel.

3. Landforms and Vegetation of the Pekina Catchment

The catchment above the Pekina Reservoir is 139 km^2 in area, and its mean altitude is 550 m. It is a structural basin formed in a syncline and enclosed by ridges of Appila Tillite (Fig. 3-**a**). The cross-sections, Fig. 4, show how the siltstone formations within the basin have gentler hillslopes, and even gentler extensive pediment slopes that average about 3%. Pekina Creek is incised below the level of the pediment surfaces. The long profile of Fig. 5 shows that the stream is incised 5 m to 10 m below the pediments for much of its length above the outlet gorge. The maximum incision in the gorge is 40 m at the dam site. At Orroroo, below the the gorge, the stream flows on a narrow fan that is inset below the pediment surface for 3 km before merging with it.

Slope classes

Sope classes have been mapped as shown in Fig. 3-**b**. The spacing of 10 m contour-lines

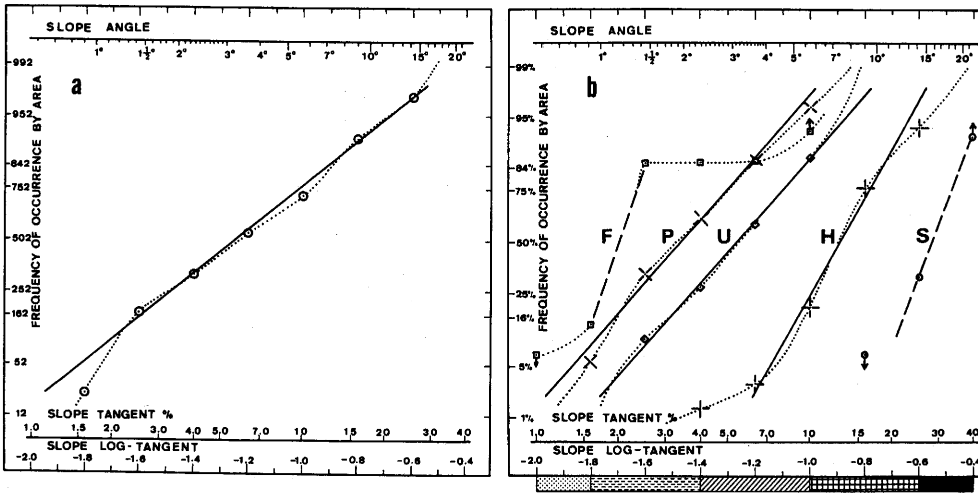

Fig. 6 Frequency distribution of slopes **(a)** and frequency distribution of slopes in each of the types of landform pattern **(b)** in the Pekina catchment.

on 1/50,000 maps was classified using contour gauges. Except in the most dissected parts of the area individual hill slopes are more than 300 m long, so that their gradients can realistically be estimated at this map scale. The frequency distribution of slope tangents, from 277 data points, is almost perfectly log-normal (Fig. 6-**a**). A tendency to log-normality in slope frequency distributions has been observed elsewhere (Hatano, 1961; Speight, 1971) but not explained.

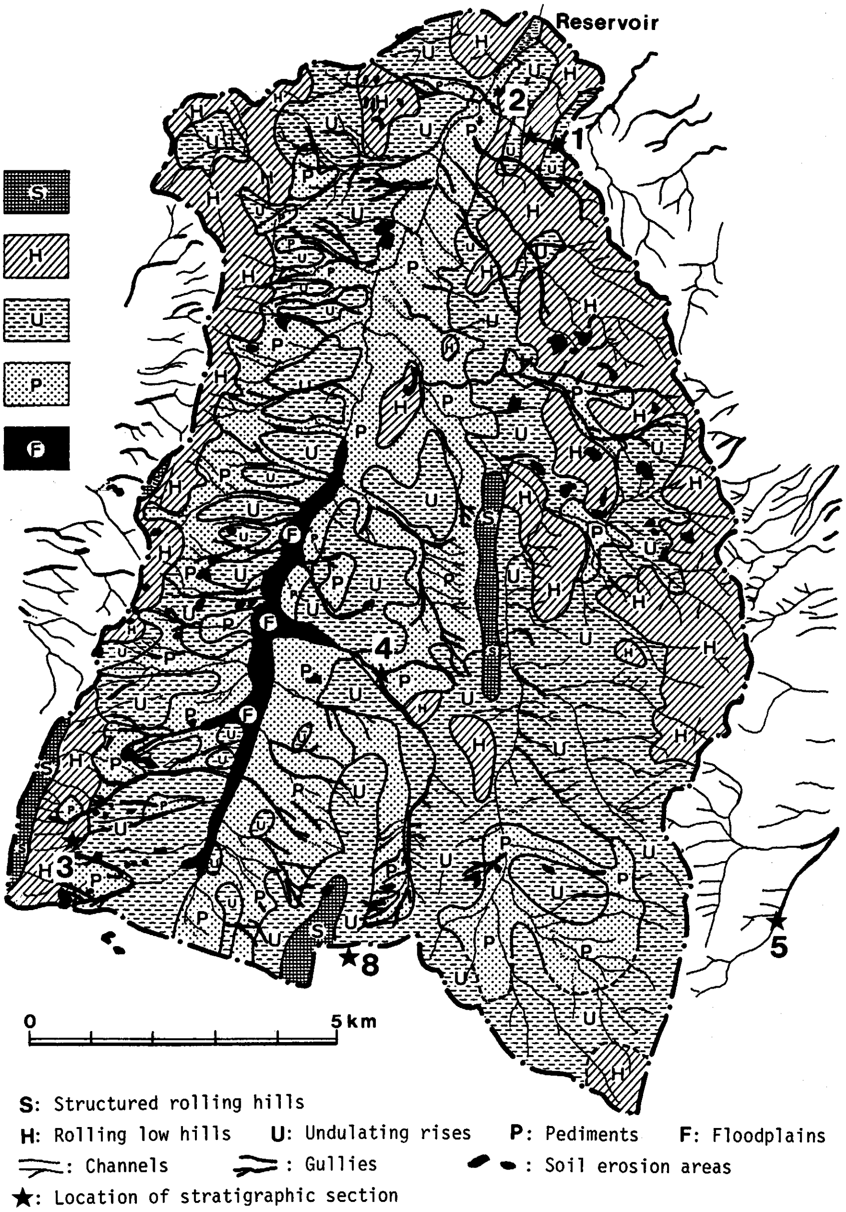

Fig. 7 Map of landform pattern types of the Pekina catchment.

Landform patterns

By interpretation of colour air photos at 1/40,000 scale five types of landform pattern have been distinguished and mapped as in Fig. 7. Not only slope, but also relief, stream pattern and other attributes were used to distinguish between them. However, as Fig. 6-**b** shows, each type is rather distinctive and homogeneous in its slope frequency distribution. Table 1 summarises slope characteristics of the landform patterns, and also gives the typical relative relief of each, and the proportional area that it occupies. In many cases pediments lie immediately below rolling low hills or structured rolling hills, so that there is a sharp concave break of slope. As Fig. 6-**a** shows, however, there is no class of slopes underrepresented in the catchment as a whole.

Vegetation

The distribution of vegetation (Fig. 8, Takeuchi and Matsumoto, 1985) shows a marked relationship between vegetation type and landform pattern type. *Casuarina cristata* open scrub is concentrated in structured rolling hills covered with thin soil near major drainage divides. *Eucalyptus socialis/E. foecunda* scrub which is known as mallee scrub and *Eucalyptus odorata* low woodland are distributed in rolling low hills, while *Eucalyptus leucoxylon/E. odorata* low woodland mainly in undulating rises. *Eucalyptus leucoxylon/E. camaldulensis* woodland is distributed in pediments and along stream channels (Fig. 10-**a**), particularly along the higher-order channels. Most of vegetation which had covered almost all catchment before European settlement were cleared for agriculture in the late 19th Century, since 1873, except for steep slopes near divides where agricultural development was difficult (Katahira, 1985). Only 7.0 % of the catchment area is now covered with natural vegetation. This intensive and large-scale vegetation clearance initiated serious water erosion.

4. Erosion, Sedimentation and Gullying

Water erosion has taken place mainly on the surface of cleared fields, particularly on

Table 1 Slope frequency distribution and relief in the Pekina Catchment

	Structured rolling hills	Rolling low hills	Undulating rises	Pediment	Flood-plains	Total
Symbol	S	H	U	P	F	
Area(km^2)	3.0	32.5	58.0	41.5	3.5	138.5
Area(%)	2.2	23.5	41.9	30.0	2.5	100.0
Mean slope						
degree	15.5°	7.1°	3.2°	1.9°	1.1°	3.3°
log-tan	−0.560	−0.893	−1.277	−1.477	−1.700	−1.247
Std. devn.	—	0.153	0.240	0.238	—	0.339
Skewness	—	0.118	−0.053	0.119	—	0.010
Kurtosis	—	1.32	1.01	0.91	—	0.84
Relief(m)	110	55	16	2	3	150

undulating rises and pediments. Erosion areas are reported to have decreased due to the change from two-year crop-fallow rotation to three-year fallow-crop-pasture rotation (McQuade *et al.*, 1981), as well as due to construction of contour banks (Matheson, 1978),

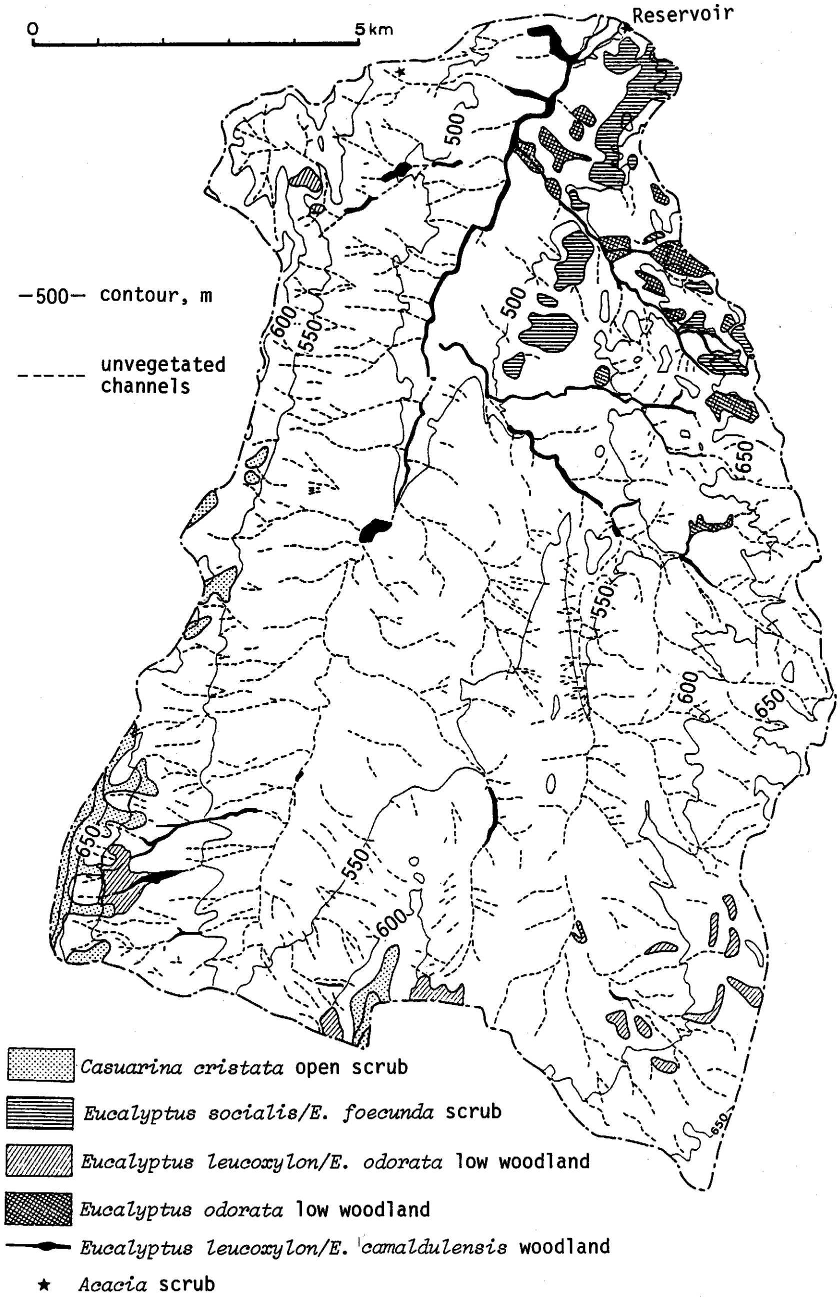

Fig. 8 Vegetation map of the Pekina catchment (after Takeuchi and Matsumoto, 1985).

since the 1940's. However, the areas experiencing serious water erosion have continuously expanded in many places in the catchment. Numerous field observations were made concerning erosion, sedimentation and gullying. Eight sites at which detailed

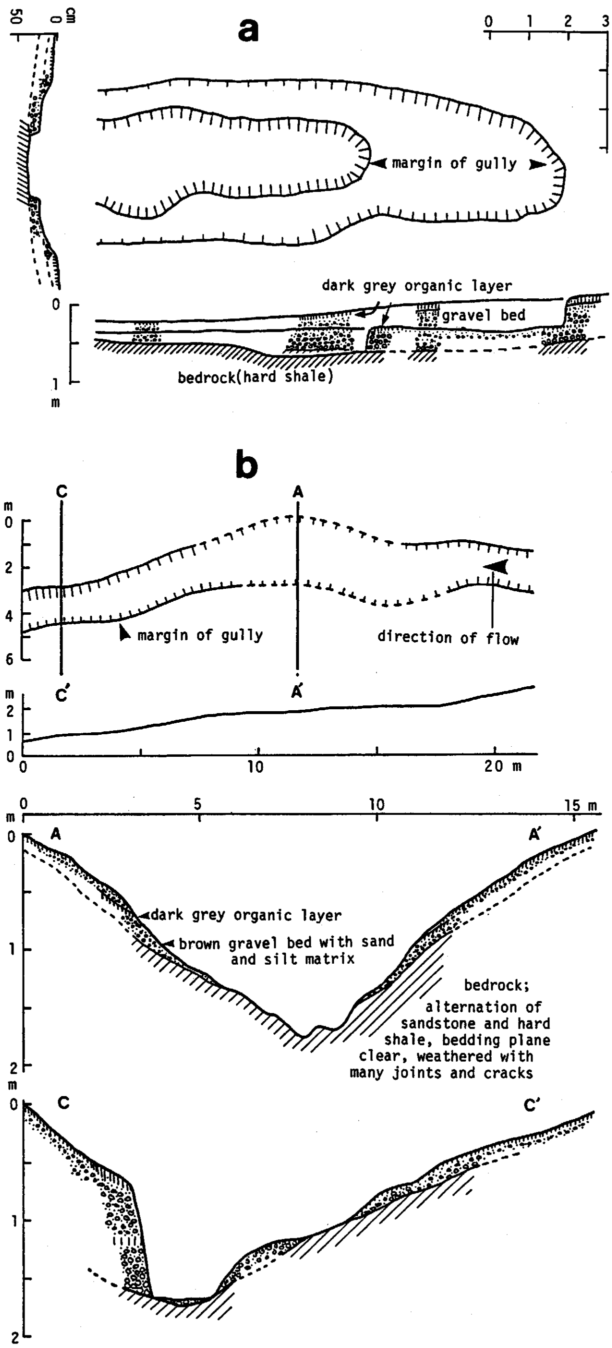

Fig. 9 **a**: Head of a gully in the landform pattern undulating rises at Loc. 1 ; plan and sections. **b**: The middle course of a gully in rolling low hills at Loc. 2 ; plan, profile, and cross sections showing the stratigraphy.

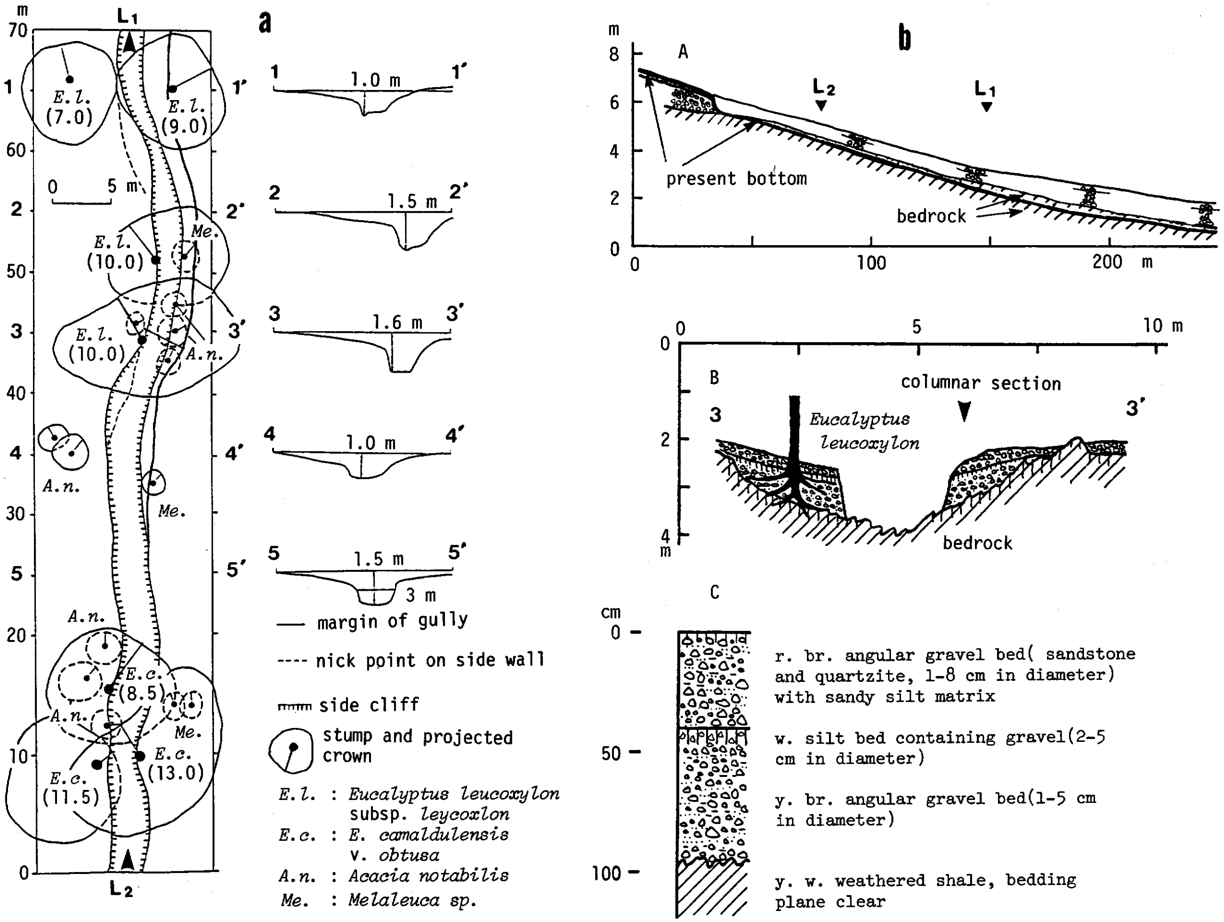

Fig. 10 **a** : Gully course and cross sections in the lower part of rolling low hills at Loc. 3, showing distribution of trees, mainly *Eucalyptus* spp ; **b** : Longitudinal (A) and cross (B) sections of a gully of Fig. 10-**a**. Detailed stratigraphy is shown in (C).

observations were made are marked on Fig. 1 and Fig. 7.

Hills and undulating rises

Both of the hilly landform patterns in the Pekina catchment are covered with very thin and dark coloured soil except where bare rock is exposed. The vegetation is generally sparse even in the areas undisturbed by European land use. There is practically no problem of soil erosion because of lack of soil, except in some areas of deeply weathered rock. The broad-crested undulating rises also have many bare rock sites, but the rock is deeply weathered, resulting in deep and extensive soil erosion in many places (Fig. 7).

In the lower parts of hills and undulating rises, and in the steeper upper parts of pediments there is a weathered rock mantle or a thin colluvial or alluvial deposit of 2 m or less. The gravel is divided into layers on the basis of palaeosols and unconformities (Figs. 9 and 10). The overlying soil is relatively thin, less than about 10 cm. Many newly developed gullies are observed to reach into the bedrock beneath the thin angular to subrounded gravel beds, but the gully depth is generally less than 1 m (Figs. 9 and 10).

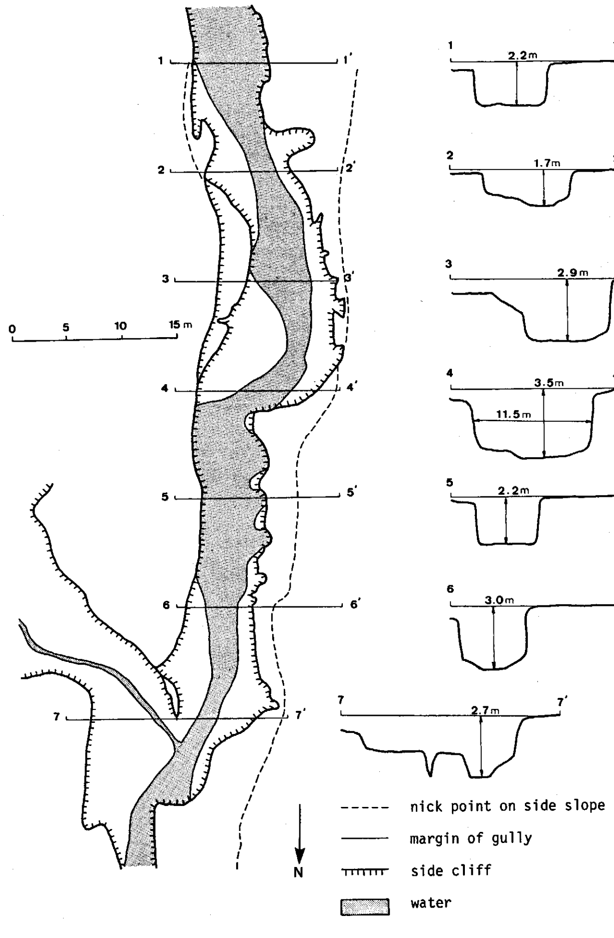

Fig. 11 Big gully developed in the central part (Loc. 4) of the Pekina catchment; plan and cross sections. The stratigraphic section at 4-4' is shown in Fig. 14-**a**.

Sheet erosion areas extend widely around the heads of new gullies, resulting in serious degradation of cultivated land (Fig. 15).

Pediments and fans

The lower, gentler parts of pediments and fans are areas inclined at less than 4% toward the main stream channels, covered with thick alluvial or colluvial deposits 2 m or more in thickness. Serious sheet erosion areas are few, but deep gully erosion to 2 m or more, in some places 5 m, is well developed. The alluvial deposit consists of angular to rounded gravel, sand and clay divided into at least 4 units including the present floor sediment at Loc. 4 in the central part of the Pekina catchment (Figs. 11 and 14-**a**). The lower part of each unit consists of gravel, indicating transportation and/or erosion was dominant in the stream course, and the upper part coarse sand with clay matrix, suggesting that deposition became dominant as runoff decreased. Buried old channels, recognized by sediment facies, show shifts of stream course by the accumulation of boulders and the shape of the cross section of unconformities. The present gully inherits

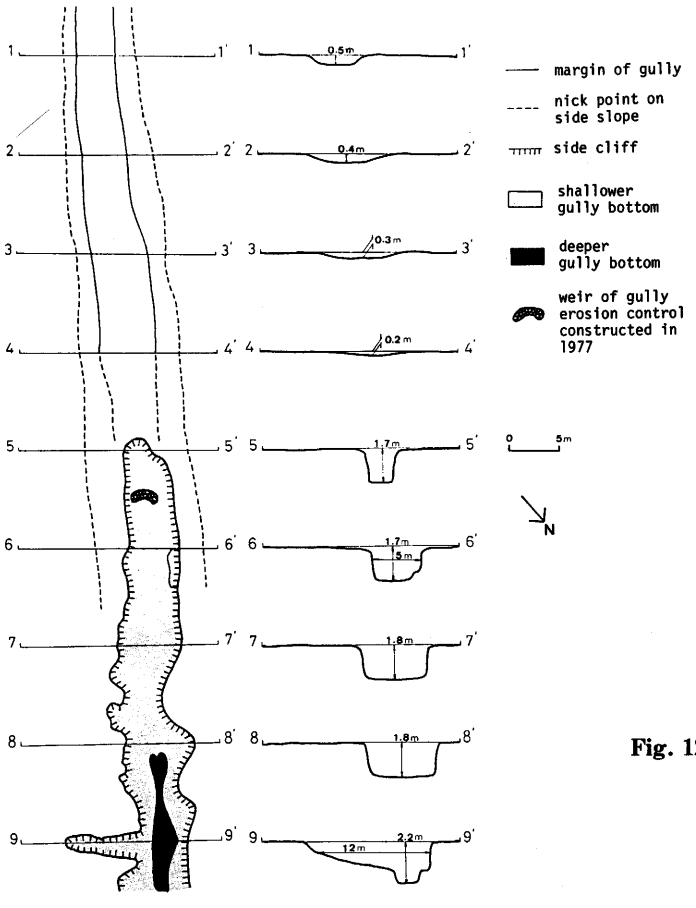

Fig. 12 Gully newly developed in a pasture/crop field on the pediment at Loc. 5; plan and cross section. The stratigraphic section at 5-5' is shown in Fig. 14-**b**.

old channels with only a little shifting, and has now reached bedrock.

The floodplain indicates areas of fluvial deposits with very flat surface. Along the northern course of Pekina Creek, the floodplain (or terrace) surface is clearly distinct from the lower pediment at a nick point on the slope from hillfoot to the creek, but the boundary between the flooplain and the lower pediment becomes obscure along the southern course of the creek. Sheet erosion is not serious, and gullies have been newly developed along tributaries, showing the same characteristics as in the lower pediment.

Deep gullies have been newly developed in thick alluvial/colluvial deposits of lower pediments not only in the Pekina catchment but also in surrounding areas. To the east, at Loc. 5, the gully-head has a marked nick point where it meets the old shallow channel (Figs. 12 and 14-**b**). The stratigraphy of subsurface material is again divided into 4 units including the present floor sediment. Their facies have the same characteristics as those at Loc. 4, showing clear shapes of buried old channles (Fig. 14-**b**). The present gully inherits buried old channels. The uppermost horizon of the second unit contains timber whose carbon date is "Modern", suggesting that deposition and erosion alternated

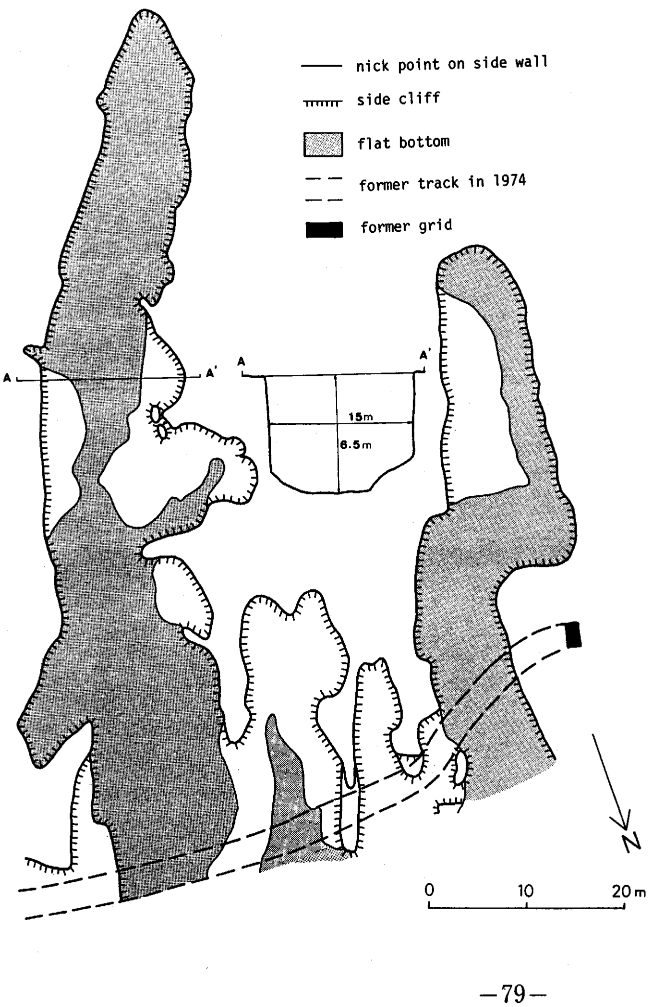

Fig. 13 Big gully developed since the winter season of 1974 at Loc. 6, south of Yacka. The stratigraphic section at A-A' is shown in Fig. 14-**c**.

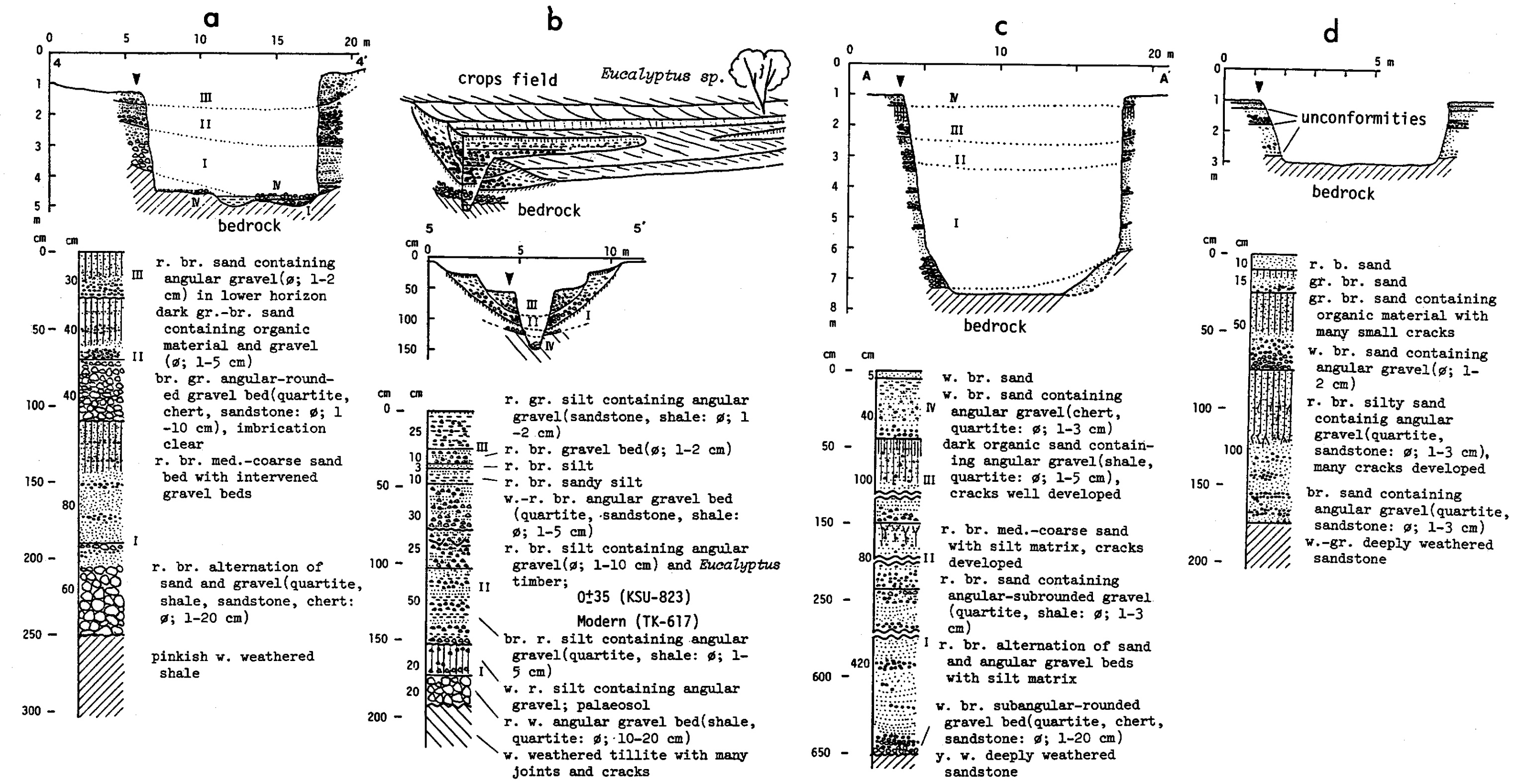

Fig. 14 Cross sections and columnar sections. **a** : Loc. 4 shown in Fig. 11 ; **b** : Loc. 5 shown in Fig. 12 ; **c** Loc. 6 shown in Fig. 13 ; **d** : Loc. 7.

rapidly in recent years. Five cycles of gully development can be recognized at Loc. 6, south of Yacka (Figs. 13 and 14-**c**). Soil development with dense cracks and organic material is observed in the uppermost horizon of some units of sediments. There is no evidence of channels with stream water flow on the surface around the present gully heads. A big gully is developed on the middle part of a pediment at Loc. 7, near Caltowie. Three cycles of deposition are recognized (Fig. 14-**d**). The uncomformities of subsurface material do not show clear shape of channels, but the present gully is located in the floor of a broad and dry valley.

5. Discussion and Conclusions

The soil erosion that occurs mainly in rolling hills and undulating rises, and in upper pediment areas is classified into two levels of severity. One is deep and widespread sheet erosion combined with gully erosion. It occurs at place with deeply weathered bedrock. The other is shallow sheet erosion around the heads of newly developed gullies. At Loc.

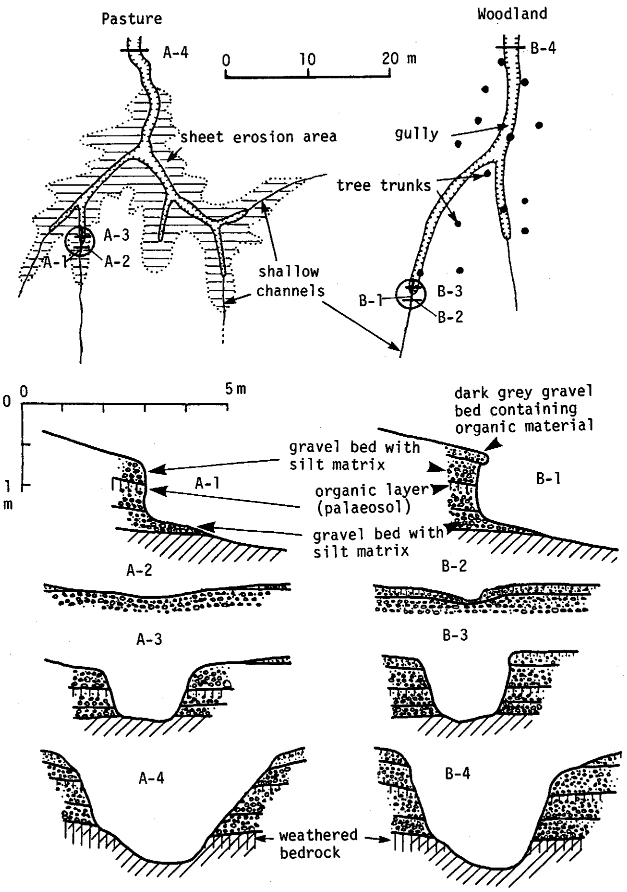

Fig. 15 Schematic distribution pattern of gullies and sheet erosion areas showing differences in the pattern and stratigraphy between pasture and woodland (from the observation in undulating rises at Loc. 8).

8, sheet erosion areas are extensive around the head of gully developed in pasture (Fig. 15-**a**). The uppermost thin gravel bed with organic material has been seriously eroded, resulting in bare land. This type of soil erosion is thought to be peculiar to the cultivated land because, in woodland, gullies have been developed without serious sheet erosion (Fig. 15-**b**).

Almost all gullies newly developed in pediments have reached bedrock, have a marked nick point with a vertical wall at their heads, and inherit buried old channels. A schematic stratigraphic section of such a gully is shown in Fig. 16-**A**, and its longitudinal profile in Fig. 16-**B**. They show four cycles of gully development, and the present gully bottom reaches the bottom of the oldest cycle and is cutting into bedrock, though the bottom of the upstream shallow channel does not reach the bedrock. Pools on present gully bottoms are supplied with water flowing out from the lowest gravel bed directly overlying the bedrock in many gullies. No stream course can be recognized above the heads of a big gully at Loc. 6, south of Yacka (Fig. 13). These observations support the idea that gullies, particularly those large gullies whose heads are in the lower pediment, are eroded mainly by ground water flow concentrated in buried old channels, not by surface water flow.

The stratigraphy of sediments observed on the walls of newly developed gullies shows cycles of alternating deposition and erosion. The carbon date of the timber obtained from the uppermost horizon of the second unit at Loc. 5, east of Pekina catchment, is "Modern". It was buried after 1950 judging from the extreamly high content of ^{14}C (Fig. 14-**b**). Therefore, it can be said that there have been some cycles of gully development since European settlement. The head of the gully has advanced upstream at the mean rate of about 1 m/y at Loc. 5, and of 5 m/y and 10 m/y at Loc. 6. At such rates, deposition and erosion could alternate rapidly. The change of sediment facies from the lower gravel bed to the upper sand bed with clay matrix in each unit of subsurface material suggests that the hydrologic fluctuations correspond to climatic fluctuations. The relations of the intensity of gully and soil erosion to fluctuations of climate, particularly rainfall, and to the management of land will be examined in the future.

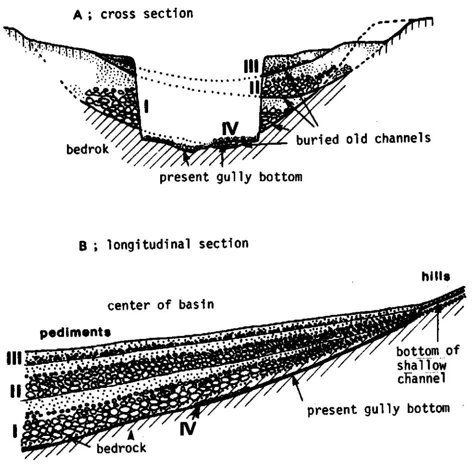

Fig. 16 Schematic cross section (A) showing four cycles of gully development and shifting of channels in the lower pediment, and longitudinal section (B) of a gully from hills to lower pediment.

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