Colloquium
Climatic Change and Geomorphology in Tropical environments
(Brussels, 6 May 1992)
Royal Academy of Overseas Sciences
pp. 7 - 20 (1994)

Geo-Eco-Trop 16, (1 - 4), 7 - 20

GEOMORPHOLOGICAL INDICATORS OF CLIMATIC CHANGES IN ARID REGIONS. CENTRAL AUSTRALIA

Témoignages géomorphologiques de changements climatiques dans une région aride. L'Australie centrale.

H. BREMER *

RÉSUMÉ

Les paléoclimats peuvent être perçus grâce à divers indicateurs. Le relief et les sols sont des indicateurs à long terme pour des régions suffisamment étendues. Ils permettent de reconstituer le cadre dans les limites duquel seront menées des recherches plus locales et à plus court terme, telle que l'analyse palynologique.

En ce qui concerne l'Australie centrale, l'évaluation des périodes de fort écoulement des rivières présente de sérieux écueils. Les lacs y montrent une évolution en plusieurs phases et ne sont en rien comparables aux lacs des régions à rivières permanentes telles que la Riverina (intérieur du SE de l'Australie). Les sols et les produits d'altération tels que les concrétions carbonatées indiquent qu'une alternance de phases humides et sèches a succédé à la phase de latérisation du Tertiaire. Les grands champs de dunes se sont également élaborés en plusieurs phases au cours du Quaternaire. Les dunes les plus régulières apparaissent vers le centre d'un anticyclone présumé où devaient souffler des vents assez faibles.

ABSTRACT

Paleoclimates may be deduced from different indicators. Relief and soil are valuable indicators for long term changes in a fairly large area. Thus they may be used as a frame for investigations on a short term scale and of more local significance, such as pollen analysis. In the case of Central Australia the pitfalls in evaluating higher river stages are outlined. The lakes of this part of the continent seem to show multiphase evolution and are not to be compared with lakes in fluvial areas like the Riverina. Soils and weathering features e.g. calcretes point to alternate wet and dry phases after the lateritization period in the Tertiary . The large dunefields in Australia have been built up in several phases during the Quaternary. The most regular dunes occur towards the centre of the deduced anticyclone where light winds must have been blowing.

* Geographisches Institut der Universität, Albertus-Magnus Platz, D. 5000 Köln 41

INTRODUCTION

In tropical countries relief indications of palaeoclimates are not as easy to be found as are those of the glacial and periglacial heritage in the ectropics. There are fewer bogs in the tropics thus the vegetation history by pollen analysis has its limits. As decomposition is very active almost no fossils are preserved. There is no tree ring chronology possible in tropical areas and in most arid parts; as a result of this a counter check to C_{14} dating is lacking. Glaciations seem to have had only limited extension due to the generally low altitude of the mountains or the small size of areas above the snow line. In Central Australia glaciation is missing as well as the periglacial features. Thus there seem to be no agreed-upon time scale for climatic changes derived in the area itself where findings of the arid and tropical part could be linked to. Fossil soils most important in subdividing large loess deposits in Europe are perhaps one of the main indicators of former climates in the tropics, too. As they are rarely buried they are more likely to survive in the dry part than in the humid tropics. In the wet tropics further weathering will overprint soil features of a dry climate, sediments may be reworked, and landforms reshaped.

One of the first reported indications of palaeoclimates were the misfit river beds. The inheritance from a wet climate though, is not only a question of size, as may be shown in Central Australia. Dunes and lakes are indicators mostly rather well to be interpreted in a climatic context but their age is highly disputable. There are more arguments about pediments, planes, and inselbergs, forms of restricted planation like plain bands, stretch slopes (BREMER, 1981). There is less debate about the differences in weathering concerning soils, though weathering features like Büssersteine (penitent rocks, ACKERMANN, 1962) have been rarely evaluated.

THE STUDY AREA

The study area, Central Australia, lies just south of the tropic of Capricorn. It receives a mean yearly precipitation of 150 mm (SE, SW) to 250 mm (Alice Springs). There are exceptional years, where heavy rain showers may add up to 1000 mm. As a result the vegetation cover is extremely variable from almost barren to complete in the grass and herb stratum. The reaction of the bush and tree stratum (mainly *Acacia aneura*) is of course less pronounced. Grass and herbs indicate more the yearly precipitation whilst the tree cover is controlled by long term drought periods.

Central Australia is part of the Precambrian shield. In the centre palaeozoic sedimentary rocks are intensely folded and the more resistant rocks crop out in long narrow ridges west of Alice Springs. To the east there is a similar set-up of intramontane basins and ridges in crystalline gneisses and schists. The strike of the rocks is generally from the west to the east whilst the river net is mainly north-south aligned. There are only very short east-west reaches in the rivers.

THE RIVERS

Already the outlay of the river net suggests an inheritence from an old plain, relicts of which may be detected on top of the ridges. The main rivers, like the Todd River, the Hugh River, the Finke River run to the Amadeus basin in the south and even beyond to the Lake Eyre basin. Together with their tributaries they cross the ranges in spectacular gorges. Some of them are rather wide like those of the Finke River in the MacDonnells or the Krichauff Ranges. Others are extremely narrow like Stanley Chasm, Redbank Gorge or Kings Canyon (BREMER, 1967). The differences in cross profile and form under otherwise similar conditions like rock resistance, discharge area, gradient, rainfall distribution are not understandable by mechanical erosion in a dry climate; but they are controlled by preceding weathering under a moist and hot climate (BREMER, 1971). The age of the gorges must be at least lower Tertiary as their bed is in the level of the intramontane and foreland plains which do not differ much in height. These again have not been considerably lowered since Cretaceous time. Relicts of the intense weathering of early Tertiary or Cretaceous time are to be found on top of the ridges in form of a thin ferricrete. The plains are covered by relict oxisols most likely from Tertiary time, too. The walls of the gorges especially in the case of small valleys are silicified right to the level of the river bed, an indication of the intense weathering, too.

There seems to have been very little change of the narrow valleys post-incision, terraces are not detectable - perhaps the transverse valleys are to short anyway. There are flood sediments to be found, detected and dated by BAKER *et al.* (1983). In the narrow valley "desert floods" may rise up to 10 metres. This seems to be due more to flow dynamics - the sand load moves in suspension in slowly advancing eddies - rather than to the volume of discharge. Thus a higher discharge or a more frequent one due to a wetter climate might not show in the narrow valleys.

On the plains the rivers are not or only little incised. After high floods some sand banks have shifted slightly, a bit eroded in a few places, with some accumulation in others. On the whole there is little disturbance of the vegetation, the river gums especially (*Eucalyptus camalduensis*) are usually not uprooted. Generally the transport of sand seems to reach not very far, as in the flood-outs of the Finke R. there are only fine fractions, mainly silt and clay deposited.

Conclusions : There seem to be very little erosive power in the rivers of the MacDonnells. Rivers on the plains transport sands perhaps in a rather small amount.

THE LAKES

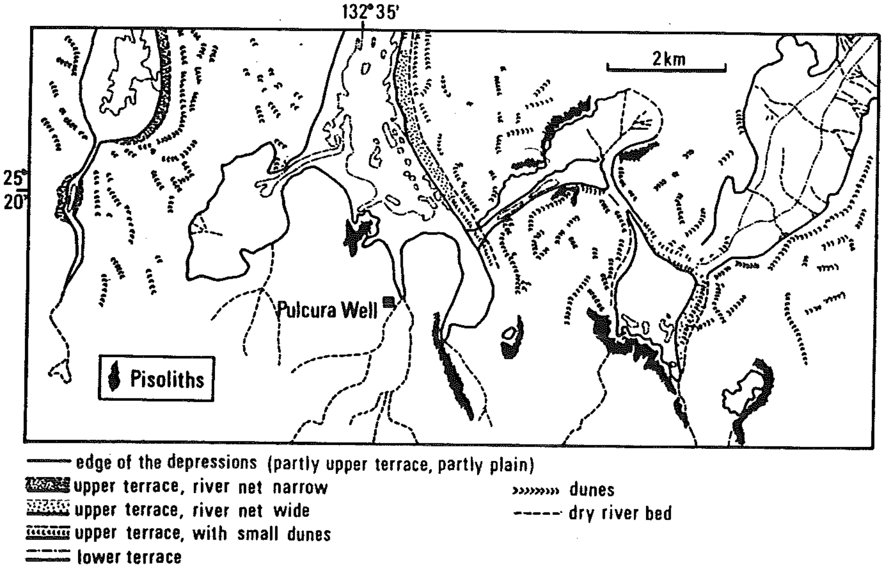
In the arid lakes of Australia 80 % clay minerals, mainly kaolinite are to be found as recent accumulations (FÖRSTNER, 1977). Besides a detrital composition of especially talc, felspars, and minerals like Co, Ni, Cr point to an almost complete lack of recent chemical weathering. Carbonates are missing in the sediments, through there are calcretes close to the lakes. FÖRSTNER (1977) reports dolomite as not existent in actual deposits; but at 25 m depth in the deepest sample 15 % dolomite was found in the Lake Mac Farlane area. On the Warburton River and the Lake Eyre (WOPFNER & TWIDALE, 1967) there seem to be more recent deposits, too.

These deposits shed light on the sources for the large dunefields. It seems unlikely that recent deposits are blown out as clay and salts are highly cohesive. In some dunes further south clay pellets are to be found but they are not reported from Central Australia. Dunes at the down wind rim of the salt lakes, the lunettes, consist almost completely of quartz sand only very occasionally there is a grain of the precipitates. The quartz grains must come from old sediments in the axis of the Amadeus trough, they are exposed in cliffs around the lakes. The salt lakes are up to 10 m deep depressions in the plain.

The salt lakes are lowered into a plain of at least Tertiary age; this is because near Pilcura Well there are pisoliths extending right to the edge of the plain above the salt lakes. The ground plan of these lakes is rather peculiar (Fig. 1a and b). The many irregular extensions in E-W as well as in N-S direction suggest that the blow-outs are not only due to wind work but have also been controlled by preceding weathering. Perhaps there existed a broad valley - a planation strip (BREMER, 1981) which was filled up. Out of these materials and the old weathering mantle the depressions were blown out.

There seem to have been two stages because there are two terraces. It is not very likely that these terraces are due to a rise in lake level as in that case the interlake areas would have been flooded too and a very long (more than 50 km) lake should have

1a. Salt lakes and dunes near Pulcura Well



1b. Air photo mosaic Kulgera, southern N.T., Australia

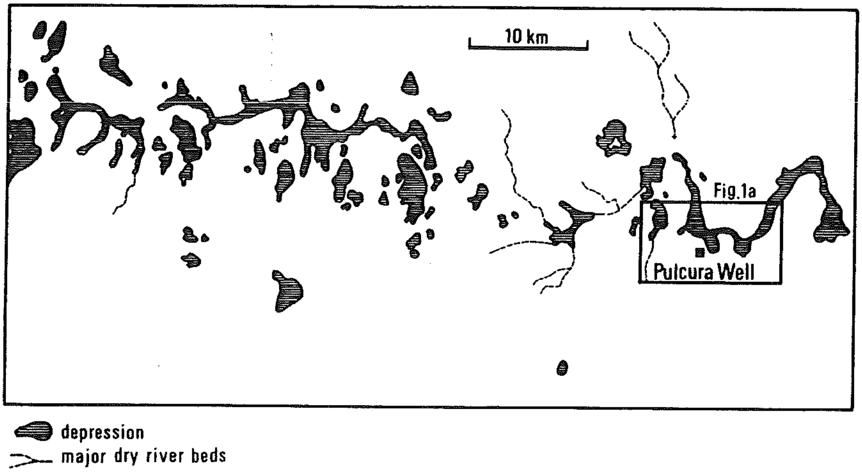


Fig. 1 : Salt lakes near Pulcura Well. The lakes are lowered up to 10 m into the Tertiary plain inherited from moist and warm climates as is show by the lateritic pisoliths and the oxisols in this plain. A terrace and two generations of dunes at the edge of the lakes (partly lunettes) are indications of a multiphase development. The recent sediments are not the source of these dunes. The outline of the salt lakes (lower part of Fig. 1) proposes a control by deep weathering in the centre of the Amadeus trough being irregular due to differentiation in moisture conditions. This would point to a decline of the very wet conditions of the pisolith time towards a semihumid/humid climate.

existed. This should have had an outlet, but nothing is known about a large river draining the axis of the Amadeus trough. The terraces instead seem to have developed during stillstand phases in the lowering. Therefore the depressions are not to be evaluated for dry and wet phases during the youngest Pleistocene. The proof of this conclusion is even difficult with the tectonically induced and greatly enlarged Lake Eyre, the "Lake Dieri". LÖFFLER and SULLIVAN (1979) propose a successive shrinking since Tertiary time; whilst WOPFNER and TWIDALE (1988, 1992) consider the dunes on the former lake bed as Holocene, implying a flooding of the area in the last cold age. From the large extent of the dune fields and the slow sand delivery by the rivers this seems rather unlikely. This is suggested by datings, too.

Conclusion : The inland lakes are probably not to be compared with lakes in the Riverina (BOWLER & WASSON, 1984). The sediments in the inland lakes show the extremely low recent weathering rate.

CALCRETES

The lack of calcium in lake sediments leads to the conclusion that this element does not seem to move to a considerable extent under recent conditions. Calcretes and caliche in Central Australia seem to be related to wet phases in the Pleistocene (BREMER, 1967). For the Strzelecki dunefield WASSON (1984) mentions the youngest dated carbonate as 7 600 B.P. near Moomba. Limestone deposits in Central Australia of Tertiary age occured in already separated lakes (WELLS *et al.*, 1970). The source of the calcium for the calcretes is not obvious as there are calcretes in areas where there is no connection to limestones at all. An overview on extension, mineralogy and formation of calcretes is given by MILNES and HUTTON (1983).

Perhaps the Ca may come from crystalline rocks and circulate with the ground water, but than it is difficult to understand that there is no lime precipitation in the lakes. Other sources proposed are cyclic salts or calcareous dust carried over long distances. ISBELL *et al.* (1983) report a decrease of ions in actual rains from the coast to the inland but still consider the precipitates and calcrete as due to cyclic salts. Deposited on top of the soils the calcium may be transferred and recrystallized in macropores, the concretionary stage though asks for more movement by soil water. Sometimes at the edge of river beds there are thin caliche deposits.

All three forms are to be found in Central Australia, but only the calcretes more frequently. The age of these calcium carbonate deposits in unknown. They postdate the intensive weathering of the oxisols and ultisols. In southern Australia where calcretes are linked to eolianites the $CaCO_2$ precipitation in soils seem to have occurred in the wet phases of the Pleistocene (MILNES & HUTTON, 1983). BUTLER and CHURCHWARD (1983) consider the exposed sea bottom during low sea levels as a source of the calcite. There is a decline in the amount of calcareous pedogen features from the coast to the inland, e.g. the lake Torrens area. Thus the relatively rare occurrences in Central Australia fit into the picture.

Conclusions : Calcretes are most probably relic features in Central Australia as was deduced from their morphological position (BREMER, 1967), the lake precipitates, and thin sections of soil samples.

THE DUNES

Dunes are easy to detect on the ground and especially on air photos or even on satellite imagery. If they occur in today rather densely vegetated areas they are a good indication of a former dryer climate. In Australia there are very large dunefields, covering about 40 % of the continent (WASSON *et al.*, 1988). They extend from 38° to 15° of latitude, over a wide reach from temperate winter rain climate to areas which receive up to 1000 mm/year precipitation in 5 months.

These dunes at the outer rim of the dune distribution are not coastal features and it seems most likely that they are relic dunes. But it is not easy to define a boundary to still active dunes which are reported from the Lake Eyre region by WOPFNER and TWIDALE (1988, 1992), and TWIDALE and WOPFNER (1990). In the center of Australia vegetation changes are spectacular between years with good rains and almost complete cover of the surface on the one hand and the other hand dry years when only acacia bushes 10 metres and more apart are left, partly due to overgrazing. The dunes though keep their cover of dried out grasses and herbs.

There is little movement of sand along the crest of the dunes in the western part of the Simpson Desert. A new build-up of dunes seems to take place along the Finke R. and the younger lunettes of the salt lakes in the Amadeus trough. These recent dunes are of yellow colour, whereas the sands of the Simpson Desert are red. Therefore BREMER (1967) distinguished two generations of dunes. Furthermore as red dunes encroached onto soils (oxisols) with calcretes and there were calcretes developed in the upper part of dunes a complex history was concluded; this history may be even extended after newer results.

At first the oxisol was formed under a wet tropical climate, the lower limit is at least 1650 mm rainfall/year (SPÄTH, 1981). These soils may be very old and impoverished in clay in the upper horizon. Still the sand grains carry the heritage of the wet time in the form of solution caverns and a partial cover of hematite iron skins (Fig. 2). These sands make up the main part of the dunes judged from the colour. It seems impossible to have such an intensive weathering after the deposition of the dunes. There are anyway no soil horizons in the dunes besides the calcretes nor enrichment of clay or iron near the base.

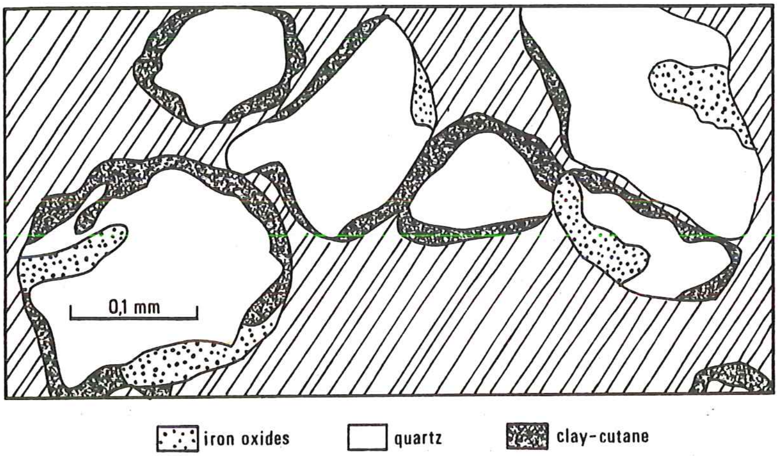


Fig. 2 : Quartz grains from dunes of the western side of the Simpson Desert show definite signs of former weathering similar to quartz grains and soils especially those on neighbouring sandstones.. There are solution features filled with the dark red matrix most likely consisting of hematite and clay (microprobe). The skins around the grains are interrupted in places presumably due to saltation. These skins consist of dark red (hematite) and yellow (goethite) iron/clay complexes.

In the interdune corridors there is a weakly defined horizontation by a higher clay content below 10-15 cm. This might be recent but on the whole the oxisols are relict features as there is calcium or/and salt penetration in fissures (Fig. 3). The formation of calcretes in these red soils seems to point towards a wetter climate than today. This is in accordance with the lack of calcium in the dunes of the Simpson Desert, near Deep Well dunes are encroaching a plain with calcretes in an oxisol. And near New Crown there are calcretes in the dunes themselves about 1/3 from the top downwards (BREMER 1967). Perhaps there are even two phases of calcrete formation. These phases point towards a wetter climate than today whilst the accumulation of the dunes implies a dryer climate.

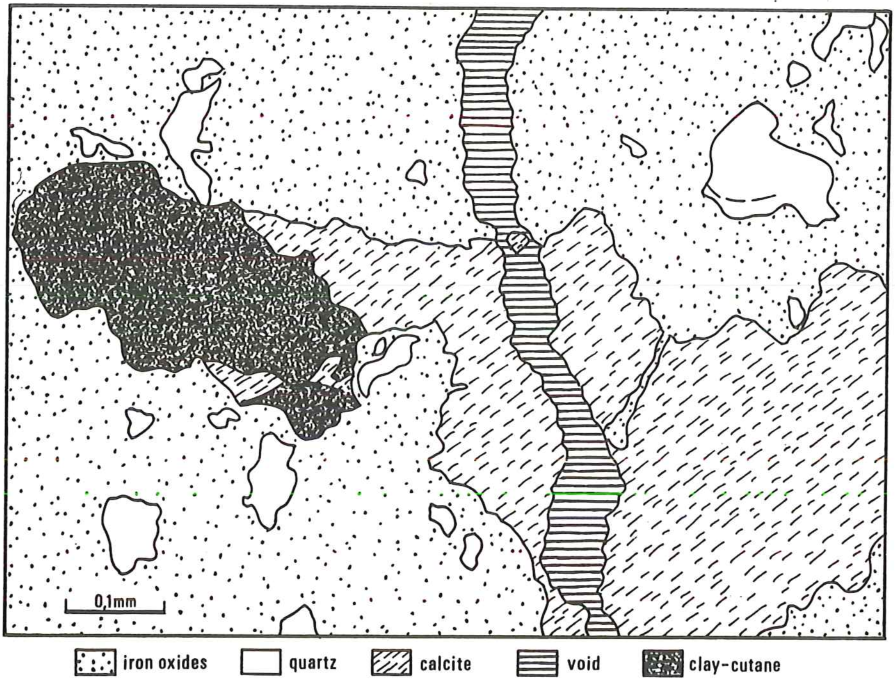


Fig. 3 : An old oxisol is indicative of intensive weathering especially if the primary minerals are completely destroyed and only some quartz grains are preserved and even they show corrosion features. This soil has been cracked and in the fissure, in a first phase, clay-goethite complexes and skins were deposited; later calcite has intruded. In small fissures of the calcite amorphous iron has invaded. This points to a relic character of the calcrete which is more obvious in thin sections from Queensland which today is in an area of 900 mm rainfall (SANDER, 1992).

This multiphase development of the dunes at the western side of the Simpson Desert and in the Amadeus trough sheds light onto several questions in the extensive discussion about dunefields in Australia. From the trend of the large dunefields an anticlock-wise wind system can be derived (BREMER, 1967; BROOKFIELD, 1970). The corresponding high pressure cell is similar to recent air pressure conditions, though the axis of the anticyclone may have been shifted for a few degrees of latitude. Still, anticyclonal winds are generally not very strong. Even with an increased temperature gradient between the cold sea and the hot interior during the cold ages it is hard to envisage much stronger and steadier winds. The differences between the dune forming time and today are probably more in a higher degree of aridity and thus a thinner vegetation cover.

In a very detailed study WASSON *et al.* (1988) collected data about dune forms for each 15 minute quadrate. Longitudinal dunes dominate on the Australian continent. The long narrow crested linear dunes occur probably in a moderately variable windfield more in the southern part of the continent. The very short narrow crested linear dunes in the south and the broad crested linears in the north and west are to be found at the rim of the continental wind whorl; network dunes are found on the floodouts and at the edges of basins in its centre. Parabolic and crescentic dunes occur in small areas of quartzose sands.

The most regular dunes are the longitudinal narrow crested ones of the Simpson Desert, running uninterrupted for several or even tens of kilometres. It is hard to envisage a variable windfield as WASSON *et al.* (1988) proposed for these regular landforms. Similar regularity in orientation seems to occur in the Great Sandy Desert, which extends from almost the centre of the great whorl to the northwestern rim. Both dunefields are developed in large sedimentary basins, where Tertiary weathering most likely will have left very sandy and uniform soils. Perhaps the sands were piled up with increasing aridity in longitudinal stretches due to heating of the surface and development of a helical flow as described by BESLER (1992) for initiating longitudinal dunes. The regularity might then have been reinforced causing a positive feedback. The variable winds of today would concern only the upper part of the dunes and not change the whole form.

The division of the longitudinal dunes into an inner core often extending right to the surface and an outer mantle (see also WASSON, 1988) would explain the assumed very different ages : Holocene by a few C_{14} datings and the reference to a completely flooded Lake Dieri in the last cold age (WOPFNER & TWIDALE, 1988, 1992); and Pleistocene with more C14 dates beween 25 000 and 13 000 B.P.; a minor phase at 3 000 - 1 000 B.P. (WASSON, 1984; CALLEN & NANSON, 1992). WASSON (1984) distinguishes for the Simpson Desert the pale dunes near Lake Eyre, the red-brown ones on the slightly higher ground. WOPFNER and TWIDALE (1988) too mention an abrupt change in colour of the dunes near the Finke River, but consider the red ones as developing from the yellow ones as there is a transition north of Lake Eyre. Again this might be explained by reworking and incorporating the younger sands.

To sum up : The large dunefields most likely developed over a long time. In the evaluation for palaeoclimates the very regular longitudinal forms probably should not be put together with the smaller irregular dunes perhaps of quite different age. The still open questions of different ages might be solved not only by further dating but too with increasing sedimentological and pedological work on the dunes and the corridors.

THE SOILS

In Central Australia oxisols and ultisols are widely spread. As well as lithosols on slopes and rises they cover almost the whole surface. There can be little doubt that these soils are relict formations. From the precipitates in the salt lakes it was already concluded that recent chemical weathering is almost completely lacking. The occurrence of calcretes in oxisols proves the relic character, too, as calcite would not endure intensive weathering as was concluded earlier (BREMER, 1967). In thin sections there are indications of multiphases e.g. in pore fillings (SANDER, 1992).

The wide extent of the relic soils leads to the conclusion that there has been little erosion since the onset of aridity. There is some sand transport in the rivers, the source of which are mountain slopes and valleys. Plains and flat relief elements have been little lowered, perhaps a few metres. The forms have not changed considerably as otherwise the soils would have been removed.

Conclusion : The soils in Central Australia are mainly relict features. Their wide extent shows the very small erosion under arid conditions.

PEDIMENTS

Pediments or glacis have been considered as a typical landform of arid climates, most likely due to their extensive occurrence in the American West. This is also a region of young tectonic movements. Under similar arid conditions in Central Australia there are no pediments nor the pertinent fanglomerates. This may be due to the generally low relief and the rather small extent of the hills and mountains. There are almost no fans in Central Australia. In BREMER (1967) a case was described, where a quartz dike could be followed from the range to the foreland, where the quartz pebbles were lying in the strike of the dike. Thus they were not transported, just projected downwards by the removal of the fines. This occured near the outlet of a transversal valley, and thus indicating a lack of lateral erosion as well as a missing fan. In other places there is up to 1 m of red loam deposit derived from the widely spread oxisols. There are almost no stones in these deposits; if they do occur they are small, up to 1-2 cm, and arranged in a stone-line.

Generally the gradients of the plains at the foot of the mountains in Central Australia are an order lower than in other arid regions (Tab. I). This is in part due to the overall small relief in Central Australia, but also to the little erosion under arid climate.

Tab. I : Gradients in ‰ (BREMER, 1963)

	Piedmont plains	Plains	Large rivers
Central Australia	6 - 10 (20)	2	0,7
Arid regions	100 - 200	10 - 30	1 - 2
Tropical humid areas	10 - 50	2 - 4	0,4

Conclusion : Plains at the foot of the mountains in Central Australia are relict features from a hot and humid climate.

CONCLUSIONS FOR PALAEOCLIMATES

Different indicators for palaeoclimates in a now arid region are discussed on the example of Central Australia. Rivers in the ranges and lakes are difficult to evaluate as these erosional forms may have developed over a long time and may be very old. Even the dunes seem to have been formed in several phases. Climatic implications for the large dunefields are not easily deduced as the most regular dunes occur more to the centre of the large continental anticyclone where only light winds can be expected. The soils and the pedogen calcrete are relic features of a humid and semi-humid climate. As the calcretes develop usually with some lateral soil water movement local moisture conditions must be taken into consideration. Perhaps at this stage of investigations Quaternary climatic changes are more easily to be deduced in the wetter parts of Australia (BOWLER *et al.*, 1976; BOWLER & WASSON, 1984) or even from marine deposits off the continent (e.g. CHAMLEY, 1986; LOCKER & MARTINI, 1989). The deduced palaeoclimatic evidence is partly contradicting.

The morphogenetic approach has a disadvantage of inherited landforms, soils, and deposits. It has the advantage of giving the possibility to check local results on a regional basis. The results of soil samples, deposits, C^{14} dates, pollen analysis are usually locally pertinent. Their regional meaning - and this is important for palaeoclimate - may be derived at by connection with the morphogenesis.

BIBLIOGRAPHY

ACKERMANN, E., 1962. Büssersteine - Zeugen vorzeitlicher Grundwasser-schwankungen. *Zeit. Geom.*, N.F., 6, 148-182.

BAKER, V.R., PICKUP, G. & PULACH, H.A., 1983. Desert palaeofloods in Central Australia, *Nature*, 301, 502-504.

BESLER, H., 1992. *Geomorphologie der ariden Gebiete*. Darmstadt.

BOWLER, J.M., HOPE, G.S., JENNINGS, J.N., SINGH, G. & WALKER, D., 1976. Late Quaternary climates of Australia and New Guinea. *Quaternary Res*, 6, 359-394.

BOWLER, J.M. & WASSON, R.J., 1984. Glacial age environments of inland Australia. In : J.C. VOGEL (Ed.), pp. 183-208.

BREMER, H., 1963. Der Einfluss von Vorzeitformen auf die rezente Formung in einem Trockengebiet - Zentralaustralien - Wiss. Abh. Dt. Geographentag Heidelberg, 1963, Wiesbaden, 1965, 184-196. nachgedruckt m. Nachtrag in : MENSCHING (1982), 192-209.

BREMER, H., 1967. *Zur Morphologie von Zentralaustralien* - Heidelberger Geogr. Arb., 17.

BREMER, H., 1971. *Flüsse, Flächen - und Stufenbildung in den feuchten Tropen*. Würzburger Geogr. Arb., 35.

BREMER, H., 1981. Reliefformen und reliefbildende Prozesse in Sri Lanka. In : H. BREMER, A. SCHÜTGEN & H. SPÄTH (Eds.) , pp. 7-183.

BREMER, H., SCHÜTGEN, A. & SPÄTH, H. (Eds.), 1981. *Zur Morphogenese in den feuchten Tropen. Verwitterung und Reliefbildung am Beispiel von Sri Lanka. Relief, Boden, Paläoklima 1*. Stuttgart.

BROOKFIELD, M., 1970. Dune trends and wind regime in Central Australia. *Zeit. Geom.* Supp., Bd 10, 121-153.

BUTLER, B.E., & CHURCHWARD, H.W., 1983. Aeolian processes. In : Division of Soils, CSIRO, pp. 91-99.

CALLEN, R. & NANSON, G., 1992. Discussion - Formation and age of dunes in the Lake Eyre Depocentre. *Geol. Rdsch.*, 81, 2.

CHAMLEY, H., 1986. Continental and marine palaeoenvironments reflected by west Pacific clay sedimentation. *Geol. Rdsch*, 75, 271-285.

Division of soils, CSIRO, 1983. *Soils , an Australian viewpoint.* Melbourne.

FÖRSTNER, U., 1977. Mineralogy and geochemistry of sediments in arid lakes of Australia. *Geol. Rdsch.*, 66, 146-156.

JENNINGS, J.N. & MABBUTT, J.A., (Eds), 1967. *Landform studies from Australia and New Guinea*. Canberra.

LOCKER, S. & MARTINI, E., 1989. Phytoliths at DSDP Site 591 in the southwest Pacific and the aridification of Australia. *Geol. Rdsch.*, 78, 1165-1172.

LÖFFLER, E. & SULLIVAN, M.E., 1979. Lake Dieri resurrected : an interpretation using satellite imagery. *Zeit. Geom.*, N.F., 23, 233-242.

MENSCHING, H., (Ed.), 1982. *Physische Geographie der Trockengebiete. Wege der Forschung*. Darmstadt. 536 p..

MILNES, A.R., & HUTTON, J.T., 1983. Calcretes in Australia. In : Division of soils, CSIRO, pp. 91-99.

RICH, D.C., YOUNG, R.W. & APLIN G., (Eds), 1988. Environment and development in Australia. *Australian Geogr.*, 19.

SANDER, H., 1992. Polygenetic soils of Australia and their typical pedofeatures. *Zeit. Geom.*, N.F., Suppl. Bd. 91, 35-41.

SPÄTH, H., 1981. Bodenbildung und Reliefentwicklung in Sri Lanka. In : BREMER *et al.*, pp. 185-238

TWIDALE, C.R. & WOPFNER, H., 1990. Dune fields. In : TYLER, TWIDALE, DAVIES & WELLS (Eds.), pp. 45-60.

TYLER, J., TWIDALE, C.R., DAVIES, M. & WELLS, C.B., (Eds), 1990. *Natural history of the North-East Desert*. Royal Soc. South. Australia, Adelaide.

VOGEL, J.C. (Ed.), 1984. *Late Cainozoic palaeoclimates of the southern hemisphere*. Rotterdam.

WASSON, R.J., 1984. Late Quaternary palaeoenvironments in the desert dunefields in Central Australia. In : VOGEL (Ed.), pp. 419-432.

WASSON, R.J., FITCHETT, K., MACKEY, B. & HYDE, R., 1988. Large scale patterns of dune types, spacing and orientation in the Australian continental dunefield. *Australian Geogr.*, 19, 89-104.

WELLS, A.T., FORMAN, D.J., RANFORD, L.C. & COOK, P.S., 1970. Geology of the Amadeus Basin, Central Australia. *Bur. Min. Res. Geol. Geophys. Austr. Bull.*, 100.

WOPFNER, H. & TWIDALE, C.R., 1967. Geomorphological history of the Lake Eyre Basin. In : JENNINGS & MABBUTT (Eds.)., pp. 118-143.

WOPFNER, H. & TWIDALE, C.R., 1988. Formation and age of desert dunes in the lake Eyre depocentres in Central Australia. *Geol. Rdsch*, 77, 815-834.

WOPFNER, H. & TWIDALE, C.R., 1992. Reply. Response to R.A. CALLEN and G.C. NANSON. *Geol. Rdsch*, 81, 595-599.