GEOLOGICAL AND HYDROLOGICAL INFLUENCES ON THE DEVELOPMENT OF MEANDERING VALLEYS IN THE SHOALHAVEN RIVER CATCHMENT, SOUTHEASTERN NEW SOUTH WALES

With 7 figures, 2 photos and 2 tables

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Zusammenfassung: Geologische und hydrologische Einflüsse bei der Bildung von Mäander-Tälern im Abflußgebiet des Shoalhaven Rivers im Südosten von Neu Süd-Wales

Im Jahr 1954 machte Troll darauf aufmerksam, daß die wissenschaftliche Untersuchung von Talmäandern weit hinter dem Studium alluvialer Mäandertypen zurückgeblieben ist. Seither, und das ist größtenteils G. H. Durys Tätigkeit zu verdanken, ist die Untersuchung von Talmäandern eng verbunden mit der allgemeinen Theorie über die Bildung von Mäandern. Die vorherrschend hydrologischen Modelle, die in den letzten Jahren vorgeschlagen wurden, vernachlässigen jedoch wichtige geologische Einflüsse bei der Mäanderbildung im Grundgestein.

Die Verbreitung von Mäandern im Grundgestein im Abflußgebiet des Shoalhaven Rivers hängt größtenteils von der Beschaffenheit des anstehenden Gesteins ab. Mäander werden am besten in gut gefügtem, widerstandsfähigem Gesteinsmaterial ausgebildet, besonders in Sand- und Quarzitgesteinen. Mäander bilden sich aber auch im weniger widerstandsfähigen Gestein, wenn das Einschneiden des Flusses schnell genug erfolgt. In diesem Gebiet existieren Mäander nur spärlich in Hochland-Sümpfen, in denen die Versickerung eine wichtigere Rolle spielt als der geradlinige Abfluß, oder in Schluchten, wo widerstandsfähige Aufschlüsse unterschnitten werden. Studien über die Shoalhaven-Region zeigen ebenfalls einen stark strukturellen Einfluß auf das Ausmaß und die Erscheinungsformen von Mäandern. Bei einigen Flüssen nimmt die Größe der Mäander flußabwärts zu, bei anderen ab. Manche Erscheinungsformen von Mäandern stimmen mit der Langbein'schen und Leopold'schen Theory of Minimum Variance überein, andere wiederum nicht. Diese Studie unterstützt nachdrücklich Trolls Aufforderung, sich bei der Erklärung von Mäander-Tälern nicht mit nur einer einzigen Ursache zu beschäftigen.

Barely two decades have passed since Troll (1954) lamented that the study of meandering valleys was still overly constrained by the cyclical scheme which W. M. Davis had proposed half a century earlier, and that it lagged far behind current advances in the study of alluvial meanders. Ten years later, due essentially to the efforts of Dury (1954, 1958, 1964a, 1964b), this was no longer so. Dury demonstrated that the morphology, both in plan and section, of many valley meanders was identical to that of alluvial meanders. He also presented compelling evidence supporting changes in climate and channel-forming discharge as the cause of the general disparity between the dimensions of valley and stream meanders for comparable drainage areas. As Dury (1964a) himself put it, "the term 'meandering valley' now acquires additional significance; it implies that valley meanders are homologues of stream meanders". And when Langbein and Leopold (1966) proposed the Theory of Minimum Variance for the general phenomenon of meandering, they suggested that meanders ought to be best developed in bedrock, as the distorting effect of non-homogeneous material should disappear during incision. Additional support (Leopold, 1969; Schumm and Shepherd, 1973) for Dury's observation that pool and riffle sequences occur in bedrock and alluvium alike seemed the final link needed between the study of meandering valleys and the general theory of meandering.

Closer inspection reveals one apparent shortcoming. The effects of bank and bed material so clearly demonstrated for alluvial streams (e.g. Hjulström, 1942; Leopold and Wolman, 1957; Schumm, 1963) have no real counterparts in the new scheme proposed for meandering valleys. Evidence of geological constraints on meandering continues to appear (e.g. Hack and Young, 1960; Hack, 1965; Dury, 1966, 1970; Blank, 1970), but has been allotted only a very minor role in a dominantly hydrologic model (Langbein and Leopold, 1966; Dury, 1964a, 1977 in press). Indeed, in asserting that "the incised meander is the most outstanding example of the autonomy of erosion with regard to structure", Birot (1966) simply wrote off a century-old tradition that had linked meandering in bedrock with lithological and structural constraints (see Troll's 1954 review). Yet there has been no thorough attempt to assess the relative importance of hydrologic and geologic factors in varied settings.

Assessing the relative importance of these two factors is obviously far more difficult for bedrock than for alluvial channels. So slow is the response of bedrock to erosive processes that the relationship between the two can rarely be observed directly. The problem must therefore be approached indirectly by comparing the distribution, dimensions and morphology of bedrock meanders both to hydrologic patterns and to variations in structure and lithology. Results from such an investigation in the Shoalhaven River catchment of southeastern Australia are outlined here.

I. Regional setting

The Shoalhaven and its tributaries drain some 7500 km² of plateau land in southern New South Wales (Fig. 1). The river rises closes to the coast southeast of Canberra, but flows northwards, then eastwards to enter the Tasman Sea near Nowra 150 km.

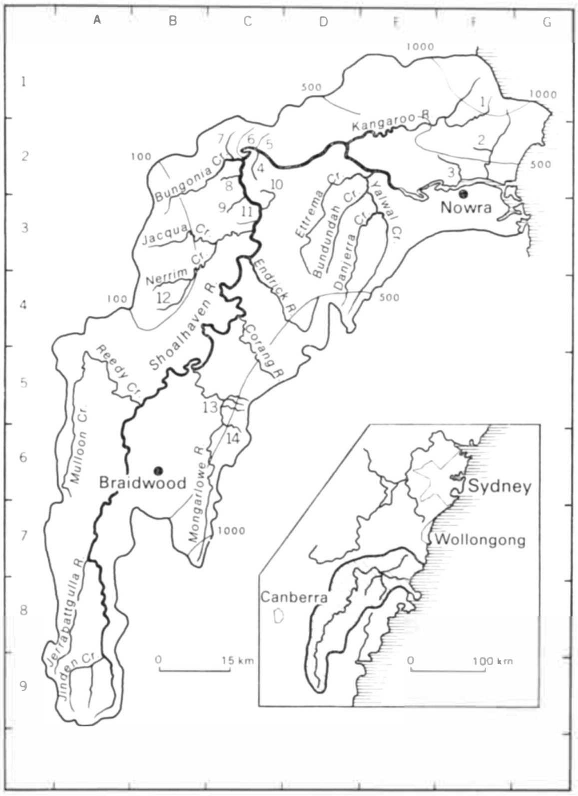

Figure 1: Location map of the Shoalhaven River catchment showing streams listed in the text, and estimated average annual runoff in millimetres. Numbered streams: 1– Broger's Creek 2– Tandingulla Creek 3– Bomaderry Creek 4– Tryer's Gorge 5– Ottawa Creek 6– Barber's Creek 7– Jerrara Creek 8– Beck's Gully 9– Long Creek 10– Tim's Gully 11– Washed Away Creek 12– Nadgigomar Creek 13– First, Middle and Third Curradux Creeks 14– Sapling Yard Creek.

south of Sydney. From a hilly headwater terrain with a maximum elevation of about 1400 m. the Shoalhaven flows on to a high plain which falls gradually northwards from 700 to 550 m. Streams in the south are incised only a few tens of metres into the plain, but in the north have cut narrow canyons to depths of 500 m. Dissection is even more pronounced in the eastern part of the catchment where the Shoalhaven and its two main tributary systems, those of the Kangaroo River and Yalwal Creek, have carved a rugged plateau landscape. The youthful appearance of the gorges belies their true age, for they date from far back in the Tertiary (Young, 1977).

Its circuitous course to the sea carried the Shoalhaven River through two major geological provinces. The upper two-thirds of the catchment lie in the Southern Highlands Fold Belt, a zone of Paleozoic rocks that underwent repeated orogenic deformation and granitic intrusion (Packham, 1969). The remainder is in the southern extremity of the Sydney Basin, where Permo-Triassic sediments and volcanics were subjected only to epeirogenic warping. Most valleys in the fold belt are cut either through tightly folded metasediments or through massive crystalline outcrops. Consequently, this is an area of abrupt lateral change in any geological constraints offered to stream flow. The more easterly streams encounter marked vertical changes in rock type. There a gently-dipping sequence of arenaceous and argillaceous beds of early Permian age is separated by a great wedge of latite flows and tuffaceous sandstones from yet another arenaceous-argillaceous sequence of late Permian and Triassic age. stratigraphic details are given in Fig. 2.

While the climate of the entire catchment can be classified as warm temperate (Köppen's Cfb), conditions do vary markedly from one part to another. Average annual rainfall increases from 650 mm. on the western side of the high plain to more than 1800 mm. on the coastal edge of the plateau in the northeast. The increase in estimated annual runoff is more than tenfold, ranging from about 100 mm. in the west to 1200 mm. in the northeast and to 900 mm. in the southeast (Fig. 1). The highest peaks of the catchment lay below the level of Pleistocene glaciation, but relict periglacial mantles in the headwater ranges and vegetated sand sheets on the high plain (Galloway, 1969), together with widespread alluvial fills and apparently underfit channels (Young, 1974), point to considerable variation from present-day conditions.

II. Distribution of bedrock meanders

Although many valleys in the Shoalhaven catchment are highly sinuous, others are remarkably straight. In some cases straight reaches separate two or more meandering tracts along a single valley. As most of the changes coincide closely with geological boundaries, it seems that the properties of some rocks promote meandering while those of others suppress it.

1. Erodibility

The extensive development of meanders in the Permo-Triassic sandstones of the northeastern part of the catchment, and their almost complete absence from adjacent siltstones, provides a striking parallel to the variations of channel sinuosity noted between clayey and sandy alluvium. In both instances the development of meanders is dependent on cohesion, though the relation between cohesion and grain size is of course reversed. Although seepage through the coarse-grained arenites which comprise much of the Permian Nowra and Snapper Point formations, and also the Triassic Hawkesbury Sandstone, promotes cavernous weathering, these rocks appear resistant to other types of weathering. Most outcrops along streams are quite fresh and resistant to physical impact. Weathering proceeds more rapidly in the tuffaceous Kiama Sand-

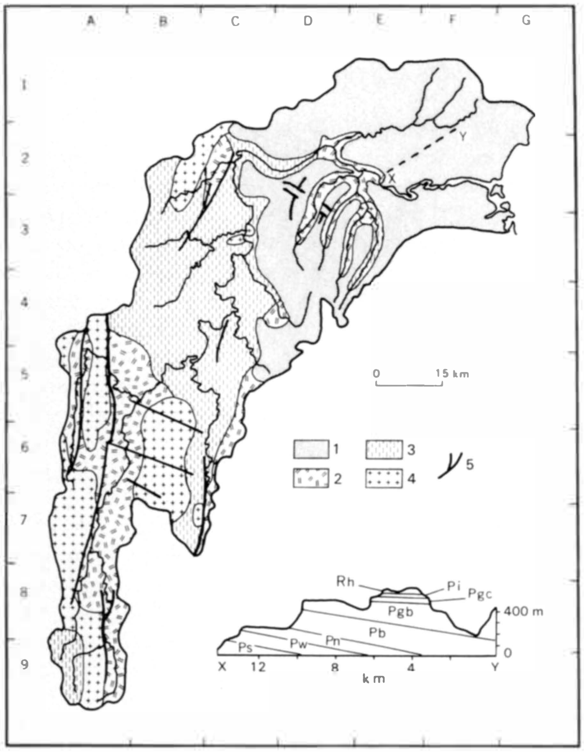

Figure 2: Generalised solid rock geology of the Shoalhaven River catchment: Cainozoic basalts and alluvium not shown.
1– Permo-Triassic sediments and volcanics 2– Siluro-Devonian sediments and volcanics 3– Ordovician meta-sediments 4– Plutonic rocks (mainly granodiorite) 5– Major faults.
Section: Details of Permo-Triassic stratigraphy. Rh– Triassic Hawkesbury Sandstone Pi– Permian Illawarra Coal Measures Pgc– Permian Gerringong Volcanics (Cambewarra Latite) Pgb– Permian Gerringong Volcanics (Budgong Sandstone) Pb– Permian Berry Formation Pn– Permian Nowra Sandstone Pw– Permian Wandrawandian Siltstone Ps– Permian Snapper Point Formation.

stone, but outcrops of this formation are far more resistant than are the invariably friable exposures of siltstone. Studies of the engineering potential of the Berry and Wandrawandian siltstones showed that quarried faces became unstable so rapidly that even large boulders could be easily shattered after only a few months exposure (FRENDA, 1964).

The general relationship between rock type and channel form in this region is well illustrated by the Kangaroo River and its tributaries which cross a variety of gently dipping sediments on their south-westerly course to the Shoalhaven River (Fig. 1. F 1). The Kangaroo's eastern tributary, Broger's Creek, has cut beautifully symmetrical meanders through the Kiama Sandstone; a short straight reach within the meandering tract coincides closely with friable sandstone interbeds. As the creek flows from these tuffaceous sandstones on to the siltstones of the Berry Formation its valley flares markedly into a broad, relatively straight trough. The upper reaches of the Kangaroo River which cross the Berry siltstones are also devoid of meanders. Once the river leaves the siltstones and crosses onto the Nowra Sandstone, it enters a narrow winding gorge; farther downstream it runs through a second broad straight trought cut through the Wandrawandian Siltstone, which in turn gives way to a meandering tract as the Kangaroo cuts its way through the sandstones and conglomerates of the Snapper Point Formation.

Similar examples could be cited from many streams in the eastern part of the catchment (YOUNG, 1974) but it is of more value to consider the single exception to the general rule. Some 6 km. north of Nowra township Tandingulla Creek has cut half dozen symmetrical bends to depths of about 10 m. into thinly bedded siltstones of the Berry Formation (Fig. 1, G 2). Like most outcrops of siltstone in the region, the top 3 m. or so of the meanders walls are heavily weathered, but outcrops nearer the stream bed are relatively fresh with well-preserved joint planes. The meander arms lead from one set of joints to another, and one reach follows a series of lamprophyre dikes which parallel one of the main joint sets. The preservations of relatively resistant jointbounded outcrops of siltstone at this site seems due to rapid incision following the diversion of Tandingulla Creek from a previous course (YOUNG, 1974). Rapid incision on the new course outstripped weathering of the siltstone, and the creek cut a sinuous channel along intersecting fractures in quite fresh rock. In contrast, slow rates of incision of other valleys in the area (YOUNG, 1977) gave ample time for weathering to proceed, thereby promoting both slope failure and lateral stream erosion.

The relationship between meander distribution and bedrock type in the Shoalhaven area is similar to that reported from ohter regions, notably from northern France (BLANCHE, 1940). However, the example of Tandingulla Creek clearly shows that this relationship is dependent not only on the inherent characteristics of rock, but also on rates of weathering and of stream incision. The development of incised meanders, as Troll emphasised, cannot be divorced from the peculiarities of the valley in which they are found.

2. *Structural Guidance*

Virtually all meanders cut into the gently-dipping strata of the eastern part of the Shoalhaven catchment are aligned on intersecting joint planes. The windings of small streams like Bomaderry Creek, which joins the Shoalhaven from the north at Nowra, can be traced along individual fractures. All but one of the meanders incised 20 m. or so into Nowra Sandstone along this creek lead from one joint set to another; the single deviation seems in part due to massive block

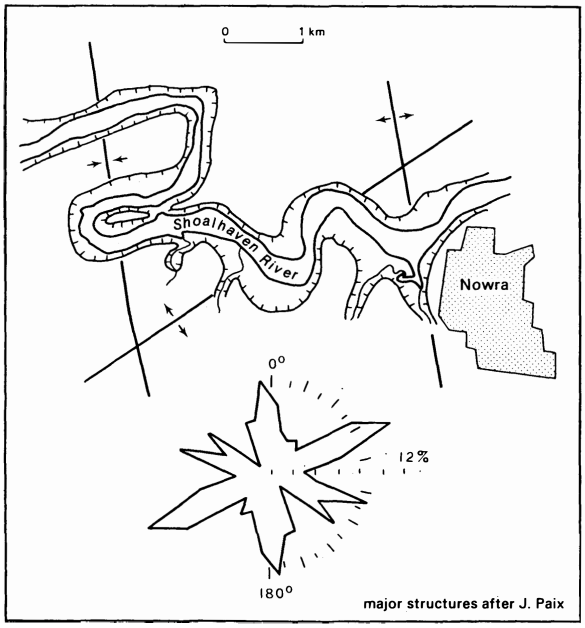

Figure 3: Alignment of joints and entrenched meanders on the Shoalhaven River near Nowra.

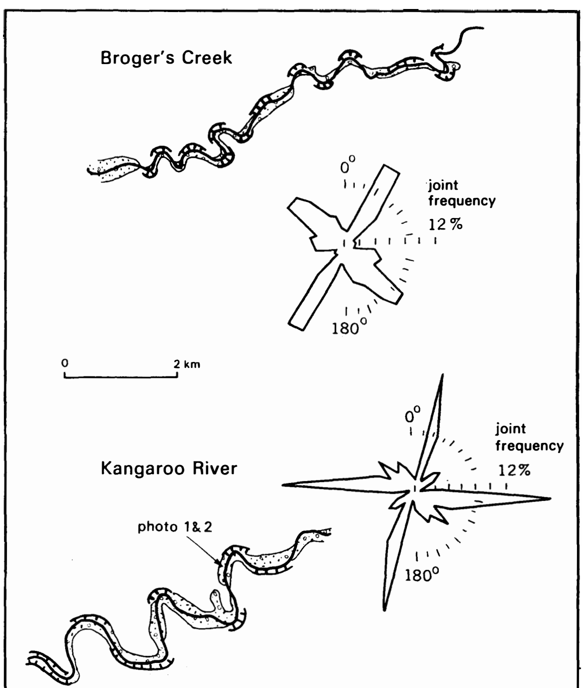

Figure 4: Alignment of joints and meanders on Broger's Creek and the lower Kangaroo River.

collapse from the eastern valley wall. Coincidence of channel and joint orientation is by no means limited to small streams, for it is clearly evident on the Shoalhaven River near Nowra (Fig. 3). The rank correlation coefficient for joint and channel segment orientation on this part of the river is +0.62 (99% confidence level), a significantly high value since divergence from intersecting joints must necessarily accompany the development of smoothly curved bends.

Alignment of meanders along intersecting joint planes can be readily demonstrated elsewhere on the Nowra Sandstone (Young, 1974), and equally well from other strongly jointed rocks in the area. Apart from two reaches where the effects of lateral movement during incision are most obvious (and on which preliminary comments were unfortunately based some years ago (Young, 1970), the beautifully symmetrical bands of Broger's Creek closely follow prominent joint sets in the Kiama Sandstone and sandy transitional beds at the top of the Berry Formation (Fig. 4); for the total meandering tract r = +0.72 (99% confidence level). The windings of the lower Kangaroo River through the Snapper Point Formation were also initiated along two sets of very prominent joints intersecting roughly at right angles. The valley's centre line here corresponds very closely with the joints (Fig. 4), and, though the stream was subsequently reduced to a state of underfitness (Young, 1974) and in places moved laterally across the alluvial fill, some 40% of the present day channel still follows the main joint sets (r = +0.42; 95% confidence level). See Photos 1 and 2.

Close correspondence of joint and channel alignment is of course no proof of structural control, for release of confining stress during valley excavation might well have generated unloading joints parallel to river windings (cf. Bradley, 1963). At first sight this might well seem to be the case along the Shoalhaven River near Nowra where there is unequivocal evidence of massive block movement along the valley walls. Numerous crevasses up to 10 m. deep, 6 to 8 m. wide, and many tens of metres long occur immediately behind the Nowra Sandstone cliffs which bound the Shoalhaven's entrenched meanders. Displacement of beds on either side leaves no doubt that the crevasses were caused by block movement outwards towards the valley centre. However, unloading along valley sides here has merely widened pre-existing joints, not generated new ones. The crevasses follow the most common joints encountered in the sandstone, and these joints (Fig. 3), which occur in two sets parallel to and two sets diagonal to local folds, are clearly the product of systematic tectonic stress rather than of irregular release of confining pressure following valley cutting. Similar conclusions can be drawn for the very regular patterns of jointing encountered in the Kiama Sandstone along Broger's Creek and in the Snapper Point Formation along the Kangaroo River. In all of these cases the measured joints antedated and controlled the development of the valley windings.

Streams draining tightly folded metasediments in the western part of the Shoalhaven catchment are

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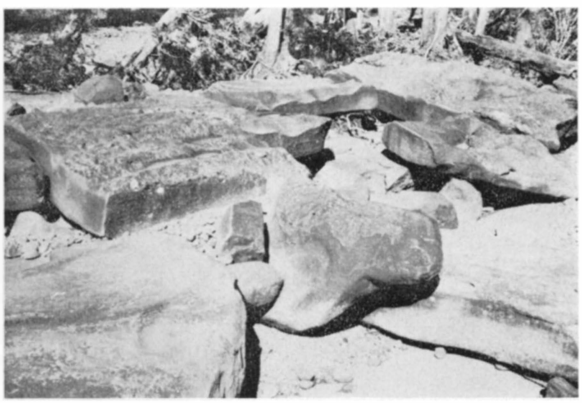

2

Photo 1: Erosion along intersecting joint planes has isolated large blocks of the Snapper Point Formation on the bed of the lower Kangaroo River; the photo shows low flow conditions.

Photo 2: Blocks of Snapper Point Formation quarried from the bed of the Kangaroo River immediately downstream from the site of Photo 1. Note the well-preserved joint faces on the blocks. The great size of individual blocks shows that the most significant erosion of the bed occurs during high flood stages.

generally straight where they parallel the strike, and sinuous where they cross it. The effect of preferential lineation is well illustrated in the subcatchment of Nerrimunga Creek which drains eastward to the Shoalhaven across marked northerly structural trends (Fig. 5). The strikingly parallel meanders arms of the Nerrimunga system have extended along almost vertically dipping bedding planes, especially where quartzites and sandstones abut against slates or shales. The turning point on many of these bends seems to have been initiated on joints which cut obliquely across the regional strike.

The distribution of meanders on many other streams in the western part of the catchment, especially on the Mongarlowe and Corang River (Fig. 1, C 4–6), can be readily explained in terms of channel alignment to the strike of folded metasediments. Nearer the head-

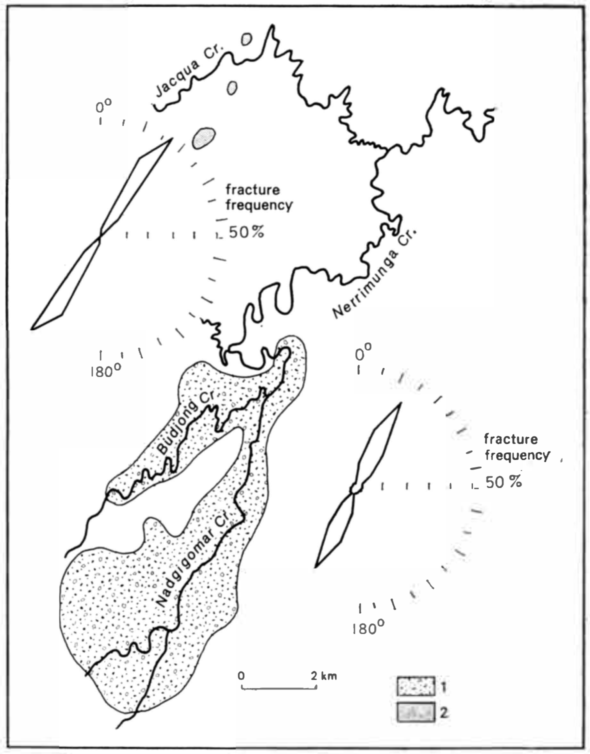

Figure 5: Alignment of stream channels and bedrock lineations in the catchment of Nerrimunga Creek. 1– Silcrete and associated weathering profiles (generalised distribution) 2– Laterite.

waters, where the folded Ordovician beds give way to plutonic, volcanic and sedimentary rocks of Siluro-Devonian age, stream sinuosity is determined largely by patterns of jointing and faulting. The winding course of the upper Shoalhaven in the vicinity of Krawaree (Fig. 2, B 9) is interrupted where the river flows straight along a fault. Fault guidance is also prominent further downstream on the Shoalhaven, on its headwater tributary Jerrabatgulla Creek, and on the very straight streams that drain westward across the Braidwood Batholith (Fig. 2, B 6).

In a number of cases the simple relationship between meander distribution and fracture patterns is complicated by marked local variation in rock resistance. Tim's Gully, which joins the Shoalhaven near the mouth of Nerrimunga Creek (Fig. 1, D 3), follows a highly sinuous course through tightly folded metasediments except where it encounters friable slatey and phyllitic beds. In those reaches the gully is very straight indeed. While Nerrimunga's southern tributary, Nadgigomar Creek, follows the regional strike for much of its course, it fails to meander when crossing the strike in a number of places. But in this case weathering history rather than inherent rock characteristics is of prime importance. Nadgigomar Creek drains part of the high plain which was deeply weathered in early

Tertiary times. Detailed mapping (YOUNG, 1974) of massive silcretes formed on the sandy and gravelly floor of this ancient valley showed that it was originally of low sinuosity, resembling the *flachmuldental* or "tray-shaped" valleys reported from many tropical areas. Low sinuosity was maintained after incision into the relict profile, for once the stream penetrated the silcrete it encountered the intensely rotted material of the pallid zone. Although lineations are beautifully preserved in this zone, the weathered rock crumbles at hand pressure and exerts little influence on stream alignment.

Although rock resistance and the selective erosion of fractures were both recognised in early studies of valley meanders, their combined effect on channels was virtually ignored. Instead, as TROLL (1954) emphasized, meanders were too often classified either as lithologically controlled *(Gesteinmäander)* or as structually controlled *(Kluftmäander)*. This distinction has little to commend it, for, in light of the field evidence presented here, the selective erosion of lineations seems very much dependent on rock resistance.

3. Seepage

Not all streams cutting resistant, well-jointed outcrops meander. Bedrock windings are noticeably absent from very large areas on the sandstone plateaux of the eastern part of the region. These areas are drained by irregular swampy depressions strikingly similar to the *dellen* described by SCHMITTENHENNER (1925). The depressions form simple branching patterns, and SCHMITTHENNER'S comment on the characteristically low sinuosity of *dellen* („Krümmungen und vor allem Windungen, wie sie die Flüsse und Täler zeigen, fehlen") applies equally well to the Shoalhaven swamps as to the German cases he cited.

It does not seem that these shallow, swampy upland valleys are primarily stream-cut features, but rather are seepage hollows formed primarily by weathering of the sandstone. Nor do the constraints of intersecting joint patterns, so marked elsewhere on the Shoalhaven sandstones, play a significant role in their formation. Because of the generally high permeability of the sandstone, water can seep downslope on a broad front and is not limited to a path that winds through the junctions of a few major fractures. Jointing asserts itself once dominantly linear flow is established, for streams issuing from the lower ends of the swamps show a high degree of structural control.

4. Gradient

Channels meandering in bedrock are often steep, far steeper in many cases than their alluvial counterparts. But, for streams of given size, there seem to be critical gradients beyond which meanders are rarely found. What is more, in the Shoalhaven region these critical gradients are consistently higher for channels in rocks of high dip than for those in rocks of low dip

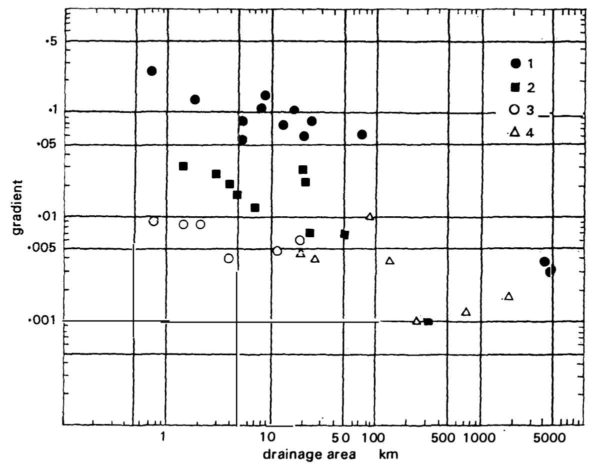

Figure 6: Gradient per unit drainage area of meandering channels. 1– Folded bedrock 2– Gently-dipping bedrock 3– Alluvium (Shoalhaven catchment) 4– Alluvium (after Leopold and Wolman 1957).

Data in Figure 6 show that, for channels of comparable sinuosity and drainage area, maximum gradients in folded rocks may exceed those in flat-lying beds by a factor of three, and those in alluvium by a factor of ten or more. Differences between alluvial and bedrock meanders can be readily explained in terms of resistance to erosion, while the differences between the two types of rock is due to variations in retreat of nickpoints. Rapid undercutting and collapse of joint-bounded blocks drives resistant outcrops heardward through gently-dipping rock, destroying lineations transverse to the bed, and thereby suppressing meandering. As beds with steep dips are generally worn down rather than undercut, lineations in them can be maintained at relatively constant positions and meanders developed at high gradients. The upper limit of meandering in the latter case, at least for low order streams, seems to be determined by the movement of debris slides or avalanches down the channel during high rainfalls. HACK and GOODLETT (1960) and also PAIN (1968) have noted in other areas that "chute" avalanches tend to trim the sides of small channels, and thus presumably counteract any meandering tendency. Concentrations at gully mouths of boulders far too large to be moved by stream flow leave little doubt that such avalanches are widespread here.

5. Some anomalies

The distribution of incised meanders in the Shoalhaven catchment clearly demonstrates that rock characteristics do play a significant role in the development of sinuous stream courses, though that role is obviously more complex than is indicated in most previous studies. But despite its greater complexity, the scheme proposed here cannot account for all of the bedrock meanders in the catchment. East of Tallong, for instance, the Shoalhaven gorge (Fig. 1, D 2) cuts obliquely across the regional strike of tightly folded beds, including numerous massive quartzite outcrops, yet its course is remarkable straight.

It is easy in places like the Tallong area to sympathise with BIROT's general dismissal of structure but his decision was too hasty. On streams like the Kangaroo River, Brogers, Nerrimunga and Jacqua Creeks, and farther downstream on the Shoalhaven itself, meanders do follow major fractures through resistant outcrops; and this is no mere chance relationship. Moreover, it can now be seen why meanders are rarely found in the swampy upland valleys of the plateaux or in steep gorges and gullies: critical gradients for meandering even vary with rock type. Clearly, the development of the great majority of entrenched meanders in the Shoalhaven region was not autonomous with regard to structure. Nonetheless, it may still be argued that, regardless of geological influences, bedrock meanders tend to be geometrically similar to their alluvial counterparts. In short, the structural relationships outlined here may be "conditioning" rather than "controlling" (cf. GREGORY and MOORE, 1931).

III. Meander Dimensions and Form

If structure and lithology are at best "conditioning" factors, the systematic trends observed in the dimensions and morphology of meanders in alluvium ought to hold equally well on bedrock bends. For instance, the very close adjustment of alluvial meander wavelengths to bankfull discharge (DURY, 1976) should also be detectable in an analysis of bedrock meanders. So too should a regular pool spacing, a mean wavelength-to-width ratio of about 11 (DURY, 1976 and in press), a mean radius of curvature-to-width ratio of approximately 2 (BAGNOLD, 1960; HICKIN, 1974), and a tendency for meanders to describe curves of minimum work (LANGBEIN and LEOPOLD, 1966). Claims that bedrock meanders do in fact have these attributes have certainly been put forward, but, apart from the data on downstream trends in wavelength and on wavelength-to-width ratios amassed by DURY (1964a; 1976; and in press), they are supported more by inference than by evidence. DURY has reported pools beneath alluvium at bends in many valleys (see also SCHUMM and SHEPHERD, 1973), but systematic pool development in bedrock has been demonstrated for only two streams, the Colorado in Arizona (LEOPOLD, 1969) and the Hawkesbury in New South Wales (DURY, 1966, 1970). Prior to this study of the Shoalhaven region no serious attempt had been made to determine whether the relationship between channel width and meander radius which seems to underlie the development of alluvial bends also holds for bedrock meanders. Furthermore, while LANGBEIN and LEOPOLD argued that sine-generated curves of minimum work should be developed best in solid rock, they gave only three supporting examples. PAGE (1972) and I (YOUNG, 1970) subsequently found other examples in eastern Australia, but our studies were limited largely to valley sections of low gradient on gently-dipping strata. In short, little is known of the degree to which meander form and dimensions vary with changes in lithology and structure.

1. Downstream changes in dimensions

As there is clear evidence of channel reduction to an underfit condition in parts of the Shoalhaven catchment, wavelength of the bedrock meanders cannot be directly related to bankfull discharge. As present day discharges for all cases in question increase downstream, there is no reason to suspect that prior discharges did otherwise, and thus drainage area can be used as a surrogate for stream flow. However, marked contrasts in runoff over the catchment (Fig. 1) prompts extreme caution in comparing data from different tributaries. It seems unwise to include meanders from the Kangaroo and upper Shoalhaven River in a single analysis when runoff per km.^{2} for one is now five times greater than for the other. Each subcatchment is therefore analysed separately; rank correlation rather than parametric tests is used because of the small sample sizes. Even when discharges is constant, wavelength will progressively decrease as a meander tightens towards the cutoff stage, and while this is probably of little significance in samples that are large, variable sinuosity could markedly influence wavelength trends in those that are small. Thus downstream trends in the curved channel length around meanders are compared to those for wavelength.

Table 1: Downstream Trends in Meander Dimensions

Stream	No. Meanders	Rank Correlation Coefficient	
		Wavelength/ Drainage Area	Meander Channel Length/ Drainage Area
Brogers Cr. – Kangaroo R.	12	+0.88*	+0.88*
Ettrema Cr.	15	+0.69*	+0.79*
Shoalhaven R.	10	+0.30	+0.72*
Tim's Gully	19	+0.63*	+0.65*
Bundundah Cr.	8	0.00	+0.69
Jacqua Cr.	13	−0.64*	−0.63*
Nerrimunga-Budgong Cr.	25	+0.17	−0.21
Tryer's Gorge	10	−0.07	+0.47
First, Middle, & Third Curradux & Sampling Yard Crs.	36	+0.14	+0.13

*) Significant at 95% confidence level or greater. All symmetrical bends with sinuosity >1.5 included.

Although they vary greatly from one stream to another, downstream trends in wavelength over the Shoalhaven catchment give little support to claims that the dimensions of bedrock meanders increase proportionally with discharge. Correlation coefficients for more than half the cases lie well below +0.5 (Table 1). Only the Kangaroo River-Broger's Creek system displays a highly consistent downstream increase in wavelength (+0.88; 99% confidence level), though increases significant at the 99% level also occur on Ettrema Creek (+0.69) and Tim's Gully (+0.63). In contrast to these three streams, however, there is a significant downstream decrease in meander wavelength on Jacqua Creek (−0.64; 95% confidence level).

Downstream trends in curved channel length are more consistent than are those for wavelength. Over half of the cases have coefficients greater than +0.6, and coefficients for some streams are very much greater than those obtained for wavelength data. Yet only one of these improved coefficients, that for the Shoalhaven River itself (+0.72), is significant at the 95% level.

Regardless of which index is used, geological factors can hardly be relegated to a "conditioning" role on Jacqua, Nerrimunga and the Curradux Creeks. Discharge increases downstream in all three cases, but the first shows a distinct downstream decrease in meander dimensions, while the other two shown no consistent trends at all. The most cursory examinations of airphotos reveals the close adjustment of these channels to lineations in the folded rocks through which they flow. Also field evidence from Nerrimunga Creek quickly rules out the alternative hypothesis that relates meander size to calibre of bedload (cf. HACK, 1966). In this instance the usual downstream decrease of calibre is reversed, for the load changes from clay to sand and then cobbles as streams of the Nerrimunga system flow from the pallid zones of deep-weathering profiles into more sound rock.

Comparison of data from the Shoalhaven region with those available elsewhere is obviously needed, for 6 of the 9 streams studied here, comprising 70% of the 148 meanders dealt with, show either a significant downstream decrease in wavelength or no consistent trend at all. DURY (1958; 1964a) lists wavelengths for ten individual streams with at least 8 bends each (this was the minimum number for streams in the Shoalhaven study). All of his examples show very consistent downstream increases in wavelength. When the Shoalhaven date are added to DURY's, 13 of the 19 streams, comprising 68% of a total 316 meanders, have highly consistent downstream increases in wavelength. The dominance of stream flow in these 13 cases seems beyond doubt, but, even when allowance is made for the possible inclusion of meanders formed under varying hydrologic regimes, the significance of geological factors in the remaining streams can hardly be denied.

2. *Wavelength, width and radius of curvature*

Average trends for my data on ratios among wavelength, width and radius of curvature for bedrock meanders in the Shoalhaven catchment are to be published elsewhere (DURY, in press) and are not repeated in detail here. It suffices to note that average values for the catchment are insignificantly different from those observed on alluvial meanders. Attention is directed instead to variations on and among individual streams, some of which have thus far seemed to exemplify hydrologic control and others geological constraint.

Mean wavelength-to-width ratios for bedrock meanders on most streams in the catchment correspond very closely to the mean of 11 obtained from alluvial meanders. Nonetheless, the very tight bends of the Shoalhaven River do deviate markedly from it, and while this deviation may in part be due to the very great widths recorded in the tidal reaches, the close adjustment to structure described earlier seems to be the prime cause. Furthermore, the very considerable scatter of values for Tim's Gully, Nerrimunga Creek and Jacqua Creek cautions against placing too much reliance on average relationships. Certainly, many meanders on these three streams bear little similarity to the simple plan geometry observed in alluvium.

Regardless of their wavelength-to-width ratios, the bedrock meanders of streams studied here closely approximate the mean radius of curvature-to-width ratios seen in alluvial bends. Work by Hickin has left little doubt that adjustment towards a radius-width

Table 2: Dimensionless Ratios for Bedrock Meanders

Stream	Wavelength/Width				Radius of Curvature/Width		
	No. Meanders	Range	Mean	Standard Deviation	Range	Mean	Standard Deviation
Kangaroo-Brogers	9	7.3 –14.9	11.7	2.72	1.5–4.98	2.56	1.14
Shoalhaven	9	3.68– 7.45	5.98	1.77	1.5–2.9	2.24	0.57
Tim's Gully	19	6.3 –17.5	11.9	3.09	1.3–4.0	2.6	0.62
Nerrimunga	15	4.5 –20.2	10.2	3.89	1.6–3.8	2.4	0.84
Jacqua	13	5.5 –18.2	10.5	4.35	1.2–3.3	1.9	0.59

ratio of about 2 underlies the development of meanders in alluvium, while studies of flow through pipes and open flume channels (BAGNOLD, 1960, HICKIN, 1974) indicates that resistance due to curvature increases very greatly for lesser values. HICKIN (1974) was apparently correct in predicting that radius-to-width ratios for many bedrock meanders would be similar to those in alluvium, for the mean of 2.35 and the standard deviation of 0.79 obtained from 65 bedrock bends in this catchment correspond closely to the comparable values of 2.11 and 0.13 that he obtained from 50 alluvial bends on the Beatton River. Yet closer inspection reveals one important difference between these two sets of meanders; only 14% of the Beatton River bends have ratios tighter than the critical value of 2, but 32% of the bends in the Shoalhaven catchment fall below this value. Indeed, the mean values for Jacqua Creek falls virtually at the lower extreme of those recorded on the Beatton. Structural constraints in this case have maintained far tighter bends than are apparently found in alluvium.

3. Sine-generated curvature

According to LANGBEIN and LEOPOLD (1966), not only the ratio of radius-to-width, but also the total curvature of meanders tends towards a reduction of energy loss. This condition, they argue, is most closely approximated by sine-generated curves defined by the simplified formula

$$\phi = \omega \sin \frac{s}{M} 360°$$

in which ϕ is the angular deflection from the mean downvalley direction at a given distance (s) along the total meander length (M), and ω is the maximum angular deviation from the downvalley direction. They also point out that variations in energy loss due to bedform will be reduced when pools are located on bends, and shallows lie on the relatively straight meander arms. I have shown previously (YOUNG, 1970) that meanders on Broger's Creek and the Kangaroo correspond very closely to sine-generated curves. In fact, three of the Broger's Creek bends correspond more closely to the theoretical form than do the examples given by LANGBEIN and LEOPOLD. Although the modern channel of this creek can be classified as an Osage-type underfit (cf. DURY, 1964a), with 4 or 5 pools on each meander, the cobble bars between them are superimposed on bedrock undulations of much greater magnitude. Long reaches on either side of the cabble bars are remarkably free of sediment, and a survey of them, from which trends in the valley floor beneath the bars were estimated, shows that depressions in the bedrock floor occur only on the extremities of bends. Before its width and pool spacing were reduced to their present size by a climatically induced decrease in the magnitude of channel forming discharge, Broger's Creek conformed very closely indeed to that model of meandering channels which is "the most probable result of the processes that on the one hand tend to eliminate concentrations of energy loss and on the other tend to reduce the total energy loss to a minimum rate" (LEOPOLD and LANGBEIN, 1966). Both the form and the orderly downstream increase in the size of meanders on Broger's Creek and the Kangaroo River are identical to those encountered in alluvial channels. Nonetheless the abrupt changes in sinuosity at major lithological boundaries, and the orientation of much of this channel along interesecting joint planes cannot be dismissed as being merely coincidental, or even be relegated to a minor role. It seems that here is an instance in which bedrock characteristics have *reinforced* rather than constrained hydrological tendencies towards meandering.

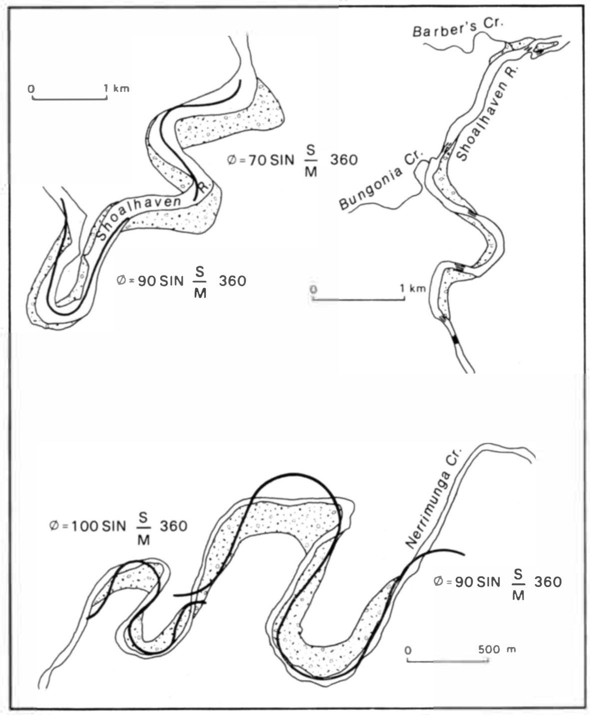

Figure 7: Examples of meander morphology in the Shoalhaven catchment.

A – Comparison of meanders and sine-generated curves near Nowra

B – Pool spacing in the Shoalhaven Gorge south of Tallong

C – Structural distortion of meanders on Nerrimunga Creek; comparable sine-generated curves shown.

Similar conclusions can be drawn for the Shoalhaven River near Nowra. Close adjustment to jointing is again obvious enough, but so is the similarity of channel planimetry to sine-generated curves with a maximum deflection of 90° in one case and 70° in the other (Fig. 7). Configuration of the channel floor here is still unknown because of the considerable estuarine fill. However, several of the Shoalhaven bends above Tallong which also describe sine-generated curves do have contemporary channel bedforms in keeping with the minimum variance model; pools only occur on the bends and active cobble bars are limited to meander inflections (Fig. 7). There can be do doubt of hydrologic dominance in the latter case, for the channel windings show no adjustment to structure whatsoever.

Irregularities often are "averaged out and only the regular form is preserved" (LANGBEIN and LEOPOLD, 1966); but often they are not, and systematic deviations from sine-generated curves are maintained. Meanders with exceptionally straight arms are encountered again and again in the Shoalhaven catchment (Fig. 7), especially on small streams crossing the strike of folded rocks. These observations raise no real difficulties for the Theory of Minimum Variance, merely indicating that LANGBEIN and LEOPOLD underestimated the persistence of lineative influences on the planimetric form of bedrock meanders. Surprisingly, the main challenge to the theory arising in this study comes from a stream whose planimetric form seems quite normal.

The general curvature of meanders on Tim's Gully resembles that encountered on the Broger's-Kangaroo system; some meanders have fairly straight and structurally-guided arms, but most conform quite well to sine-generated curves. Once more, it seems, angular bends initiated along bedrock lineations have been gradually smoothed during incision, and both the total energy loss and variations in the rate of loss reduced. An entirely different picture emerges from study of the gully's bedforms. Instead of an orderly sequence of pools and shallows, many reaches have chaotic arrays of rapids, falls and plunge pools. Although this remote valley could not be studied during high flood stages, one can still safely conclude that variation in rates of energy loss are very different from those encountered in meandering alluvial channels. Rapid acceleration over numerous 3 to 4 m. drops, and especially over the 40 m. of Sparke's Falls which lies in the centre of the meandering tract, together with high spill resistance in plunge pools, must lead to enormous differences in energy consumption. Meandering in Tim's Gully cannot be the result of a gradual increase in channel curvature at pools as the stream progressively adjusts towards a more uniform rate of energy expenditure; there are no regularly spaced pools here. Nor, given firstly the extremely tight folding with near vertical dips in the metasediments of the gully and secondly the close adjustment of the channel to those structures, can the meandering pattern be explained by inheritance from an earlier course of lower gradient.

Tim's Gully seems the very antithesis of the streams described earlier in this section, for it provides indisputable evidence of the development of meanders in conditions completely different from those seen in alluvial channels. Geological constraints cannot be relegated to a minor role here. Yet one paradox remains. Despite the chaotic breaks in gradient over much of the course, meander planimetry and downstream changes in dimensions are regular (Table I). Most curious of all is the extremely tight clustering around a mean radius of curvature-to-width ratio of 2.6, a value very close to that determined for alluvial channels. It seems that the planimetric form of meanders here developed independently of bedforms.

Tim's Gully is by no means exceptional in this region. Chaotic bedforms occur on meandering reaches of Long Creek, Jerrara Creek, Washed Away Creek and probably Weirimunga Creek (Fig. 1, C 2–4). Relatively flat bedrock floors (without regularly spaced pools) under a veneer of clastic load are found on the lower reaches of Tryer's Gorge, Barber's Creek, Ottawa Creek and Beck's Gully (Fig. 1, C 2). Nonetheless larger streams like Yalwal, Bundundah, Ettrema and Danjerra Creeks have well developed pool and shallow sequences, though the curvature of their bends often displays structural influences.

IV. Conclusions

Application of advances made in research on alluvial meanders has undoubtedly freed the study of bedrock meanders from the isolation and apparent sterility that were so characteristic of it only a few decades ago. Unfortunately, these advances have eclipsed not only the hypothesis of meander inheritance, but also much valuable work on the relationship between channel sinuosity and bedrock characteristics. Evidence from the Shoalhaven catchment leaves little doubt that bedrock influences have been underestimated in the dominantly hydrologic models now in vogue. Their role seems no less important than that of variations in floodplain materials so well documented in works on alluvial channels. Analysis of the distribution of meanders in the Shoalhaven catchment both confirms many earlier observations on the role of bedrock and allows that role to be more precisely defined.

a. As noted by WAGNER (1919) and BLACHE (1940), incised meanders occur most frequently in relatively resistant rocks. But resistance depends on more than just the inherent characteristics of rock noted in those studies. Where stream incision outstrips weathering meanders can develop in silty rocks, though they will generally not do so in the thoroughly rotted sandstones of duricrusted deep-weathering profiles.

b. Many incised meanders seem to be formed by the preferential erosion of fractures in resistant outcrops (HETTNER, 1921; COLE, 1930; JUDSON and ANDERSON, 1955; HACK and YOUNG, 1950; BLANK, 1970). This is certainly true for the great majority of meanders in the Shoalhaven catchment, though there are conditions under which meanders will not form in hard well-jointed outcrops.

c. Undercutting of gently-inclined beds in steep valley reaches tends to suppress meandering. Meanders will develop on much higher slopes in steeplydipping rocks that are not readily undercut, but their development even in such favourable settings is apparently limited by the erosive effects of periodic mass movement down small steep gullies.

d. Meandering bedrock channels are rarely found near drainage divides on the undulating plateaux in the eastern part of the Shoalhaven catchment. In this case the suppression of meandering seems due to the dominance of seepage and irregular surface flow through dense swamp vegetation.

e. Downstream trends in meander dimensions for the Shoalhaven region are very diverse, with some streams showing consistent increase and others decrease. The diversity suggest a continuum of causal relationships ranging from the dominance of hydrologic factors to that of geologic factors, with most cases falling into some intermediate position.

f. Similar conclusions can be drawn from the morphologies of the Shoalhaven meanders. Although average trends for the area are virtually identical with the mean wavelength-to-width and radius of curvature-to-width ratios observed on many alluvial channels, some streams diverge significantly from these values. Tests of the Theory of Minimum Variance proposed for meandering in general met with varied success in this region. Some bedrock meanders do closely approximate sine-generated curves and also have an appropriate pool spacing, but others, which display strong structural controls on meander planimetry and have very irregular bedforms, seem at odds with the theory.

TROLL's warning against the pursuit of single-cause explanations of valley meanders was not unwarranted, for the literature reviewed and the field evidence presented here show the origins of such meanders to be very complex. Some bear the imprint of the singularities of the streams which cut them, while others bear primarily that of the rocks into which they are carved.

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DIE AGRARSTRUKTUR DER BUNDESREPUBLIK DEUTSCHLAND

Ansätze zu einer regionalen Typologie

Mit 6 Abbildungen (z. T. als Beilage VI) und 5 Tabellen

HANS-DIETER LAUX und GÜNTER THIEME

Summary: The Agrarian Structure of the Federal Republic of Germany

The agrarian structure of the Federal Republic of Germany is characterized by considerable regional disparities. It is the aim of this contribution to describe and analyse these regional differences through a typology on the basis of a sample of 612 communities. Proceeding from the hypothesis that the agrarian structure of any region is determined not only by its agricultural situation but also by its socio-economic situation in general, in the first step of the investigation 46 variables were subjected to factor analysis. These variables are associated with the following topics. Agriculture: farm size, labour supply, socio-economic structure of holdings, extent of mechanization, land use and livestock orientation; non-agricultural sector: degree of urbanization, non-agricultural labour supply, and distance to urban centres.

Eight factors were extracted altogether, explaining 83.69% of the total variance. Factor 1 is to be interpreted as the factor of the socio-economic structure of the communities, factors 2 and 3 each represent different aspects of the structure of agricultural holdings, factor 2 stressing the contrast between small and large property, factor 3 describing the proportion of medium-sized holdings. The intensity of labour input in agriculture is characterized by factor 6, whereas land use orientation, non-agricultural labour supply, and the distance to urban centres are successively represented by factors 4, 5, and 7.

In a second step the typology of the agrarian structure was carried out by means of distance grouping. Being the most important dimensions, factors 1, 2, 3, and 6 were selected for the grouping process. The results of this multidimensional classification are shown in table 4.

The spatial distribution of the structural types (cf. fig. 6, Suppl. VI) shows clear regional differences between Northern Germany (Schleswig-Holstein, Lower Saxony, North Rhine-Westphalia), South West Germany (Hesse, Rhineland-Palatinate, Saar, Baden-Württemberg), and Bavaria. In particular the following types show a striking regional concentration: groups 1 and 2 with an overall favourable agrarian structure are almost exclusively to be found in Northern Germany, whereas group 6, which faces grave agricultural and socio-economic problems, is a typically Bavarian phenomenon. On the other hand, groups 7 and 8, characterized by small holdings and a high proportion of part-time farming are mostly concentrated in the gavelkind areas of South West Germany.

I. Fragestellung

Die Situation der Landwirtschaft in der Bundesrepublik Deutschland ist neben einem generellen Produktivitäts- und Einkommensrückstand gegenüber den Wirtschaftsbereichen des sekundären und tertiären Sektors (vgl. *Agrarbericht 1977,* Textband S. 19) insbesondere durch erhebliche Disparitäten innersektoraler Art ausgezeichnet, die sich in zweierlei Form äußern: zum einen auf lokaler Ebene als mehr oder weniger starke Einkommensdifferenzen zwischen den Betrieben bzw. Produzenten an ein und demselben Standort und zum anderen in regionalem Maßstab als Disproportionalitäten zwischen den verschiedenen Produktionsstandorten bzw. Teilräumen der Bundesrepublik Deutschland. Diese regionalen Produktivitäts- und Einkommensunterschiede aber sind zugleich Ausdruck einer jeweils spezifischen räumlichen Verteilung und Kombination der verschiedenen natürlichen,