Redeposition and Slumping in the Cretaceo-Tertiary Strata of S.E. Wellington

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Abstract

THE stratigraphy of lower Tertiary sediments in the Opouawe area is described and conditions of deposition are considered in relation to the hypothesis of slumping and redeposition Northward facies change of the Amuri Limestone into redeposited argillites is discussed, and it is concluded that the limestone also is, at least in part, of redeposited origin Consideration is given to the effects of contemporaneous growth and submarine erosion of folds, and slump structures are regarded as tectonic erosional phenomena and as indices of orogenic movement. Slump structures, including exceptional sedimentary dykes, are described and their modes of formation are interpreted in terms of bedding-plane slip.

INTRODUCTION

RECENT works by Kuenen, Natland, Gould, and others on the nature of turbidity currents and origin of graded sediments must influence geological thought to an increasing degree. The comparatively recent but already widely accepted ideas of these writers on geosynclinal sedimentation have a special reference to the young mobile belts which surround the Pacific Ocean. In New Zealand each of several orogenies has resulted in accelerated denudation and rapid deposition, slumping and redeposition from turbid flows of sediments. These processes have resulted in the formation of many greywackes in the Upper Paleozoic and Trias Jura geosynclines and in certain of the indurated strata of the Cretaceo-Tertiary troughs of the North Island.

Attention has been drawn to the subject by Cotton (1951) who gives a résumé of the literature and principles of redeposition and quotes several examples of graded beds in rhythmic sequences. In view of the recency of development of thought, it is natural that the subject of redeposition has not previously been discussed as such, but it is surprising to find, despite the wealth of examples in New Zealand, that the related study of slump structures has received only passing attention. This is probably because the tectonic structures of this intensely folded region tend to mask slump folds. Yet it may well be that many of the larger folds of New Zealand greywackes, hitherto regarded as orogenic, are themselves of slump-tectonic origin.

Slump folding has, however, often been recognised, and illustrations and descriptions have been presented by Henderson and Ongley (1923, p. 47), Grange (1927, Pl. 2, p. 29), Searle (1945, Pl. 2, p. 59), Marwick (1946, Pls. 19 and 20), Coombs (1950, p. 431), Brodie (1953), and Brothers (1954, p. 529). The most outstanding example of slump folding is perhaps that photographed by Ongley and presented by Hills (1953, frontispiece). Several examples of sedimentary dykes attributable to slump tension and concomitant intrusion are described by Battey (1949, Pl. 48, p. 440). Taylor (1930, p. 308) also describes several examples of sedimentary dykes which he considers might possibly be caused by slumping, and there are probably many similar incidental descriptions of slumping in the literature of New Zealand. So far as the writers are aware, the only work in this country which has had the study of slumping as its principle aim is by Kuenen, and it is significant that one of Kuenen's (1950, p 467) Auckland examples was earlier thought to be tectonic and erosive by Turner and Bartrum (1929, Pl. 3). This example illustrates very well

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the changing views on the subject, for Bartrum (see Searle, 1945, p. 62) was prepared in 1944 to revise his first idea and to consider that the "unconformity" might be due to interstratal sliding. With this background, and with the emphasis of recent researches in mind, it is thought opportune to present the following study of a redeposited sequence and of the slump structures associated with it.

On the east coast of the North Island, 40 miles east-south-east of Wellington, lies Te Kau Kau Point, at the mouth of the Opouawe River, and seven miles north of that, along the Coast Range, is the mouth of the Awhea River. Between the two rivers Cretaceo-Tertiary sediments have been folded into an anticline, here named the Coast Range Anticline, with its axis along the coast, and it is the sedimentary history and contemporaneous structures of the formations comprising this anticline which provide the substance of this article. One of us (J.B.W., 1955) has studied this and adjacent areas in detail in the course of field work for an M.Sc. thesis, and the accompanying map, stratigraphy, and most photographs are the outcome of that work. Analysis and syntheses of paleogeography and the outline of slumping are the result of joint effort. The thesis of sheet flowage and detailed interpretations of slumping, along with the presentation, are by Bradley.

STRATIGRAPHY

The Opouawe-Awhea area has attracted little and only passing attention in the past. Crawford (1868, p. 305) speaks of possible Mesozoic limestones and sandstones of the east coast and (1869, p. 351) describes them as being "traversed" by "reefs of diallage" (probably the greensand dykes of this account). McKay (1879, p. 79), visited the limestone at White Rock, identified it as "beyond all doubt the Amuri limestone", but added little more. King (1930, p. 508) also visited the area, but apart from a statement that the limestone is "certainly Notocene", description is casual. The present account gives the first close description of the stratigraphy,

TABLE I

STRATIGRAPHIC TABLE

NEW ZEALAND		FORMATIONS	EUROPE
Series	Stages	Pukemuri Str. Te Kau Kau Pt.	Divisions
ARNOLD	*Bortonian*	*Kandahar Fmn.*	*Mid. EOCENE*
DANNEVIRKE	*Heretaungan*	*Pukemuri Siltstn.*	*Lwr. EOCENE*
	Mangaorapan	*Awheaiti Fmn.*	
	Waipawan	*Mungaroa Lmst.*	*PALEOCENE*
MATA	*Teurian*	*Awhea Fmn.*	*DANIAN*
		Manurewa Fmn.	*MAESTRICHTIAN*
	Piripauan *Up.*	*Whangai Shale*	
	Piripauan *Lr*	*Piripauan Sandstone*	*SENONIAN*

but this is not in detail, for the intention is to concentrate on broad principles and conditions of sedimentation.

Table I sets out the formations present in the area, and the map, Fig. 1, shows their distribution. The column calls for little comment except to point out that the limestones of the Manurewa and Mungaroa formations possibly represent the thin northward interdigitations of the lowest part of the Amuri and Weka Pass limestones of Marlborough (Wellman, 1955).

In most formations macrofossils are scarce, and earlier datings by Waterhouse (1955) have been revised or amended by Mr. N. de B. Hornibrook, of the N.Z. Geol. Survey, who, along with Waterhouse, has collected from all formations and has identified microfaunas. Mr. Hornibrook's work is specially acknowledged, for, although formations are well exposed and the major structure of the area is clear, facies changes are great and precise identification of ages is essential for correlation outside the area.

Piripauan Sandstone.

The oldest exposed beds, in the core of the anticline from Pukemuri Stream to Oroi Stream, are chiefly hard, pale-grey, glauconitic sandstones with subordinate igneous conglomerates, greensands, white siltstones, and black mudstones with plant fragments. The whole closely resembles the Piripauan at Amuri Bluff, and the poorly preserved macrofossils scattered through the formation include *Syncyclonema* aff. *membranaceus* (Nilsson), *Inoceramus australis* (Woods), belemnites, and reptile bones which suggest a Piripauan age. The assemblage of beds, which is not exposed to any thickness, is not defined here as a formation but is loosely referred to as "Piripauan sandstone".

Whangai Formation.

Lying conformably above the Piripauan sandstone and extending south for some miles from near Manurewa Point to near Te Kau Kau Point are very hard but often brittle and rather silty argillites. The rocks, varying from dark grey-blue when fresh to reddish-brown or buff when weathered, resemble the brown and grey argillite underlying the flint beds at Amuri Bluff, and are akin to the Whangai Shale of Wellman (1955). Apart from some minor shaly partings the rocks lack the fissility implied by the term "shale" but are massive and have the irregular and sub-conchoidal fracture of mudstones. Their brittleness is often attributable to an intimate veining with chalcedonic silica, and their hardness is probably due to a diffuse silicification, which in extreme cases has formed large flinty nodules and concretions. The formation is not quite homogeneous but contains small lenses or pockets of greensand, one of which is seen near the top of the formation in the Pukemuri Stream section, the type section for this area. Several samples were collected from the formation, but no useful microfossils were extracted. The formation lies between the Lower Piripauan and some horizon within the Teurian, and may include part of the Upper Piripauan. As the Whangai Formation on the East Coast embraces the Upper Piripauan and Teurian (Mr. H. W. Wellman, pers. comm.), it is probable that the formation here is correctly identified.

Manurewa Formation.

This compound formation is well exposed in the shore platform at and around Manurewa Point, and is defined as a sequence about 100ft thick of limestone, greensand, and marls of Teurian age lying between the Whangai and Awhea formations. The Manurewa Formation is most complex and the character which distinguishes it is not so much its constancy of lithology as its variability. To illustrate this variability, descriptions are drawn from the sections on the Pukemuri Stream and along the shore at Manurewa Point. In the former and type section two members are found:—

(1) A lower limestone member which is 12ft thick and which consists of thin calcareous beds, most of which grade up from coarse pebbly sandstones or glauconitic mudstones into pure porcellanous limestone. The grading implies that the limestone is a redeposited sediment, and the sharp and channelled contact of the formation on the underlying Whangai Formation supports the suggestion.

(2) An upper greensand member, which is about 40ft thick, varies in habit from massive through streaky to laminated, and contains abundant pyrite nodules. The base of the greensand is channelled into the underlying strata.

At Manurewa Point, the limestone member is eroded right through, so that the greensand rests in broad grooves in the Whangai Formation. It appears that the greensand beds were deposited more or less contemporaneously with the erosion of the limestone. Around Manurewa Point there is another variation in lithology, for a third number consisting of glauconitic marl some 40ft thick occurs sporadically below the limestone. This graded marl, riddled with worm tubes, consists of calcareous glauconitic mudstones that have apparently been redeposited (this implies constancy over a wide area) and then eroded to give their present irregular distribution.

It will be observed that each of the members just described might qualify as an individual formation, for any formation should ideally be a rock unit of more or less constant composition, and should represent a period of more or less continuous deposition. Where erosion and deposition are contemporaneous, as in this case, the only convenient way of dealing with the various beds and discontinuities in the field has been to group them together. The age of the whole formation is clearly Teurian as the marls (N 168/547, = F9595)* contain *Rzehakina epigona* (Rzehak), *Dorothia biformis* Finlay and *Marssonella* cf. *oxycona* (Reuss); and because the succeeding formation is in part Teurian. The absence of any appreciable time gap is reasonably well demonstrated and the field classification of the beds as one formation is endorsed.

Awhea Formation.

The difficulty in defining the Manurewa Formation is paralleled in the Awhea and two succeeding formations, for within a small area there is a marked facies change and the three arenaceous and argillaceous formations pass southwards into one thick limestone. This passage, which applies to individual redeposited beds as well as to formations, allows of no simple treatment, and the divisions described are therefore arbitrary and of local application only.

Thus the Awhea Formation is defined as an 800ft thick succession of alternating blue-grey sandstones and black mudstones of Teurian to Heretaungan age extensively exposed along the Awhea River. In the type section in Pukemuri Stream the formation is conformable with and grades into both the underlying and overlying formations. The sharp and regular alterations of the formation consist of 3in to 6in beds of fine-grained calcareous sandstone and 12in to 18in layers of dark grey clay. The sandstone bands are uniform and ungraded, their top surfaces are clear cut and channelled, and they extend over hundreds of feet of outcrop without obvious lateral variation. In a vertical sense the thicknesses of succeeding beds and rhythms are constant or show a gradual variation so that a given height of section will consist of only one type of rhythm or of slowly changing kinds. Interruptions by greensand or fine conglomerate bands are few and are clearly aberrant.

Individual beds comprising the Awhea Formation are in general thinnest to the north, and are sandy or glauconitic in that direction, but they thicken and become more calcareous towards the south, so that the sandy beds interdigitate with increasing numbers of limestone bands, and farthest south, at Mungaroa Hill, the upper portion of the Awhea Formation is represented by about 300ft of limestone As there is a

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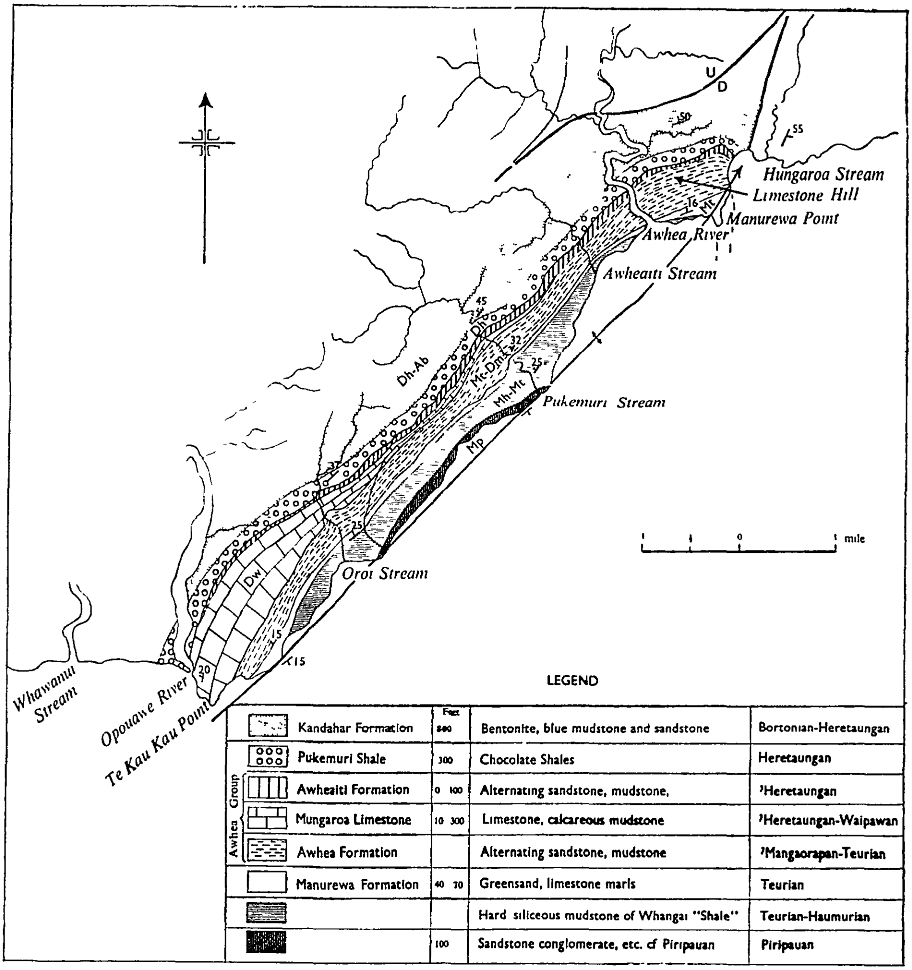
* Numbers refer to respective Map Sheet, Sheet fossil number, and Microfossil collection number in the New Zealand Geological Survey.

gradation from coarse to fine sediments in that direction, it appears that any postulated turbidity currents depositing the Awhea Formation were derived from the north. Microfaunal datings for the formation are available from the Pukemuri Stream section, and the specimens listed below are located stratigraphically relative to the Manurewa greensand at the base of the formation, N.168/556 = F9697, 50ft above the greensand; *Marssonella* cf. *oxycona, Matanzia simulans* Finlay; N168/560 = F9699, 28ft above the greensand *Matanzia simulans, Bolivinopsis spectabilis* (Gryzbowski); N168/561 = F9700 = 750ft above the greensand,*Rzehakina epigona, Matanzia simulans, Nuttallides* sp., ? *Pseudovalvulineria infrafossa* (Finlay). The above assemblage indicates a Teurian age, and the succeeding 200ft of strata contain a few fossils which suggest a Lower Dannevirke age. Mr. N. de B. Hornibrook has commented (pers. comm.) that the Awhea and similar formations are surprisingly poor in Foraminifera. (There is no substantial hiatus or unconformity between the Cretaceous and Tertiary successions.)



LEGEND

	Feet		
▨ Kandahar Formation	800	Bentonite, blue mudstone and sandstone	Bortonian-Heretaungan
○ Pukemuri Shale	300	Chocolate Shales	Heretaungan
Awhea Group: ▥ Awheaiti Formation	0 100	Alternating sandstone, mudstone,	?Heretaungan
Awhea Group: ▦ Mungaroa Limestone	10 300	Limestone, calcareous mudstone	?Heretaungan-Waipawan
Awhea Group: ▤ Awhea Formation		Alternating sandstone, mudstone	?Mangaorapan-Teurian
☐ Manurewa Formation	40 70	Greensand, limestone marls	Teurian
▤		Hard siliceous mudstone of Whangai "Shale"	Teurian-Haumurian
■	100	Sandstone conglomerate, etc. cf Piripauan	Piripauan

FIG. 1.—The Coast Range Anticline. Note: Outcrop forms have been simplified by projection of beds on to a simplified topography.

Mungaroa Limestone

The Mungaroa Limestone is named after Mungaroa Hill, in the south of the area, where the limestone reaches its fullest development, being more than 300ft thick. Mungaroa Hill is the type section for the formation, but as the fully exposed and more generally representative section on the Pukemuri Stream is well dated, the formation will be first described from the latter area. As one ascends the stream, the lowest member of the formation, some 40ft of white calcareous mudstone, is seen to lie conformably on the Awhea Formation. A middle member, 40ft thick, of alternating black mudstone and sandstone follows, and on this rests the most consistent member, a 10ft bed of white porcellaneous and banded limestone. The limestone extends for many miles along the coast, but the two lower members pass into the Awhea Formation to the north and into pure limestone to the south. It will be seen that the drawing of formation boundaries in this setting is arbitrary and depends upon whether the affinities of the sediments are on the whole calcareous or otherwise.

In the Pukemuri Stream section the formation is probably Waipawan to Mangaorapan in age for the immediately overlying strata are Mangaorapan to Heretaungan. The limestone member where it outcrops in the Awhea River is Waipawan to Heretaungan and includes (N168/583 = F9712), *Globorotalia crater* Finlay, *Bolivinopsis compta* Finlay, and *Globoquadrina primitiva* Finlay. A limestone at the mouth of the Pahaua River, the probable continuation of the latter limestone, has a clearly defined Heretaungan fauna (Rishworth, 1953).

The Mungaroa Limestone at Mungaroa Hill is not materially different from the pure limestone member at Pukemuri Stream except that it is thicker. It is without macrofossils, is porcellanous and dense, and is exceptionally well bedded on thin shaly partings spaced at intervals of from four to ten inches. At Te Kau Kau Point a peculiar assemblage (N168/579 = F9709), includes the Cretaceous elements *Pseudovalvulineria infrafossa,* large abundant *Rzehakina epigona* (sensu stricto), *Bolivinopsis* aff. *spectabilis,* and the Tertiary fossil *Clavulinoides instar* Finlay, along with miscellaneous Cretaceo-Tertiary elements such as *Marssonella oxycona* and *Nuttallides* sp. The relatively long time range indicated by these fossils from a single sample could have several explanations, but it is thought that the Cretaceous foraminifera have probably been derived (see below) and that the limestone is of much the same age as that at Pukemuri Stream.

Awheaiti Formation.

The Awheaiti Formation comprises the beds between the Mungaroa Limestone and the Pukemuri Siltstone. At Pukemuri Stream it consists of 120ft of alternating blue calcareous sandstones and black micaceous mudstones. The formation thins towards the north and at Limestone Hill is only ten feet thick, while to the south it probably passes into the limestone at Mungaroa Hill. A sample (N168/538, F8855) from a stratum just above the Mungaroa Limestone at Limestone Hill contains *Globorotalia crater, Globoquadrina primitiva, Globorotalia* aff. *collactea* Finlay, and *Bulimina* aff. *pahiensis* Finlay. The fauna is clearly Heretaungan to Mangaorapan.

Pukemuri Siltstone.

The Pukemuri Siltstone is a slumped shale and pseudo-tillite lying unconformably on the Awheaiti Formation and probably discordantly below the Kandahar Formation. It is typically developed in the Pukemuri Stream section and consists of a 50ft thick basal member of crudely sorted conglomerate and a 250ft-thick upper portion of laminated pink or chocolate shale with scattered lenses of greensand. The conglomerate, which closely resembles a tillite, has a matrix of intensely slumped and contorted shale, and contains subangular boulders of Whangai argillite, some greensand, and some Mungaoroa Limestone. The shales may have been derived from lightly consolidated Whangai argillite, for that rock even now weathers to a soft slippery clay which is prone to sliding. Despite slumping, the shales are constant in thickness along their strike, and the upper and lower members preserve their general relation, so that the formation cannot have been violently disturbed or slumped, nor have travelled far from its source area.

The unconformity at the base of the formation varies from 0° to 15° and its strike is sub-parallel to the strike of other formations and to the axis of the Coast Range Anticline. The unconformity was therefore due to a tilting of what is now the western limb of the anticline, and this probably means that the fold was accentuated at this stage. It need not be hypothesised that the anticline was emergent during the interval of the unconformity, for erosion could as well have been submarine and above wave base as subaerial and above sea level. It would, in fact, be inconvenient to propose emergence, because the erosion interval was too short to be recorded by microfossils, and one should have to propose not only an emergence but an immediately succeeding submergence. Microfaunas from the formation are Heretaungan, as shown by the fauna of the following samples N168/572 F9704: N168/573 = F9705; N168/574 = F9708, from the type section; *Globoquadrina primitiva, Globorotalia crater, Bolivinopsis compta, Elphidium hampdenensis* Finlay. As the formation is itself derived, its fossils are probably also derived and are of limited significance.

Kandahar Formation.

Named after Kandahar Farm, this formation is typically exposed in the Awheaiti Stream at the prominent bend downstream from Ewe Ridge. A sample N168/583 = F9712 from 200ft above the base contains the assemblage *Globorotalia crater, Bolivinopsis compta,* which is at youngest Heretaungan, and a second sample N168/582 = F9711 from nearby bears a Bortonian fauna including *Globigerinoides index* Finlay, and *Uvigerina bortotara* (Finlay). Several other Bortonian faunas are known in the neighbourhood.

The formation, some 500ft thick, probably rests with its basal conglomerate discordant to the Pukemuri Siltstone, but the relation between the two is obscure because the contortions below the sharply defined contact could have been formed either before, or by slumping after, the deposition of the basal Kandahar conglomerate. The widespread slumping of the siltstone does, however, suggest that disconformity would follow, and the presence in the conglomerate of hard exotic greywacke pebbles indicates that there was a regional disturbance at this time.

The Kandahar Formation, which consists of a redeposited sequence of massive blue sandstones, blue mudstones, bentonic clays, and occasional soft white marls, closely resembles the Benmore Group of Macpherson (1952, p. 268), and like it is characterised in the topography by numerous large-scale landslides. Again, the beds resemble the Wanstead Formation, described by Lillie (1953, p. 35), and probably represent the southward continuation of the upper part of that formation. Lillie's formation extends over greater time range than the Kandahar and corresponds to all the Opouawe formations above the Whangai Formation, while in this area it is only the upper Heretaungan and Bortonian strata that are the lithological equivalent of the Wanstead. Provided this is understood, there is little reason why the Kandahar Formation should not be described as the Wanstead. There is, however, some objection to the use of the traditional name Wanstead Formation, for this usage pre-empts the term formation for a thick, varied, and facies-variable sequence (which occurs in Lillie's area as well as this) and thus restricts further subdivision To remedy this situation with the least conflict of ideas it is, therefore, proposed that the name "Wanstead Group" should be used in the place of "Wanstead Formation" as last defined (by Lillie 1953, p. 35). In this way the Opouawe formations become formations of the Wanstead Group and the northwards change of facies becomes easier to describe and to follow.

CONDITIONS OF DEPOSITION

Source Area

Because of the regional distribution and regular character of the Amuri, Weka Pass, and Mungaroa Limestone and associated formations like the Whangai Shale, it is widely accepted that from Upper Mata to approximately Landon times the East Coast of New Zealand was a region of relatively quiet and stable conditions (Macpherson 1946, p. 13, and Lillie 1953, p. 75). The calcareous and muddy oozes and glauconitic sands of those times were deposited in an open sea free of coarse terrigenous detritus and were derived from a post-mature or even senile landscape. Although the source area was aged there is little doubt that some small movement occurred, and it appears probable that these were responsible for the initial slumping and consequent redeposition of the Tertiary formations and to some extent for the origin of the Whangai Shale. The siliceous clays of the latter are exceptional rock types and are only similar within the writers' knowledge to the siliceous seatearths below coal seams. Because of this it is reasonable to support that the Whangai Shale was derived by the stripping of the regolith and shallow basin deposits of an uplifted senile landscape long clothed with vegetation. The general deficiency of iron oxides and alumina in the formation indicates that the landscape was not simply lateritised, and the idea of a long-enduring vegetation explains how soils might be leached and the rocks derived from them be relatively enriched in silica.

This suggestion is complementary to Lillie's (1953, p. 78) that the landscape of origin should be "much denuded of vegetation" and is not inconsistent with his observation that the Whangai contains little organic matter. It is possible that a low country might be clothed for a long while by grasses, or scrub, and yet for these to contribute little to rivers or deltas. For comparison of the effects of rejuvenation on such a landscape, the artificial draining of heaths in the Yorkshire Pennines has resulted in the drying out, low temperature oxidation, and disappearance into the atmosphere of peats ten feet thick, and has led to the denudation of their leached underclays, all within the last century.

Following the deposition of the Whangai Shale, conditions were still quiet, but from the northward facies change of the Mungaroa Limestone into the Awhea Formation it is clear that conditions varied and that there was probably land in that direction. The coarser (but still fine) deposits of the Awhea and succeeding formations in this area, while indicating continual and slow emergence of a hinterland, contain little very coarse material such as would suggest a youthfully or maturely dissected land. At most, the deposits indicate restricted phases of uplift or localised uplifts, and appear to be at variance with the idea that the area was undergoing active folding. The characteristic twofold rhythm of sand and clay of the Awhea and other Tertiary formations is related to the terrain from which sediments were derived. Conventionally this cycle would be attributed to oscillation of relative sea-levels or to periodic inundations by floods into quiet waters, but a view slightly different from the last is preferred. It is thought that particles of the two very distinct orders of size now constituting the alternating beds were carried by a series of turbid flows, that as these slowed down the coarse material was first deposited, and that when flows halted muds were precipitated.

Marshall (1928, p. 512) has shown by ball-mill experiments that long-continued grinding of rock detritus produces grains of gradually decreasing sizes until a lower limit of sand of 1·1 mm diameter is reached. Thereafter there is a sudden drop in particle size to that of clays and the common end products of milling are fine sands and muds. In nature a similar process aided by chemical weathering operates in the fluviatile and beach re-working of detritus on and around post mature landscapes, and its products are readily recognised in the sands and clays of deltas. Cyclic slumping and redeposition of the sediments of ancient coasts must result in dual rhythms of the type described above, and in general these will be distinct from the graded and coarser beds of orogenic areas and periods. In so far as aged landscapes are regional rather than local in extent these deposits may be expected to be regional also, and, as aged landscapes bespeak continuity of conditions the deposits should be only infrequently interrupted by coarser deposits. These characters, as well as the distinct twofold rhythm, are typical of many Lower Tertiary sequences such as the Ihungia of the southern Wairarapa and probably indicate stable conditions in the source area of the material.

This argument may be qualified in several ways. In the first place Marshall's size gradings probably apply to certain rocks only, but the principle of a sudden drop to clay sizes in general. Thus the silty beds of the dual rhythms may fit the argument as well as sands might in Marshall's context. Again the presence of occasional pebbles in the silts does not invalidate the thesis, for there are probably few beaches or deltas which carry no pebbles.

It might be argued that the fine-grained deposits simply represent the farthest travelled and finest material of a turbid flow derived from a young landscape, but the presence of occasional pebbles shows that the carrying agent was capable of transporting coarse material. It is inferred then that there was no sorting of material *en route* and that the present constitution of the deposits is representative of the source material.

Redeposition of Limestone

The lateral gradation of the Awhea Formation into the Mungaroa Limestone is not merely a passage by interdigitation of beds but is a transition of redeposited silts and clays into limestone. The passage cannot be traced for any individual bed, but beds can be mapped in bulk and all gradations are seen between the facies. The contemporaneous deposition of limestone and argillites was at first interpreted by the writers as meaning that the former originated as a calcareous ooze some distance offshore and that its regular shaly partings represented the farthest travelled of the fine muds of a turbidity current coming from the land. That interpretation, which may be in part correct, was unquestioned until the Manurewa Limestone was found to be graded and to show signs of redeposition. Then the Mungaroa Limestone could be examined as a possibly redeposited formation. As the Awhea Formation passes smoothly from sandy through clayey and then to calcareous sediment it is reasonable to suppose that one gradational mechanism has been at work. The separation of the sandy and muddy fractions of normal graded beds might be functions of distance travelled and of the slowing up of a turbid flow, and the separation of calcareous ooze from fine clays might be similarly governed.

The general scarcity of Foraminifera in the redeposited clays and mudstones of the area suggests that microfossils present in the original sediments may have been separated off during transport in a turbidity current and that their re-concentration as a calcareous ooze might be like that which occurs in the preparatory washing of foraminiferal samples. The large surface-to-weight ratio of microfossils would favour their floating in a turbulent stream, and allow their consequent separation and carriage far beyond the coarser detritus. One might expect, therefore that the Mungaroa Limestone could originate in this fashion and would contain many Foraminifera, but apart from the mixed faunas cited above and a relative abundance of Radiolaria (Mr. P. Vella, pers. comm.) the limestone is poor in microfossils. It may be that the fossils were broken up in transport, but it seems more probable that the concentration of naked calcareous tests and their re-mixing with water allowed a reconstitution and recrystallisation of the carbonate into the very fine-grained and apparently chemically precipitated limestone we now see.

Independent of the above observations, the presence in the limestone of occasional greensand beds is strongly suggestive of redeposition. In terms of conventional hypotheses of deposition these bands suggest rapid and complete changes in the conditions of sedimentation, but in terms of redeposition this need not be so, and a simpler explanation is found. All that need now be supposed is that during the deposition of the Mungaroa Limestone there was a gentle warping of the sea-bed and that greensand formed on anticlinal highs. Then, as folding continued, the soft sands became unstable and slumped as a turbid flow into the adjacent troughs. The greensands of the Mungaroa Limestone possibly originated on some uplift other than the Coast Range Anticline, but it is also possible that this latter anticline was locally denuded by slumping of its soft oozes, and that its core of soft greensand was exposed. It is shown below that those soft core-rocks were quite capable of being injected into the Mungaroa Limestone some time after its deposition, and it is possible that they were also extruded as a quicksand along the crest of the Coast Range Anticline during the early stages of growth of the fold and during the deposition of the formation.

Whether the greensands were distantly or locally derived, the redeposition theory, allied with the idea of contemporaneous movement, can readily account for them. At the same time, the idea of contemporaneous folding provides us with a further mechanism of origin of redeposited limestones. If the sea floor at any time or place were covered with soft calcareous ooze and were subsequently warped, then slumping and redeposition would occur, and, with progressive folding, it would be possible for a given sediment like the limestone to have been slumped and redeposited more than once.

Summarising, we now have four possible ways in which redeposition might have affected the Mungaroa Limestone.

(a) The limestone may have been a normal ooze deposited on the sea floor, and only the thin clays may have been redeposited.

(b) The limestone may have resulted from the slumping and resorting of a mud and by redeposition of the calcareous fraction.

(c) The limestone may first have been deposited as a calcareous ooze and then have been wholly redeposited.

(d) The limestone may have been redeposited or re-worked several times.

In all this it is not implied that the Amuri Limestone has everywhere been redeposited, nor that any of the above mechanisms can be demonstrated for any particular area. It is claimed that the mechanisms have probably operated singly or in combination at many localities and that redeposition may be suspected in any area of perfectly bedded and slump-folded limestone.

In any area, however, where it is possible for a derived limestone to accumulate there must be a relative abundance of calcareous waste and freedom from other detritus, so that it would also be possible to have a primary limestone alongside that which has been redeposited. Limestones in adjacent areas and of much the same age may, therefore, have the two different origins, and even in one area any one stratum of limestone in a redeposited sequence may be composed of primary and secondary deposits.

Redeposition of Argillites.

Considering the redeposited character of the argillaceous Lower Tertiary strata, it is apparent that the very fine clays comprising large parts of formations can only have been deposited from dispersed suspensions of mud in water, and that, to allow settling, this water must have been more or less stationary The sensitivity of muddy water to gravity and to the slope of the sea floor is such that turbid flows transport sand on gradients of only 5ft per mile (Gould, 1951, p. 51). It seems, then, that redeposited silts and clays must usually be laid down almost horizontally, and that in consequence they must be deposited either on flat broad shelves or on the flat floors of closed basins. The wide extents of the lower Tertiary formations of the East Coast suggest that they were laid down on wide shelves, but there is no doubt that the area was folding during their deposition. Both Macpherson (1946, p. 17) and Lillie (1953, p 76) have described in some detail the intermittent growth of folds and contemporaneous erosion of anticlines in the region, and in the Opouawe area the same kind of growth and erosion has been deduced. If erosion were due to emergence of anticlines the basins of deposition between them would be separate and their deposits would tend to be distinctive. Alternatively, and with the same presupposition of emergence of anticlines, any widely distributed formations such as do occur could be explained only by imagining that the region was repeatedly and alternately raised and lowered, or that there was a fluctuation of sea level.

It is conceivable, however, that erosion may have been submarine rather than subaerial, and it will be shown that this concept fits the facts of the Coast Range Anticline particularly well. In that anticline the known stratigraphic evidence of contemporaneous folding and erosion is limited to the one unconformity below the Pukemuri Siltstone; but a study of slumping and redeposition meets the deficiency and can demonstrate both tilting of the sea-bed and the probability of contemporaneous submarine erosion.

Slumping: an Index of Earth Movement.

Slumping of beds is generally attributed to the local accumulation of deposits into irregular unstable piles such as those of deltas, or into thick and lens-like coastwise sediments, and to the triggering off of those piles by earthquake shock. In that view emphasis is on the idea that instability is inherent in the mode of deposition of beds, and few workers have conjectured any other common cause of slumping. Natland and Kuenen (1951, p. 26) give an example from California, where tilting of the sea-bed is held responsible for slumping, but it has not been recognised that tilting is a very frequent cause of submarine landsliding.

So far as the writers' experience goes, deltaic deposits are not inherently unstable, and though they may be thick, as in the coal measures of Britain, they show only trivial slumping in places away from orogenic or epeiric areas (Kuenen's 1948 examples of slumping from South Wales apply to deltaic deposits on the margin of the Hercynian Geosyncline). By contrast, it is in the young sediments of orogenic belts and in particular in redeposited sediments that slumping is common. Now, it has been deduced that very fine-grained redeposited sediments must have been deposited horizontally on a flat sea-floor, and in agreement with Kuenen and Migliorini (1950) it can further be argued that because they are deposited from broad and even flows of muddy water they must have been laid down in layers of even thickness and wide extent. It is hard to conceive of such beds being heaped up into unstable piles and equally difficult to imagine them suffering differential areal compaction. So it appears that, with the possible exception of deposits over supratenuous folds, they can have had no initial dips. In short, if fine-grained beds have been redeposited they must be adjusted to horizontality as delicately as if by a spirit level, and they must have been deposited at the lowest possible level. As they possess no potential energy of position there can be no triggering off of such energy by earthquake or other device, and for slumping of fine-grained redeposited beds to occur there must be some positional energy imparted to them by differential uplift (faulting or tilting) of the sea-bed.[1] Contrarywise, we can say that *contemporaneous slumping of fine grained redeposited beds is usually clear evidence of contemporaneous earth (basement) movement,* and the possibility arises that phases of movement in an area could be charted with reference to dated slump structures. Further, if directions of slumping can be registered it may be possible to record the attitude of the sea-floor at particular times.

Unfortunately there are difficulties in the way of both projects. In the first case, much slumping is not readily dated, for, as will be shown, it may occur long after

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[1] An exception to this rule will be discussed in another paper.

beds are deposited; in the second case, there is no precise relation between directions of slumping and slope of the sea floor. It is readily visualised that in a large slumping mass, as in a landslide, there will be a fanwise spread of material and that along the arcuate margin of the slide fold axes may be oriented through 180°. In addition, it can be demonstrated (p. 544) that even with individual folds the direction of movement of the strata has sometimes been oblique to fold axes. Thus the attitudes of fold axes or other reference directions in slump folds convey little direct information on the azimuth of slumping or of inclination of the sea-bed. The study of time relations is still profitable, however, and in the following pages some attempt at interpreting slump structures in terms of time and other phenomena is given.

Piripauan Sandstone Slumping.

The Piripauan Sandstones contain slumped balls of the type shown in Pl. 33, Fig. 5, and these have clearly rolled down a sloping sea-bed, to be enclosed in softer and now eroded muds. As all of the beds in question are redeposited types, it is probable that they were not inclined on deposition, and as the slump is superficial it cannot have been caused by differential loading. The sea-bed must, therefore, have been tilted for this structure to be produced.

The sandstones also contain beds of ill-sorted and slabby conglomerate or breccia which have slid and ploughed into the underlying strata in a fashion suggesting that at the time of their emplacement they formed a submarine landslide or avalanche of mud and pebbles. Such a mass (Pl. 34, Fig. 6) consists of exotic pebbles and of slabs of Piripauan sandstone and mudstone up to a foot square and four inches thick. The commonly stratified appearance of the mass and the regular orientation of the slabs are very much like those of a locally derived scree of Piripauan sediment and are unlike typical ill-sorted conglomerates of redeposited origin. On the other hand, the presence of exotic pebbles suggests a distant origin and transportation by turbidity currents. In places the relation of the breccia to the underlying beds is markedly discordant in an overstepping fashion (Pl. 34, Fig. 3), and their angle of deposition must have been that of a talus. While this is inconsistent with deposition from a mudflow, it cannot be imagined that the scree was derived by subaerial agents or by the action of waves along the shore of an emerging island. The sandstones were probably far too soft to be broken into blocks by waves, but were probably derived as slump boudins or " pull-aparts " (Natland and Kuenen 1951, p. 91) and the exotic pebbles were probably re-derived from the Piripauan sandstones. A possible cause of slumping is shown in Fig. 13, which depicts a submarine fault in soft sediments and illustrates how the soft beds may have slid and ploughed into the adjacent strata.

Manurewa Formation Slumping.

There are few signs of slumping in the Manurewa Formation, but the disconformities that have been described above are suggestive of erosion and deposition as each member was formed. In view of the great extent and the horizontality of the sea-floor during deposition of fine-grained redeposited beds, it is difficult to see how submarine currents could be sufficiently concentrated to cause even a local scouring. One should expect rather that currents would be broad and slow, but the fact remains that in the Manurewa Formation there are repeated signs of redeposition alongside those of erosion.

To explain this we imagine an ideal case of a Pacific-type coastline where the structure of the sea-bed might comprise many growing folds with axes parallel to the coast and with their crests at greater and greater depth outwards into the ocean. Then turbidity currents originating near the shore must tend to cascade from higher to lower synclinal troughs of the sea-bed and to fill them with sediment one after the other. In an ideal early stage turbidity currents must be arrested by the first anticlinal high they meet, and their load be deposited in the first synclinal basin, but as that basin fills the velocity of currents may only be checked and the impetus remain sufficient to carry flows of muddy water over the first submarine swell into the second basin. Just as heavy mists pouring from a high mountain valley to the next lower valley select low saddles in the intervening ridges, so turbid flows must canalise themselves at the lowest sags along the submarine anticlinal highs. As those would be composed of soft sediment, broad channels would be cut across them down to a profile where erosion and deposition were in equilibrium. It must not be imagined that the ridges would be sharp or the eroded channels deep, for the processes of submarine planation are not quite similar to subaerial erosion and aggradation. Here the processes of erosion of soft sediments and of transport and deposition are highly sensitive to slope, and are swift, so that they maintain a very subdued submarine relief and a relatively flat sea-floor.

So far as it concerns the Manurewa Formation this argument is not exclusive, for wave action or tidal flow may also cause erosion, but the process outlined is probably general and of world-wide application, and it explains the disconformities of the Manurewa Formation within the synthesis attempted here.

Mungaroa Limestone Slump Folds.

The slump folds of the Mungaroa Limestone are discussed at length in the third part of this paper. Intense slumping after the deposition of the formation probably coincided with a major tilting and with the formation of the unconformity of the base of the Pukemuri Siltstone. Less intense slumping probably occurred on several later occasions.

Pukemuri Siltstone Slumping.

The angular unconformity at the base of this siltstone is evidence that the formation was deposited after a phase of intensified movement, and the nature of the deposit shows that movement continued for some time. The formation is characterised by involved pseudo-tillites in its lower half and by highly attenuated folds in its upper portion (Pl. 33, Fig. 6). These folds, which are drawn out in the ratio of twenty to one, have such "plastic" forms as to indicate that the clays which comprise them must have been exceedingly soft at the time of folding. There are no signs that the formation was loaded by another formation at the time of slumping, and it is inconceivable that the laminated silts of which it is composed were laid down on a slope. It follows that the beds have been tilted and that the clays have simply "flowed" down an incline. The intense contortion of beds does not mean necessarily that they were involved in any violent sliding, and the fact that the pseudo-tillite remains unmixed with the bulk of the formation suggests that movement was slow and perhaps comparable in its velocity with that of soliflual creep. It is difficult to know whether the anticline had emerged at this stage, but that is not unlikely, and it is certain that the crest had risen at least to wave base and was subject to shallow-water erosion.

Kandahar Formation Slumping.

As this formation is even now very prone to slumping or landsliding, following recent rejuvenation of the landscape, and as it has been folded into an anticline, it is to be expected that it must have slumped, perhaps several times, during its uplift. The formation is so soft that any face cut by rivers or any large cutting which might make a considerable exposure rapidly becomes a slide, and it is impossible to distinguish any single slump structure in the formation as belonging to a particular period. Both Macpherson (1951) and Lillie (1953) attribute the slumping in their closely comparable Benmore and Wanstead formations to the presence of bentonite in the clays, and the slumping in the Kandahar formation may be similarly explained.

However little one might learn about the early slumping of the Kandahar Formation, one fact of the greatest importance emerges, namely, that this and other very thick formations that are still thoroughly incompetent can never have transmitted much "drag" across bedding or thrust along bedding planes, and that consequently most thrust and fold structures in them must have been caused by gravitational collapse. Even the major folds which run through these formations can never have been the direct result of compression and arching, but must be passive or draped folds and have been caused by elevation or subsidence of the basement rocks below.

This conclusion is obvious, but the important application of it is not immediately apparent. Many rocks, like the redeposited and now lithified Cretaceous strata of the region, are not very different in composition or origin from the Kandahar Formation. While some structures of these strata were clearly developed after lithification, there are many others which were probably due to slumping of one kind or another but which cannot now be easily distinguished from tectonic structures. The writers have observed in the Kandahar Formation pseudo-tectonic structures such as boudins, attenuated beds and "pebbles", drawn-out crush-breccias, sheared formations, and so on, and consider that the majority of similar forms in the Cretaceous strata may be better attributed to slumping than to "compression".

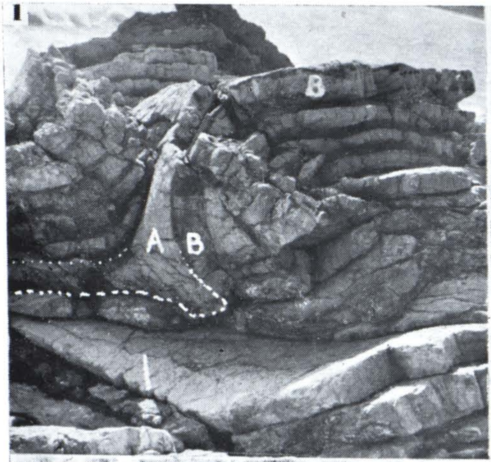
General.

If it is accepted that "slump erosion" may be due to tilting of the sea-bed it is reasonable to ask what might be the angle of slope on which sliding would occur. From the standpoint of mechanics, thick redeposited and perfectly stratified formations sliding on laminae of clay must be only slightly more stable than equally thick masses of clay. Because some Tertiary clays flow under subaerial conditions on angles of less than 5° it seems probable that submarine slumping may occur on even gentler slopes, perhaps as low as one or two degrees. These assessments are compatible with those of Milne, Heim, and Arkangueslsky, who, according to Fairbridge (1946, p. 84), have demonstrated that submarine slumping occurs on slopes of 2° to 3°, and who claim that slumping of normal sediments is inevitable on all slopes of more than 5°.

A second consideration concerns the broad characters of uplift and erosion of anticlines and of the infilling of synclines. It is in the nature of turbidity currents that they, like rivers, must seek the lowest level and that they should deposit their load as their velocity decreases. Thus synclines will be sites of deposition and, as described above, anticlines may be the scenes of contemporaneous submarine erosion. With relatively rapid folding, erosion and deposition might just keep pace with the tilting of the sea-bed and so maintain stable slopes of fold limbs at about 2°. With any faster folding, slumping would necessarily ensue until a stable slope was re-established and the sea-floor as a whole would remain relatively flat. Any halt in folding would, of course, allow deposition to restore horizontality in a very short time.

Special interest attaches to the submarine erosion of growing anticlines as they reach wave base, for the soft young sediments at their crests must be eroded by every severe storm and the debris must be carried away by turbidity currents. It is unlikely, therefore, that any fold of very young sediments can ever emerge from the ocean. The net effect of wave-base erosion, of redeposition, and of slumping must be to maintain a nearly horizontal sea-bed, and thus any emergence in an area of young sediments must tend to be regional and of a plain rather than of island chains.

There are marked exceptions to the above generalisations in the East Coast area, for it has sometimes happened that rising folds were stripped of all the soft cover at their crests and that their hard basement cores were exposed. These cores were not subject to slumping and rapid erosion, and as uplift continued they emerged at the surface of the sea as long and rugged island chains of old rocks. Such a chain probably gave rise to the conglomerate at the base of the Kandahar Formation, and throughout the Tertiary such ridges of Trias-Jura greywacke or of somewhat softer Cretaceous strata probably gave rise to the greywacke pebble beds which occur in the Tertiary sediments.



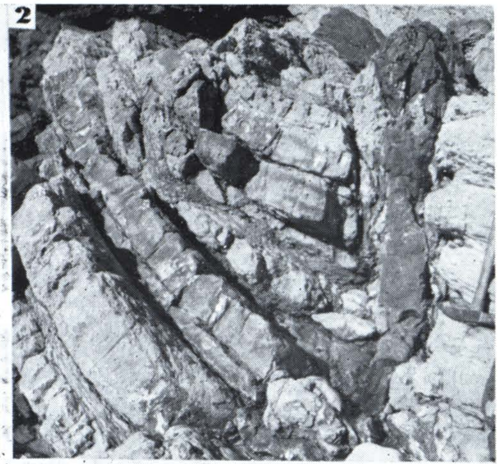
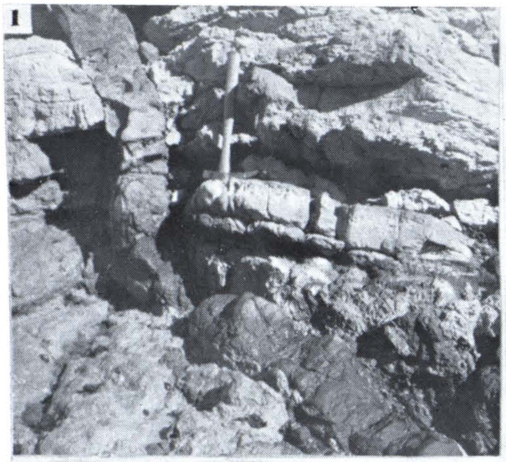
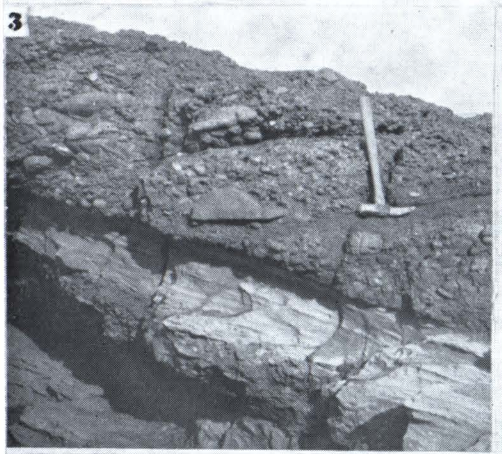
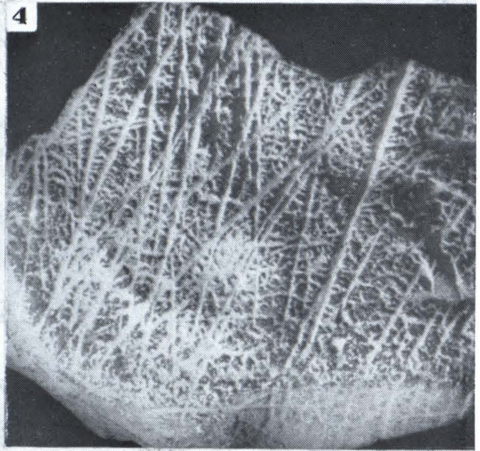
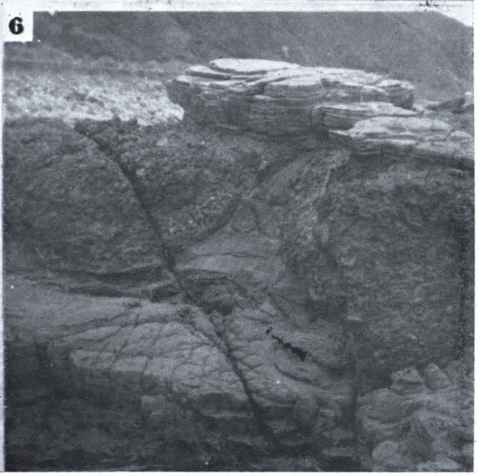


FIG. 1.—Paralloid Fold, diameter 6ft, Mungaroa Limestone, Te Kau Kau Point. FIG. 2.—Same as Fig. 1 with sandstone dyke. FIG. 3.—Same as Figs. 1 and 2 with 18in thick sandstone dykes and sills. FIG. 4.—Skew Fold, Te Kau Kau Point. Note oblique fissures. FIG. 5.—Mud Ball. Piripauan Sandstone. FIG. 6.—Attenuated distortional slump folds, Pukemuri Siltstone, Opouawe River.









FIGS. 1 and 2.—Greensand dykes in Mungaroa Limestone, Te Kau Kau Point. The 20ft. dyke of Fig. 2 has been etched out by wave action. FIG. 3.—Scree (submarine ?) of Piripauan Sandstone in Piripauan Sandstone. FIG. 4.—Calcite filled joints in Mungaroa Limestone. (*Photo*: *M. King*.) FIG. 5.—Greensand dykes in Whangai argillite. FIG. 6.—Slumped conglomerate in Piripauan Sandstone. (Adjacent to Fig. 3.)

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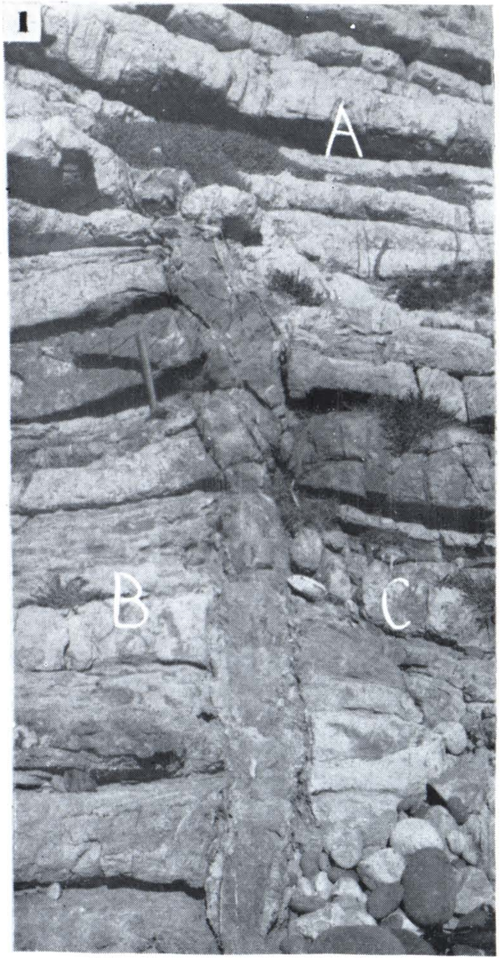

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FIG. 1.—Greensand dyke in Mungaroa Limestone at Limestone Hill. Note thickening of beds next to dyke and vertical offset of beds on either side; the bed above the hammer head intrudes the dyke. FIGS. 2 and 3.—Comma folds at Limestone Hill. Beds average 10in thick.

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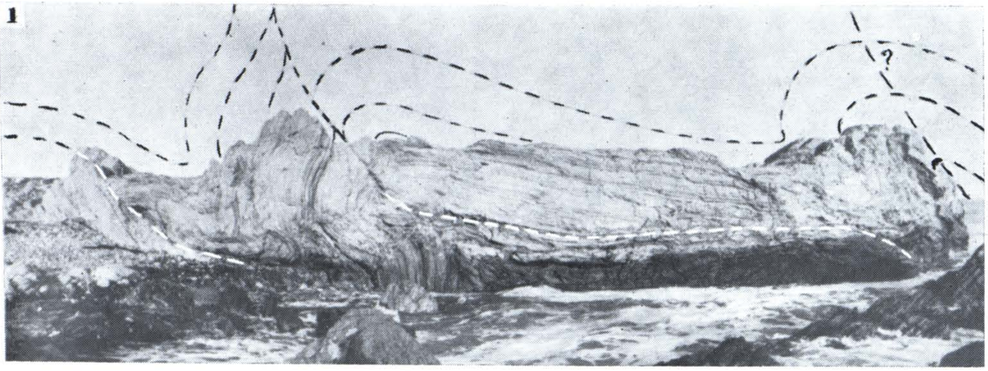

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FIG. 1.—Lower extremity of a 60ft long drag fold. Mungaroa Limestone, Te Kau Kau Point. Note how passages of thrust fault into bedding plane slide allows attenuation with least distortion. (*Photo*: *D. Kelly.*) FIG. 2.—General view of slumped limestones, same locality as 1. FIG. 3.—Slump Drag-Folds in Amuri Limestone, Kaikoura Peninsula, Marlborough. (*Photo*: *G. Shaw.*)

FIG. 1.—Diapiric Fold in Mungaroa Limestone at White Rock. Note plastic unbroken form of beds and steep plunge of fold axis towards the viewer.

In late Pliocene times narrow reefs of greywacke rising from deep water were particularly prominent in the Wairarapa district, and when subsequent uplift raised all of that district above sea level rugged chains of hills were exposed. These unexpectedly jagged ranges, 500ft above the neighbouring flat but synclinally warped country, are very characteristic of the district and are called "taipo" ranges. The Taipos, occupying the crests of asymmetric anticlinal highs, are usually strongly faulted on one side and may be lightly faulted on the other. Many are still undergoing uplift, and, while they may be regarded as young horsts, their topographic expression is that of ancient residuals.

It is now possible to explain how formations like the Whangai or Wanstead might be deposited across a wide terrain which consisted at the time of deposition of a succession of actively warping and eroding folds. As the sea-floor was substantially flat and horizontal, and as sediments were spread out very smoothly over vast areas by turbidity flows, it follows that a continuous formation might be deposited over what are now separate basins. Subsequent erosion on the anticlinal highs would not affect deposition already accomplished or lithological correlation. Indeed, it might be expected that facies variations would be independent of structure and that there could be a steady facies variation across several troughs. The hundreds of miles of distances over which broad lithological correlations can be made on the East Coast are thus compatible with continuous folding, with the present topography, with unconformities, numerous disconformities and discontinuities, and with the pronounced slumping of strata.

SLUMP STRUCTURES

The sediments of the Opouawe area do not merely allow the exploration of broad conditions of deposition but also permit the detailed examination of slump structures and the study of their relations to redeposition and contemporaneous movement. The number and variety of slump structures displayed in the area are probably a reflection of the variety of formations and of the frequency of the earth movements that occurred during deposition. Structures new to New Zealand writing include the highly attenuated folds and pseudo-tillites of the Pukemuri Siltstone, the slumped mud-balls and breccias of the Piripauan Sandstones and the deep-seated slump folds and the sandstone dykes of the Mungaroa Limestone. Most of these have been or will be mentioned only in passing, and attention will be concentrated on the processes of slumping as witnessed by the structures of the Limestones.

Laminose Flow.

One of the most important structural consequences of redeposition results from the separation over wide areas of the coarse and fine sediments which make up graded beds and alternating rhythms. The differently constituted layers have widely different properties, and in particular have very different reactions to shearing stress in the plane of bedding. Thus, when beds are tilted and a component of their weight becomes a sliding or shearing force along bedding planes, the *resistance to slip of the formation as a whole is no more than that of the weakest beds.* If these layers are of very soft clay, then the angle of rest of the formation, even though it is largely of hard rock, will be that of the clay, and sliding will occur on slopes of low angle. This process of bedding-plane slip is very important in the Mungaroa and similar well-bedded limestones, for in such formations the partings, though thin, have been very weak and slippery, so that the individual beds have slid over each other with a remarkable freedom.

The term *laminose flow* is proposed for the mass phenomenon which is like that occurring when a stack of papers is tilted and slides forward. Sheets move forward and downward singly or in groups, depending on small frictional differences between them, and in general there is a cumulative movement towards the top of the pile so that absolute speeds and distances travelled increase upwards. This is laminose flow in its simplest and probably in its commonest form where it closely resembles laminar flow. There is, however, a fundamental distinction between these processes which is that "laminose" implies a flow of parallel sheets of different consistencies, whereas laminar commonly refers to flow in a homogeneous medium.

Because of its nature bedding-plane slip will always be difficult to demonstrate, and it is conceivable that the process may be a common one and yet remain undetected. In the Opouawe area, and in general, the only direct evidence of laminose flow is that shaly partings are slickensided and that the surfaces of beds are grooved. Even slickensides are of doubtful value for demonstrating penecontemporaneous bedding-plane slip, for Kuenen (1950) lists them as criteria of tectonic folding; and it seems probable that the slickensides in the Mungaroa limestone occurred long after the lithification of the formation. Fortunately there is more convincing evidence of penecontemporaneous laminose flow in the character of the slump folds and fissures which occur in the limestones at Te Kau Kau Point and Limestone Hill.

Paralloid Folding.

The simplest kind of slump fold in the Mungaroa Limestone is that shown in Pl. 33, Fig. 1, and an analysis of the fold as it appears in the field shows the following features:

(*a*) The limestone beds are arranged in groups of which the individuals are parallel to each other, and although beds are bent they are not markedly thickened, thinned, or otherwise internally distorted. These characters are typical of parallel folds and of competent strata.

(*b*) The group of beds overlying the fold is not parallel to the fold as a whole, and, further, the core of the fold is missing or "squeezed out". These features are characteristic of non-parallel folds and of incompetent beds.

Taking (*a*) and (*b*) together we find that the fold is of a distinctive kind in which limestone beds have behaved as highly competent with regard to the intervening beds (the clay partings), which have been highly incompetent. Further, the incompetent layers are so thin that they have rarely disturbed the parallelism of the competent beds, but they have been so highly incompetent that they have allowed occasional "squeezing out" and complete departures from parallelism between groups of competent beds. Folds of this type, which combine the ideal properties of both parallel and non-parallel folds, will be called *paralloid.*

(*c*) Beds at the nose of the fold are delicately folded, and this, taken in conjunction with the stratigraphic fact that the beds have never been very deeply buried, means that the beds were plastic at the time of folding.

(*d*) In the beds at the nose of the fold there are wedge-shaped fissures normal to bedding and parallel to the hinge line. These imply that the beds were in some sense rigid at the time of their folding, and that they were under no great load of overlying beds, for plastic beds under a heavy load would not develop tensional fissures.

(*e*) The monoclinally and less folded beds (A in the figure) immediately overlying the fold can be traced along the strike and are seen to loop under the fold. It follows that, as the fold was formed after the deposition of overlying beds, the beds in the interior of the fold have been introduced and apparently injected in their folded form into their present position.

To avoid difficulties of interpretation rising out of this proposition, and to resolve other apparent contradictions of paralloid folds, a scheme of movements in accord with the principle of laminose flow has been worked out. It is assumed that at the time of folding of the Mungaroa Limestone the layers of limestone were plastic and that they were interbedded with exceedingly soft and slippery clay. The whole mass of limestone was tilted so that beds slid forward in the manner already described for sheet flowage, and all movements were in the same directional sense. Thus, when a local friction developed between two beds (perhaps due to a local silicification) a small recumbent anticline was initiated and grew without any injection being involved (Fig 2). By analogy with the sliding sheets of paper mentioned earlier, the folding would correspond to that which is commonly seen towards the bottom

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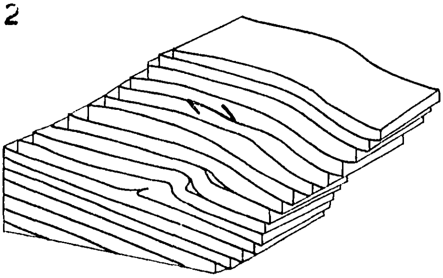

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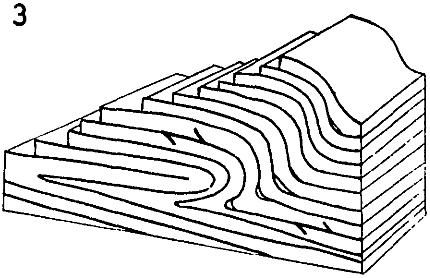

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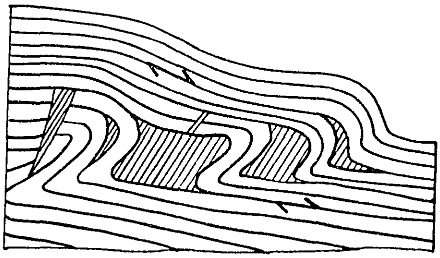

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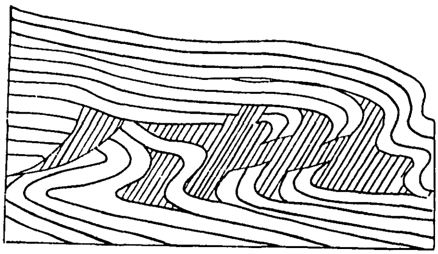

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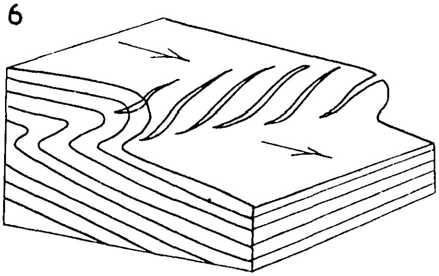

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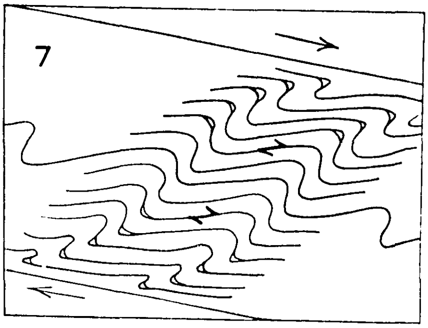

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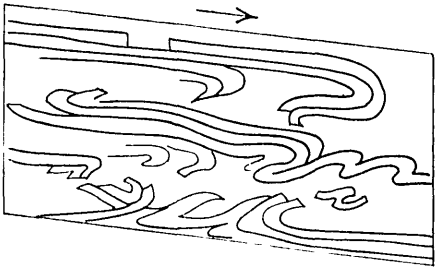

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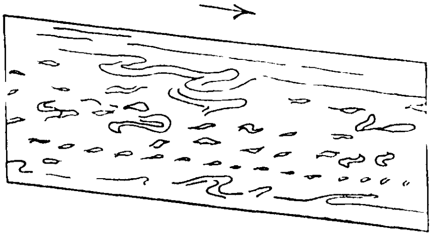

Figs. 2 and 3.—Paralloid fold *cf.* Pl. 33, Fig. 1. Figs. 4 and 5.—Paralloid folds injected with greensand. *cf* Pl. 33, Figs 2 and 3. Fig. 6.—Skew fold *cf.* Pl. 33, Fig 4. Fig. 7.—Slump drag folds. Figs. 8 and 9.—Sheared-out drag structures.

of the moving pile and successive stages of growth would be like those of Figs. 2 and 3.

Growth of the recumbent anticline proceeds by forward rolling like that of a caterpillar track and by the accretion of overlying beds. As in the motion of a tank and its track, the speed of the anticline is only half that of the uppermost limb, and the bed A (Pl. 33, Fig. 1), immediately overlying the fold, travels even faster than the top of bed B of the limb. While travelling over the fold bed A is eased along by the caterpillar action of the beds below, but on passing the nose its movement is restrained by the friction of the surface below it. As bed A crosses the nose it is therefore in a state of compression in the direction of its flow, and it tends to fold. The downward-directed pressure of the overlying strata allows no relief either forward or upward, and the only relief of pressure is that in the synclinal angle, so that the bed is forced in and becomes part of the fold. It would be incorrect to say that the bed had been "caught up in the syncline", for the action does not faintly resemble that of a wringing machine or other catching tool. This point is illustrated better below (p. 537), where it is shown that if the controlling effect of the vertical directional pressure is eliminated there is no tendency for layers to become caught in synclines, and each bed forms its own independent fold.

As long as the caterpillar fold is small its function is that of a bearing, for it reduces friction by introducing extra lubricated surfaces below the overlying mass As the fold grows, however, the forward rolling action requires the bending and unbending of more and more layers of sediment, and the internal friction of the fold increases. From the fact that in the Opouawe area folds reach a constant maximum of some 7ft diameter it appears that the growing friction imposes a limit on the growth of folds. The final limit must be peculiar to any given area, for it must be dependent on many minor factors such as the steepness of the sea-floor and the consistency and spacings of beds.

The theoretical end of the caterpillar folding process is interesting; it can be imagined that when one fold in a mass grows to its maximum size another begins to form elsewhere, and so on, until a sufficiently large portion of a formation adopts the stable form of "locked" folds whose total internal friction equals the driving force and prevents further motion. This is one application of the principle that folding produces structures with increasing resistance to the deforming force, and it means that a mass of beds sliding down a slope may halt before they reach a flat floor. In a complementary sense it means that a formation which has slumped and folded will be less ready to slump on a second occasion. The operation of this process in nature is sometimes witnessed in the halting, for no apparent reason, of a snow-slide or a landslide on a uniform slope, and it is to be expected that the process must affect slumped beds also.

Apart from the last mechanism, slumping masses are normally halted when beds "flatten out" on a bench or in a trough of the sea-floor and their collective surface attains a stable slope. It is the inclination of this top surface that determines sliding, not the attitude of the floor beneath the sliding mass, and all slumping tends to reduce that inclination. With superficial sliding the levelling process is very obvious, but with deep-seated paralloid folding and with deep-seated deformation the process is a little obscure. With paralloid folding there is always a doubling up of beds in the direction of inclination, and the cumulative effect of many folds is to produce a relative uplift in that direction. There may be no real uplift, and all that happens is that the slope of the surface of the mass is reduced until an equilibrium slope is attained.

Competence and Incompetence.

We may now reflect on the meaning of the terms competent and incompetent in relation to the partings and limestone beds. The terms are purely relative and in our example the plastic limestone beds were only competent in so far as they were surrounded by vastly less competent layers of clay. In any other conjuncture they would have been incompetent, and it is only because of this and because the partings are so thin as to appear insignificant that there is any difficulty in the comprehension of the folding process.

Whatever the mode of deposition of the limestones it seems that the clay of the partings must have been transported by muddy water from a distant source. The suspended particles must have been extremely fine to have spread over such wide areas, and in view of the common occurrence of bentonite in the lower Tertiary deposits it would be consistent to suppose that the partings were precipitated from a colloidal suspension of that mineral The fineness of the clays would readily explain the perfect lubrication of partings and perhaps explain why they are so thin as to be almost invisible. It is obvious that if any inclined stratum of clay were thick and were weighted by a firm and heavy burden of limestone the clay would simply flow along bedding planes to zones of lower pressure. In general there would be an upward flow like that of oil into anticlinal crests. In the hypothesis presented here these would be tensional areas and zones of fracture, and one might expect, therefore, that such areas would be the site of clay intrusions or extrusive bentonite springs of the type now found in Hawke's Bay. On the flanks of anticlines the clay partings must, under these conditions, have thinned out until they reached some limiting size dependent on the viscosity of the clay, and one might assume for a restricted area that this would be constant for all partings. This thickness would have to be adequate to allow bed sliding, but insufficient to allow the formation of clay lenses or masses between beds of limestone.

The consequence of the presence of thick lubricating partings between beds is well illustrated by the folds of Pl. 33, Fig. 3 at Te Kau Kau Point, where a fluid medium of greensand has been injected between the limestone beds during slumping. The sand, which was under a hydrostatic pressure similar to that of the limestone, was pervasive and sought out all zones of pressure relief and equalised all directional stresses except those carried inside the limestone beds themselves. The limestone beds were fed forward by the process of caterpillar folding into a mass of quicksand just as a ticker tape is fed into the air, and each bed behaved independently (Figs. 4 and 5). First one bed and then its successor looped out in front of the paralloid fold, but on this occasion (cf. p. 535) there were not even slight directional pressures to guide the folds which accordingly looped at random.

If one imagines the last situation carried one step farther, the whole of the overlying mass of limestone must advance over a mixture of greensand and broken limestone. From Ecuador, Brown (1938, p. 359) describes how a mass of limestone several miles in extent has slid forward over a sole-plane breccia hundreds of feet thick, and it seems that the disintegrating folds at Te Kau Kau Point provide a connecting link between that example and paralloid folds. Both the paralloid fold and the breccia serve as lubricating structures, the former as a kind of roller bearing and the latter as a greased plane. Despite a superficial appearance that violent orogenic forces operated in each case, the processes were probably slow and gentle and the stress gravitational.

The disrupted folds again demonstrate the relative sense of the terms competent and incompetent. In them we see the competency of a greensand less than that of the limestone, but in neighbouring localities greensand layers which are now indistinguishable from the last have behaved competently with regard to limestone. It seems that competence might in these bases be not relative to the materials involved but to the kinds of stress imposed on the beds. There is some evidence that the greensands become fluid when subject to sudden shock or to shearing stress and remain firm under a steady load. Such reactions are understandable if the sands contain even a small amount of mechanically unstable clay in their matrix.

Greensand intrusions are generally useful for distinguishing tensional zones which existed during or immediately following the formation of paralloid folds. This is illustrated by Pl. 33, Fig. 2, which shows a wedge-shaped greensand dyke cutting down from behind the nose of a fold and passing through the core into the bottom limb. Only one mechanism could have opened the original fissure this dyke fills; the beds overlying the fold must have moved forward over the fold and dragged the nose along with them (Figs. 4 and 5). Frequently such dykes cut only into the centre of folds and give a false impression that the folds have been burst from within, but this example is unequivocal. The intrusion may be interpreted as having occurred as the fold reached its limiting size and just when the internal friction in the nose had rendered the fold more or less rigid. The concomitance of fissuring and intrusion is particularly well demonstrated, for it is obvious that the fissure was formed while sliding of the overlying beds was still proceeding, and it is evident also from the smoothness of the dyke walls that there can have been no interval between fissuring and intrusion. If that were so there would have been some flow and lateral off-setting of the individual beds forming the walls of the cavity.

The concept of paralloid folding has an obvious and wide application to the study of folded nappes, some of which may readily be construed as large paralloid folds. Harrison and Falcon (1936) have shown that flap folds may be formed by the forward rolling of superficial limestone beds down the slopes of young anticlines, as in Persia, and in paralloid folding we have a similar mechanism which can produce nappes at some depth below the surface. In New Zealand an example of a large-scale paralloid fold in the Amuri Limestone of Marlborough has been described by Thomson (1919, p. 328, Fig. 6), and from his text this appears to be about 100ft in diameter. The form of Thomson's fold is that of Fig. 3, and though the structure may not be far-travelled it can only be construed as a small nappe. The fold, whose axial plane plunges forward and downward in the general direction of dip of beds, would conventionally be described as "overturned", but it is clearly a fold which has been formed in that position and not one which has been turned over.

In the neighbouring area of Kekerangu, Macpherson (1951, p. 276–7) has recognised formation during the Pliocene of asymmetric folds and overfolds riding over the young Marlborough Conglomerate, and speaks of "incipient or arrested nappes". The Marlborough Conglomerate, with its slabs of Amuri Limestone 30ft across, is attributed by Macpherson to the mass sliding of young strata and is likened to Collet's orogenic sediments of the Alps. The way in which a sliding fold-mass of limestone can break up has already been described for the Opouawe area, and Macpherson shows how these sliding masses fared as they travelled into deeper water. On page 276 he states, "the remarkably large masses of Amuri Limestone, chert, and older rock types . . . almost certainly slid down the flanks of the embryo folds and were included with the coarser clastics". Very clearly Macpherson's views on the growth and erosion of growing anticlines are the same as those of the writers, but, whereas he studied fold structures in limestones which are now deeply eroded into the synclinal areas, the Opouawe area only covers the events on the crest and upper flanks of a growing fold.

Sandstone Dykes.

A distinctive feature of slump folds as compared with tectonic folds lies in the directional relations of their tensional and compressive structures. Tectonic folds are usually considered to be the result of crustal compression on a sub-continental scale, and when small groups of folds are studied it is usually assumed that the forces causing folding have been imposed from outside the area. This view allows that regional directions of compression and tension may be normal to each other.

With slumping it is otherwise, for the motivating force is gravity applied and localised inside the slumping mass. The resolution of gravity and of downward

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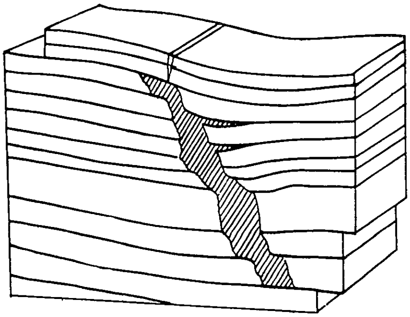

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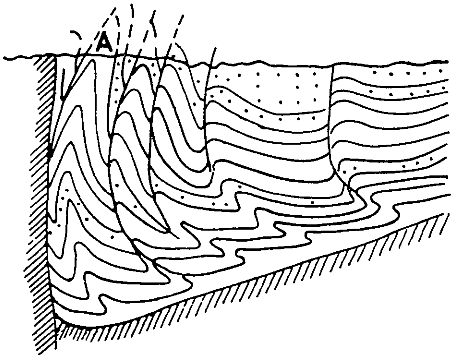

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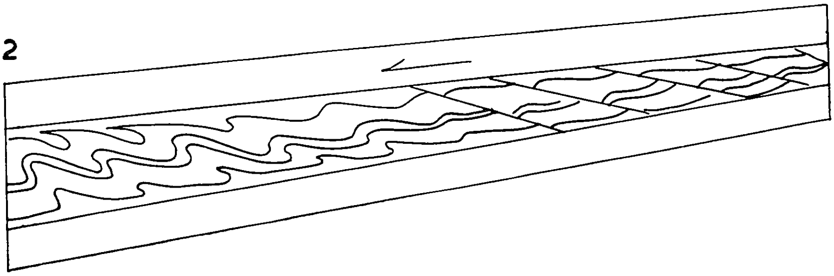

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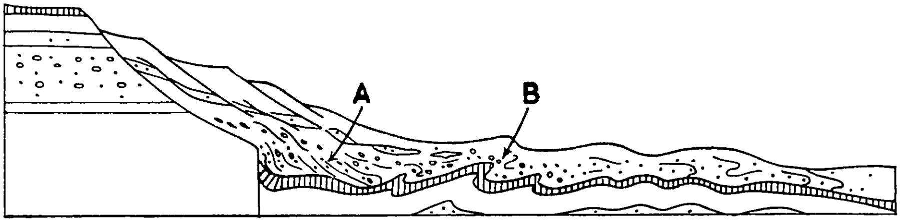

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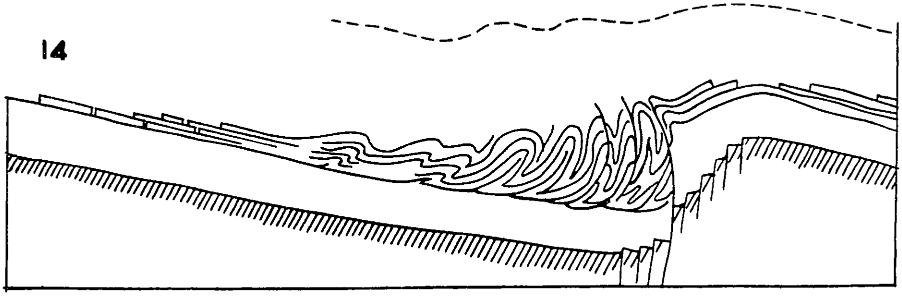

FIG. 10.—Sandstone dyke *cf* Plate 34, Figs 1 and 2. FIG. 11.—Passage of slump folds into diapiric folds *cf.* at A, with Pl 37 and, at B, with Pl. 36, Fig 1 FIG. 12.—Slump-drag folding to show transition from tension (right) to compression (left) and thickening down dip. FIG 13.—Slump across fault plane *cf* at A and B, Pl 34, Figs 3 and 6 FIG 14.—Mass slumping into fault angle.

movement into the plane of sliding results, therefore, in movements which are relative to the adjacent country and which may cause compression against one part of the country rock and tension in the same direction in another part. This generalisation, that compression and tension may be parallel, applies to the slumped formation as a whole and does not apply to individual folds or fissures.

Tensional structures are common in the slumped formations of the Opouawe-Awhea area, but the most numerous and instructive are those sandstone dykes and tensional fissures in the Mungaroa Limestone and Whangai Formation near the mouth of the Awheaiti Stream (Pl. 34, Figs. 1, 2 and 5: Pl. 35, Fig. 1). The sandstone-dyke fillings, which are mechanically weaker than the limestone, are often eroded, leaving trenches, but they are stronger than the Whangai Shale and stand out above the formation as residual ridges. The filling is a textureless grey-green sandstone coloured with glauconite and occasionally including mud pellets and small rectangular prisms of calcite. The latter, which resemble phenocrysts of feldspar in the dyke and which might possibly mislead one into regarding the dykes as igneous, are in fact the fragmented thick shells of *Inoceramus*. The presence of these Cretaceous shell fragments signifies that the sand was intruded from the Piripauan sandstone members 300ft below the limestone, and it may be supposed that intrusion of the sand from that level was a hydrostatic response to tensional fissuring and relief of pressure. Why the sands flowed as readily as they did is a problem, for there are no obvious reasons, and it can be surmised that lack of sorting and a very small clay content along with the presence of water must have been sufficient to produce mobility.

Some dykes, particularly the 20ft-wide dyke at Te Kau Kau Point (Pl. 34, Fig. 2) were probably the result of sedimentary infilling of open fissures. The greensand in this case contains carbonaceous "fucoid" remains which are randomly disposed in horizontal planes and are suggestive of bedding-plane deposition rather than of intrusive flow structure. There is no great conflict in the two lines of evidence, for the two types of filling could conceivably have occurred at different times and under slightly different conditions of depth.

Because of their positive or negative relief and their contrasting colour and texture against the white and bedded limestone, the dykes are conspicuous in the field and can be seen from some distance. The broader character of the dykes is variable, some dykes being vertical and others being inclined, and thickness varies from a few inches to several feet. Usually there is no obvious system among the dykes, because they are relatively few and are too scattered, but two miles south of Limestone Hill the Whangai Formation is cut by numerous sandstone dykes which fall into a rectangular pattern (Pl. 34, Fig. 5). In the foreground of the figure the hammer rests on a ridge-like dyke which runs from left to right and, parallel to it, and 15 yards from the camera, another light-toned dyke stands out. Marked by a piece of box wood and leading away to the top-right there is a third dyke at rather more than 90° to the first two. The regularity of the pattern suggests that the dykes were caused by one system of stresses and that they were opened simultaneously by a movement in the direction of the bisector of the obtuse angle between the fissures. If this were so it would imply that the dyke fissures were caused by a resolution of a principal tension into two tensional shears. Allowing then that the Whangai Formation was capable of resolving stresses by shearing, it can be concluded that the formation was relatively rigid and relatively consolidated, and that the dykes were intruded at least as late as those in the Mungaroa Limestone.

Among the most interesting of all the dykes is that illustrated by Pl. 35, Fig. 1. This is a clean-cut dyke which looks as though it had been forcibly injected into the limestone and had pushed aside the walls and upturned the edges of layers of limestone in its path. Those are, however, only apparent effects, and a closer examination shows several features of the dyke walls which suggest that they were not bent by a forcible intrusion. It is observed, for example, that beds towards the base of the dyke show a tendency to turn down instead of up and that beds half-way up the dyke are thickened at the contact. Again there is a vertical offset of beds on one side of the structure with respect to the other, and a bed is missing from its place near the top on the left side of the dyke. This last cannot be attributed to a phase of erosion between the intrusion or the dyke and the deposition of the unfaulted beds above it, for there is a general conformity at this horizon and the dyke was certainly intruded after the deposition of the whole of the limestone.

On any other hypothesis it would seem to be impossible to explain the formation of the dyke without invoking some compound mechanism such as faulting and unconformity, but all of the phenomena can in fact be rationalised in terms of one process, laminose flow. For convenience the beds in the figure are grouped into three blocks lettered A, B and C, and it is supposed that before fissuring occurred the limestone reacted as two blocks, an upper, A, and a lower, BC. Now if it be imagined that laminose flow occurred and that the block A moved to the left over block BC it will be apparent that the latter could be split by drag of the overlying beds and that the block B would move away from block C, leaving a fissure behind it. It is evident that beds at the top-right corner of block B must have been poorly disposed to withstand the frictional drag due to continued movement of the block A and that "shearing out" could account for the elimination of the top bed at the corner of the block.

Apparently some beds at the time of separation were highly plastic, and they tended to be squeezed back by load pressure into the space they had left, just as mortar may be squeezed from between two bricks. A very small amount of flow did occur in the beds low down on the left side of the dyke, and this resulted in thickening of beds next to the contact. Flow could become possible only because of some local relief of pressure, and it seems that an inflow of greensand rapidly neutralised the relief which was consequent on fissuring. Flow of beds was, therefore, restricted, but there was a continuing relief at the top-left of the dyke where the uppermost bed of block B was being sheared off. This relief extended down the side of the block and allowed a thickening of beds and caused the cumulative upturning which gives the impression of forcible intrusion.

Though important in themselves these plasticity mechanisms are subordinate to the mechanism of laminose flow. The implication of that process in this instance is particularly sweeping, for it is not merely that block A has moved forward but that all of the limestone up to the surface of the ground or bed of the sea must also have moved forward. The nine-inch width of the dyke shows only the minimum movement of block A over block C, and as there is no other visible effect of this movement it must be accepted that very large movements would leave no trace either, and it is possible that hundreds of yards of movement have occurred.

It is useful at this point to enquire why it is that a limestone sufficiently plastic to be squeezed back into a cavity it had just evacuated should ever have formed a fissure in the first instance. One might expect that the plastic material would simply have stretched or, alternatively, that if rock were rigid enough to break on a sharp face it would not have flowed back into the cavity. From observations made in the field it is concluded that the limestone behaved in different manners at different times, and this would be consistent with the fact that rigidity and plasticity of rheid materials are functions of time. To short term stresses the limestone would behave as if it were rigid and would snap, and to long term stress it would react plastically and would flow. It is probable then that the fissuring was the result of a sudden jerk forward of the beds, perhaps following an earthquake, whilst the squeezing was a leisurely process due to the load of the overlying beds.

Comma Folds.

In the last example it was shown that the movement of beds on bedding planes could result in a fissure that was blind at the top, but no mention has been made of the lower end of such fissures. It is conceivable that the bottom as well as the upper end of a fissure could be closed by an unbroken bed and that a fissure might be rectangular in cross-section. The system of movements would be the same for both the upper and the lower end, and it seems probable that closed fissures of varying lengths must have been common. Such fissures were probably filled with water as they were formed, and in many cases they would be sufficiently open above or below to allow an influx of quicksand. While a greensand filling would prevent anv great flow of limestone into the fissure, it is conceivable that a water-filled cavity might allow some squeezing in of limestone from the sides and a closing of the space. By its very nature such a process would be difficult to demonstrate, but at Limestone Hill this process certainly occurred.

At that locality a fissure in the Mungaroa Limestone has been filled by a set of "plastic" folds of limestone which have apparently been extruded from the vertical wall. The structure was not easily accessible to the camera, but Pl. 35, Figs. 2 and 3, show its important features. Beds on one side of the original opening have apparently exuded from between one another as grease does from the leaves of a spring, and have given rise to a number of hanging or *comma* folds. That part of the cavity seen here is the lower portion of a rectangular fissure, and it seems that the comma folds having attained a given length became too heavy for their own support and broke away to collect on the square floor of the space. The general view (2) shows the hanging folds as some six feet long and the close-up (3) shows the nested and rather shorter dropped folds resting on a bedding plane and filling up the squared end.

The six-feet lengths of the folds must have been derived by a vertical compression and thinning of beds, and yet there are no signs of thinning in the immediate vicinity. It must be concluded that thinning at any one point was very slight and that the sideways displacement towards the fissure was cumulative; thus the six feet of movement between beds must have resulted from a thinning and sliding over a distance of many times six feet, perhaps of the order of sixty. Over this distance the mean amount of bedding-plane slip must have been three feet; yet there are no traces of sliding in the beds, and it is conceivable that, had movements amounted to thousands of feet, such signs would have been no more obvious.

The dropped comma folds present an anusual case where all the circumstances of folding are known or can be deduced. It may be assumed that the cavity into which the folds dropped was filled with water and that the force which caused the folding and breaking of the lobes was the weight of the lobes themselves. Ignoring the hanging lobes, which are in part supported by one another, the fallen lobes have a length of some three feet, and a one-inch-square section of this length must have had an approximate weight (allowing for the support of the water) of two pounds. Two pounds per square inch would then be the probable minimum tensile strength of the limestone at the time of snapping, and allowing a margin of error of two times we get a figure of from two to four pounds per square inch for the tensile strength of the rock. This corresponds reasonably well with that of cold and very stiff plasticene. The curvature of the folds next to the wall of the dyke similarly gives an idea of the bending moment causing folding, for it is apparent from Pl 35, Fig. 2, that the weight of the lobe acting at a distance of less than 12 inches was sufficient to cause bending. This can be worked out as before to show that a force of about three pounds acting as a radius of one foot would cause folding; this is like that required to bend stiff clay or plasticene

The character of the fissure must not lead one to suppose that the original cavity could ever have been truly empty or a vacuum. Allowing that the limestone had a density of 2·25, the differential pressure p.s.i. at the foot of a fissure open to the air must have increased by about one pound per foot of depth. If the limestone could support a sustained load of as much as 12lb p.s.i., which is doubtful, any cavity more than ten feet deep and open to the air would close up by inflow of its walls. It is certainly possible that fissures deeper than that could be formed by sudden stresses, but it seems unlikely that fissures full of air could have ever been formed to depths greater than 50 feet, and extremely unlikely that a vacuum could be formed at all.

Similarly with fissures formed below the sea-floor and in any way in continuity with sea-water; the differential pressure, allowing for water pressure, at the foot of walls must have increased by about 0 5lb p.s.i. per foot of depth, and the maximum depth to which permanent fissures could extend below the sea bottom would be only 20 feet. Again, temporary fissures might be formed at greater depths, perhaps to 100ft deep, but they would be infilled as in the described example. With a filling medium such as quicksand, with a density of about 1·7, a hydrostatic head of pressure would allow the sudden formation of fissures up to some 200ft deep, and in this case the fissure would remain "open", for the squeezing in of the walls would be prevented by the strength of the consolidated sand. In the last two cases it has been assumed that there was some continuity between the sea and fissure, but it is possible that fissures could be filled with connate water or greensand under pressure. Such fissures could be formed at any depth, but the figures 100ft and 200ft respectively of water and greensand would still be the measure of their possible vertical extent. With a system of echelonned dykes, or with a different filling medium, series of dykes such as the 300ft-high examples of Baldry (1938) would be feasible, and with consolidated strata there would be no immediate limit. In the case of this example, however, the limestone is so broken that it is hardly possible for a pressure system of water or quicksand to have been isolated from the sea, and it appears that the sandstone dykes must have been formed at depths below the sea-bed of not more than 200ft, and in the case of the limestone-filled dyke no deeper than 100ft. In substance, then, the latter dyke was little different from the deep water-filled fissures one sees in great landslides of clay, and the bridging beds over the dyke only mask its simple character.

Comma folds are not uncommon, but it is unusual to see so many together or to see them in sectional view. More often they are seen weathered out, singly and in full view, and then they form long, conspicuous rolls up to 20ft long and 2ft or 3ft across. Such rolls have been observed (by J. B.) in the coal measures of Britain, in the Triassic coal measure of Tasmania, and in many deltaic deposits. They can be seen in the process of formation at the bottom of deep open cut faces like those in the great clay pits in the Northamptonshire Jurassic. Sometimes they occur, at the base of cliffs of boulder clay, along the coast of North Yorkshire, and, also, more strictly comparable with the infilled dykes, they can be seen in the process of extrusion from the seat earths of shallow and wet underground workings in the West Durham coalfield, of Britain. The rocks in this last instance are Carboniferous in age and are firm enough to require extraction by picks, yet when wet they are sufficiently plastic to flow, and fill underground workings within a month. As the seat earths often occur below coal seams, extrusion is usually from the floor upwards, and is called "floor heaving" by the miners, but where a clay parting divides two seams the clay is extruded in long rolls from the walls.

Any down-cutting processes which cause local and sideways relief of pressures may cause the formation of "gouts", and undercutting by a river into a clayey alluvium will often result in the extrusion of soft clays along the banks. Phenomena vary from shallow-seated sideways extrusions of rolls to the deeper seated and upward arching of the clays of river beds. Bradley (1954, p. 199) has described a similar kind of heaving as occurring in front of rapidly retreating marine cliffs, and it is obvious that such processes of mechanical undermining of hill slopes and cliffs must produce important erosional effects

Recognising the extreme plasticity and weakness of the Mungaroa Limestone, we may review the concepts presented earlier of laminose flow and paralloid folding. No longer does the analogy of sliding sheets of paper appear to be idealised or an exaggeration, and the pliable beds sliding on their lubricated partings must have been much more like a pile of soft slithering hides. The general view (Pl. 36, Fig. 2) illustrates this point better than words, but to visualise the picture properly one must consider that every bed was soft, not one bed was in repose by virtue of its own strength, and that the beds were poised in a most delicate and uneasy equilibrium.

One might expect from the form of the folds that they were the result of some violent plunging, and the analogy of hides just given might, because it presents a short term picture, foster this impression. That would be far from the truth, for, if the processes of tilting were slow, the freedom of movement of strata was such that the beds must have adjusted themselves by equally slow and gentle movements It was because such slow adjustment was possible that the limestone could behave plastically and could form ideally smooth folds. On the other hand, where the limestone is fractured movement must have been sudden. Rapid motion undoubtedly caused the formation of sandstone dykes and fissures, and is suggested by the broken folds of Pl. 33, Fig. 3. Further, and despite the general slowness of slumping, it is probable that the folding also included many small steps of accelerated movement due to localised lurching.

Joints.

The tiny steps of movement just mentioned are revealed by the multitude of joints occurring in and peculiar to some of the slump-folded limestones (Pl. 34, Fig. 4). Joints run in every conceivable direction, and tiny offsets on all but the latest show that each set of fissures was healed by a growth of calcite before a new set was formed. Allowing that the process of healing was slow, it follows that joints were formed over a long period, and, as the directions of tension were so many, it is concluded that there were constantly changing directions of local stress. The vast multitude of tiny veins, which are locally so great in total bulk as to comprise most of the rock, clearly indicates that the strength of the rock at the time of fracturing was slight and so low that tensions could not be exerted for more than a fraction of an inch. These facts are consistent with the notion that joints were formed while the limestone was undergoing repeated to and fro adjustment, and as tilting of the sea floor or consolidation of the underlying sediments allowed movement in this or that direction.

Skew Folds.

The study of jointing in slumped folds leads to another important conclusion, that paralloid folds are not always the result of sliding in the direction normal to fold axes (Fig. 6). It has been shown that a paralloid fold may be initiated by some chance irregularity on a bedding plane and that frictional irregularities might be caused by small calcite- or silica-filled fissures reaching from one bed to its neighbour. It is the orientation of these, not the direction of movement of beds, which determines the orientation of axes of many shallow-seated growing folds. It is true that an obstacle influences only the tiny initial fold, but this in turn determines the next stage of growth, and so on. An experiment with a sheet of paper will demonstrate to the reader that caterpillar folding with motion oblique to the fold axis must involve some distortion of beds. At the same time it will be borne in mind that the limestone in question was pliable but weak to tension and was quite free to slide. It will be apparent, then, that a limestone bed could flow forward over almost any smooth obstacle, and that it could ride over the crests and troughs of an oblique fold by a development of tensional fissures. These fissures, which would be more or less normal to the direction of travel, would open out as they approached axial planes and close up as they passed them. Travel would be further aided by rotation of the small fissure blocks and the process would resemble the flow of glacier ice over a fall oblique to its course.

This process of flow oblique to fold axes is demonstrated in nature by snow slides in the valleys of roofs or along the sides of avalanches, and its results can be seen in the folds of clay along the lateral margins of landslides. Folding of this kind is shown (Pl. 33, Fig. 4) by a fold in the Mungaroa Limestone where the direction of travel was probably from right to left and across the cracks at the top of the fold. It is noted that each crack is widest at the nose and that it narrows to either flank of the fold.

So far we have spoken only of a bed sliding obliquely over a fold, but it is obvious that a bed might be involved in the lower angle of a caterpillar fold, and a kind of paralloid fold, a "skew fold", might be formed by a process of oblique flowage. The significance of the process is that axes of paralloid slump folds are not necessarily normal to what was the direction of travel of beds or to the slope of the then sea-bed.

Slump Drag Folding and Mass Slumping.

The last example shows how slump folds may achieve random dispositions, but it does not follow that folds are generally irregular. Skew folds can probably arise only at shallow depths, where fissuring is possible, and at greater depths folds must usually be formed with axes normal to the direction of transport. The study of slump folding in deep sequences cannot be explored here, but the treatment of folded beds of the order of 1,000ft thick is profitable. With this thickness of beds it must be common for massive and less readily folded beds to occur above and below thin bedded sequences, and consideration will be restricted to such groups of beds.

When sequences such as this are tilted, the overlying massive beds, while remaining unfolded themselves, will slide over the more accommodating lower layers and contort them in the process. This is depicted in Fig. 7, which shows the contortions as drag folds very similar to those of tectonic environments. The regular arrangement of slump drag folds is well illustrated by the numerous structures in the Amuri Limestone of the South Island at Kaikoura Peninsula and near the Conway River mouth (Pl. 36, Fig. 3). The scale of folds varies from that shown in the illustration to folds with limbs up to 100ft long, and so widespread are the folds that were it not for the open and general folding in the country around one might take them to be of tectonic origin.

The cause of tectonic drag folding is generally attributed to the contrary slip and frictional drag of competent beds enclosing less competent strata, and we may expediently assume the same here There seems, however, to be some lack of emphasis on the important role played by bedding-plane slip in drag folding. The operation of this slipping is readily understood if we consider the drag folds of Fig. 7 as consisting of a lower and normal paralloid fold interlocked with an overlying but inverted fold of the same kind. The sense of motion of beds in the lower half of drag folds is like that of a paralloid fold, and if the reader inverts Fig. 2 the relative movement in the upper half will be seen to be the same. As in paralloid folds, the folding and thickening of drag-folded formations (Fig. 12) results from a forward and upward relief of pressure, and axial planes are inclined in that general direction.

The detailed examination of drag folding must wait, but meanwhile the broad process is obvious, and it is clear that massive unbroken beds may glide forward and downward into tectonic depressions. It is also obvious that drag folds themselves must involve an appreciable amount of transport and allow some thickening of beds down dip. The presence of crumpled strata between unfolded beds appears to be common, and the explanation just given serves many of the examples by Miller (1922). In particular it applies to the pronounced interstratal crumplings recorded by Logan (Miller 1922, p. 591) from the Devonian limestones of Quebec, and by Miller (1922, p. 588) from the Ordovician Trenton Limestone of New York.

Comparable with the break-up of paralloid folds by injection of greensand is the break-up of drag folds illustrated by Figs. 8 and 9. Such a complete brecciation normally occurrs because of the presence of thick clay partings rather than because of intrusion, and it is restricted on the East Coast to the Kandahar and the Cretaceous formations. In the latter now thoroughly lithified formations, boudins have been formed, and these have been rolled up into cigar shapes or squeezed out into lenses. Where the beds were originally conglomeratic, pebbles have been rotated and polished, and strata appear to have suffered intense shearing. This effect is sometimes heightened because some of the more obvious "attenuated pebbles" were originally mudflakes in redeposited sediments, and confusion mounts on confusion when such beds have also been tectonically sheared.

The travel of mile-wide sheets of unbroken strata over sole-plane breccias appears to be of wide occurrence and has been described by Baldry (1938) from the Tertiary of Peru and by Kuenen (1948) from South Wales. Here, as with drag folds, the sole-plane breccias allow the transport of unbroken sheets and at the same time allow transport inside themselves and a thickening of beds down dip (*cf.* Fig. 12).

Sole-plane breccias probably represent an extreme form of drag folding and may result in more distant transport of cover beds, but the effect in each case is the same. Riding sheets may break up in transport and give rise to coarse molassic breccias of the Marlborough Conglomerate type, or they may gravitate into tectonic depressissions and concentrate their full energy of motion in complex folding in the deepest troughs.

In New Zealand a characteristic form of tectonic depression is the fault-angle structure, and Fig. 11 shows on a small scale how beds may flow down a slope and may be halted against a fault scarp. In different instances flow might be of massive beds on soles or drag folds, or, as in this case, might be laminose flow. The evidence for this structure lies in diapiric folds of the Mungaroa Limestone such as that depicted from White Rock (Pl. 37). The fold is lodged against a fault crush-zone, and both structures have been traced (by J. B. W.) for many miles along a prominent fault line. In many places the fold is paralleled away from the fault by several other folds of diminishing amplitude, and, as in the plate most are found to have steep axial plunges and rapid crestal culminations and depressions. In the figure the abruptness of change of inclination of axial plane in passing from paralloid to diapiric fold may invite critical comment, but Pl. 36, Fig. 1 showing the lower extremity of a paralloid fold at Te Kau Kau Point illustrates how rapid this change may be. A thrust plane, marked in white and running parallel to the axial plane, begins as a bedding-plane slip and curves swiftly upwards into a near-vertical attitude. By extrapolating this fold and fault upwards we inevitably arrive at the diapiric folds and thrusts of Fig. 11. This section has much in common with that described by Fairbridge (1948, p. 187) from Queensland. He shows how sandstones and clays have slid along sole planes into an asymmetric syncline, and his Fig. 6 implies much the same kind of drag folding and bedding-plane slip as are postulated here.

Much larger fault-angle depressions on a scale comparable with the major structures of New Zealand (Cotton, 1950) probably present many large gravitational folds. These are depicted by Fig. 14, which is an idealised interpretation based on the structures in the Amuri Limestone and adjacent formations of the Clarence Valley, Marlborough. The figure utilises the structures identified in that general area by (McKay 1886, pp. 94-5), Wellman (1955, Fig. 4), and Thomson (1919, Fig. 6) and the ideas expressed by Macpherson (1951) and by the authors of this paper There is, perhaps, no proof of the validity of this interpretation except that it explains most of the limestone structures within the framework of one hypothesis. It will be observed that the structures are independent of the nature of basement faults whether they be normal, reverse or transcurrent, and of whether or not some recent basement faults are superimposed on the folds. The nature of the folds is also in a large measure independent of whether sliding was submarine or terrestrial, and it is probable that sliding was effected through the beds below the limestone as well as in the limestone itself. If this view of the Clarence structure is correct, then the area cannot be an ideal one for stratigraphic study. Certainly the unconformity cautiously depicted by Thomson (1919, Fig. 6) could be misleading. Because of slumping it is probable that traces of low-angle faults would often be parallel to strikes of beds for many miles, and an argillaceous formation like the Whangai would probably thicken or thin out altogether.

Finally, and whether or not the structure supposed for the Clarence Valley is true, the view is still reasonable, and structures of this kind must be allowed for in any study of Tertiary formations of New Zealand.

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