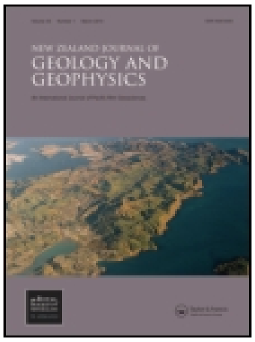

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Loess Deposits of the South Island, New Zealand, and Soils Formed on them

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LOESS DEPOSITS OF THE SOUTH ISLAND, NEW ZEALAND, AND SOILS FORMED ON THEM

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ABSTRACT

Loess deposits from 1 to more than 25 ft thick are widely distributed over the eastern and southern downlands, hills, and older plains of the South Island from Marlborough to Southland. They are wind-borne deposits derived from (1) greywackes of the Southern Alps in Marlborough, Canterbury, and north-east Otago, (2) metamorphic schists elsewhere in Otago, and (3) tuffaceous greywackes, basic igneous rocks, and schists in Southland. The loess deposits are in most places compact, of low permeability, and, with minor exceptions, contain no free lime. At least six layers of loess can be distinguished, three being assigned to the Last Glaciation and three to the Penultimate. Periods of loess deposition correspond with glacial stadia, and periods when little or no loess fell with interglacial and interstadial periods. Slight to moderate weathering took place during interstadial periods and more advanced weathering during the last interglacial period.

Present and fossil yellow-grey earths formed on the South Island loess have a subsoil pan that is considered to express compaction that took place mainly during the period of loess accumulation. Increased biological activity and more active soil formation during the warmer and wetter interstadial and interglacial periods caused fragmentation of the pan to a greater or less extent. The pan is thought therefore to be a feature inherited from the period of loess deposition and not a product of the current pedological environment.

INTRODUCTION

Loess of Pleistocene age is widely distributed over the hills, downlands, and terraces of the southern part of the North Island and of the South Island east of the Alps. In the South Island loess 12 in. thick or more mantles more than 2·5 million acres. Moreover, the soils of a large area of productive agricultural land (more than 1 million acres) are formed on loess; it is therefore an important economic deposit.

The term *loess* is used here in a somewhat broader sense than that of the United States or European usage. It is applied to any fine-textured deposit of aeolian origin other than sand dunes (where particles are transported chiefly by saltation). It thus embraces all aeolian deposits where transport has been primarily by suspension, irrespective of content of organic matter, mineralogical composition, calcium carbonate content, degree of compaction, or texture. Definitions of loess based on the properties of the loess of Europe would in fact exclude the New Zealand deposits. The term *loess*, from the German verb *lösen* to loosen, emphasises the predominantly porous nature of most European loess. Recent studies, however, have shown that some of the loess of Germany, that in which pseudo-gley soils have formed, is compact and of low permeability—like New Zealand loess. The definition proposed by Russell (1944), which requires that 50% of the particle size distribution should fall between 0·01 mm and 0·05 mm, and that the deposit should be porous, calcareous, unstratified, and homogeneous, would also exclude the New Zealand deposits, which are not only compact and of low permeability, but also non-homogeneous, and non-calcareous. Nevertheless, in spite of these restrictive definitions, the term loess is commonly used to designate any aeolian deposit of fine sandy loam texture or finer. It seems desirable therefore to accept this usage, and instead of attempting to refine the term in the interests of precision it would be more satisfactory to subdivide loess into classes according to variations in lithology, degree of weathering, compaction, or stratification. The term is used here in this broad sense.

In the South Island, loess extends as a more or less continuous mantle ranging in thickness from about 12 in. to more than 25 ft on the hills, downlands, and high terraces from Blenheim in the north to Invercargill in the south (Fig. 1), and serves as the parent material for large areas of the yellow-grey earth soils of the South Island as well as of arable yellow-brown earths in Southland. These soils support a large part of the mixed farming carried on in the South Island. They produce more than 50% of the cereals grown in New Zealand, and, as the population grows, the burden of increased production will fall heavily on them. The study of the loess deposits and the soils formed on them is thus an important aspect of agricultural research.

Previous Investigations

Loess was first recognised in New Zealand by von Haast (1879) who described the deep yellow silts of Canterbury as loessial silts of Pleistocene age. Shortly after this Richthoven's description (1883) of the loess of China appeared, and for the next few decades the South Island loess, in particular the thick deposits in South Canterbury, received a good deal of attention from geologists. Haast's view that these deposits were aeolian was supported by Hardcastle (1889, 1890, and 1908), Speight (1908 and 1917), Marshall (1912), and Heim (1906), and is no longer disputed. Various alternative views of varying plausibility, however, have been advanced. Hutton (1883 and 1905) held that the deposits were marine, because of some apparent stratification in the loess of Banks Peninsula and the presence of marine fossils, but he left no record of his collecting sites and his observations cannot be verified. It is possible that he was describing loess that had been reworked and that the deposit in question would not now be accepted as undisturbed loess. Goodall (1886) held that the loess of the Timaru district, since it rested on an isolated and elevated sheet of dolerite lava, could not be alluvium, and must therefore be volcanic ash. The aeolian hypothesis was later challenged by Wild (1919) on the grounds that its mechanical composition included more sand than the loess of North

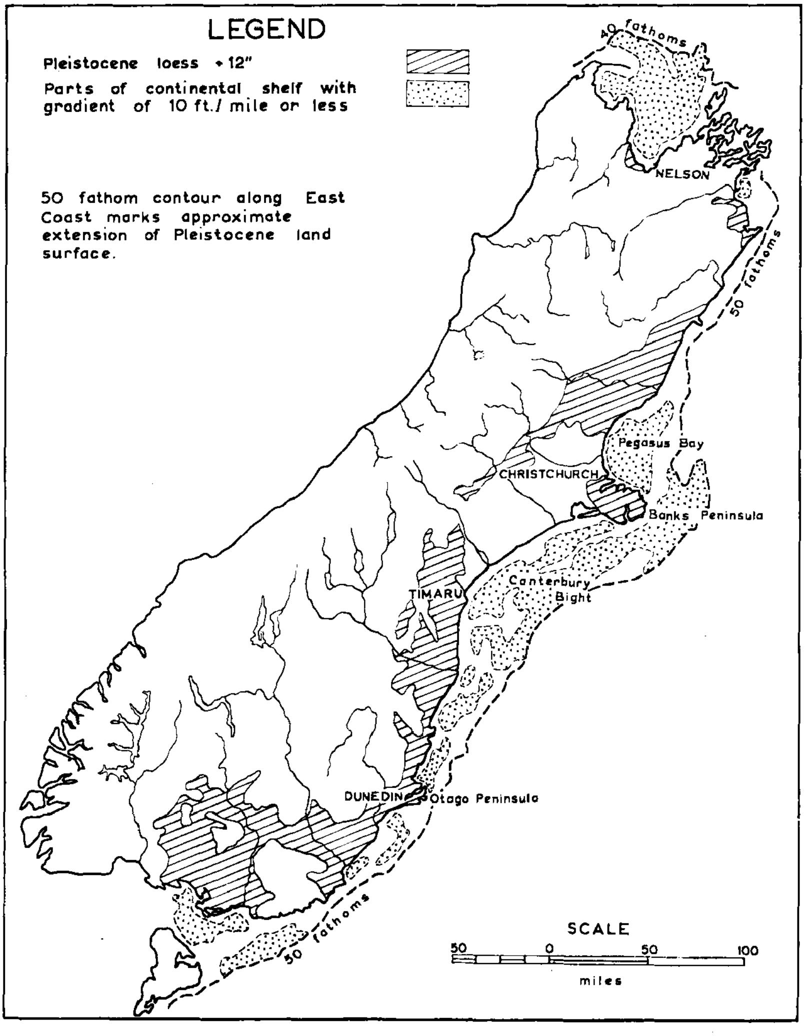

FIG. 1—Loess deposits more than 12 in. thick of the South Island, New Zealand. Parts of the continental shelf with low gradient are also shown.

America. Wild also claimed that the absence of marine fossils carried no weight in determining the origin of the loess and advanced the curious inference that "the remains of *Dinornis* and other land birds must be interpreted as evidence in favour of marine origin rather than the reverse".

Recent contributions to the study of loess include Willett's (1950) discussion of its distribution with respect to the Pleistocene snow line, and Wood's (1956) observations on the distribution and composition of the loess in the Gore district. Gage (1957), from a study of the loess of the Oamaru district in north-east Otago, concluded that "the main period of loess formation is at least as old as the maximum of the last glacial stage".

DISTRIBUTION AND NATURE OF LOESS DEPOSITS

With the exception of a few localities where the loess is currently accumulating, or has only recently been deposited from nearby sources, where the texture is a fine to medium sandy loam, the South Island loess is uniformly a silt loam. (For detailed mechanical analyses *see* Birrell and Packard, 1953.)

The loess mantle varies greatly in thickness. Over most of the downlands of the South Island it ranges from 3 ft or less to more than 25 ft, the average being about 4 ft. In a few places, notably in the Timaru district of South Canterbury and on the flanks of Banks Peninsula, the average thickness is more than 6 ft. Much loess has been removed by erosion, and on the lower slopes of hills it has been augmented by solifluxion, soil creep, and wash from higher slopes. The original thickness of the mantle received by any particular site cannot be accurately determined, and therefore isopachytes from which the origin of the loess could be studied can be drawn only approximately.

On hilly land the loess mantle is thinner and more variable in thickness. In many places it is less than 12 in. thick and can be detected only when it rests on a rock of contrasting lithology. In many places this thin veneer has been incorporated into the sedentary soil profile and the contamination of the soil by loess is by no means obvious.

A thin veneer of loess also covers the high terraces and older plains and fans both on the coastal plains and in the inland basins and valleys, mostly less than 10 in. thick but in a few places reaching 2 ft or more.

In the immediate neighbourhood of some of the major rivers loess is currently accumulating on terraces immediately to the south of the floodplain. Appreciable accumulations lying within 5 miles of the source, of fine-sand-textured loess, have been recorded from the Canterbury Plains south of the Waimakariri and Rakaia Rivers, from the downs and terraces near the mouth of the Godley River in the Mackenzie Basin, and from the Tasman Downs north of Lake Pukaki. Loess of Late Glacial and Postglacial age and of fine sand texture occurs also at Otama south of the Mataura River, and near Clydevale on the south bank of the Clutha River. Coarse-textured loess has also accumulated on the tip of Otago Peninsula near Harrington Point.

New Zealand loess is in most places compact, with permanent well defined vertical joints and less clearly defined horizontal joints. The vertical joints outline more or less symmetrical prisms ranging from 6 to 24 in. in diameter. The loess is of low permeability and contains from about 15 to 25% of clay. Loess of postglacial and recent age has a lower clay content and is much less compact. Loess in regions of high rainfall, as for example parts of Southland, is also less compact, the well defined permanent joints are wanting, and it is distinctly friable.

In Canterbury the loess is characteristically yellow to brownish yellow and weakly to moderately mottled; in Southland, where the loess contains more free iron, it is yellowish brown and more strongly mottled with rusty and orange mottles. This is partly because of the more advanced weathering of Southland loess under the higher rainfall of this region, and partly because of the higher content of ferromagnesian minerals. Under high rainfall, however, where the loess is friable, mottling is either indistinct or wanting altogether. In the Waitaki valley under rainfall of about 20 in. annually and less, subsoils in a few places contain small amounts of free lime, and near Timaru and on the flanks of Banks Peninsula there are a few small calcareous concretions in the loess, possibly derived from the weathering of enclosed moa bones. Apart from these minor occurrences of lime the loess is non-calcareous.

MINERALOGY OF THE LOESS

Regional Variation

South Island loess was derived from the basement rocks of the axial chain and the block mountains of Otago and Southland, and its mineralogy reflects the lithology of these rocks. It falls into three regional classes.

(1) Loess derived from the greywacke of the Southern Alps and their foothills extends from Marlborough in the north to north-eastern Otago somewhat south of Palmerston. Quartz and plagioclase feldspar in roughly equal proportions make up nearly 90% of the primary minerals. The remainder consists mainly of members of the epidote group (chiefly pistacite with associated clinozoisite and rare zoisite), with mica as an accessory mineral, and minor amounts of zircon, amphiboles (chiefly green and colourless hornblende), tourmaline, sphene, rare iron ores, volcanic glass (acid, with n = 1·48 to 1·50), plant opal, and sponge spicules. In the neighbourhood of loess sources there may be appreciable departures from these proportions.

(2) Loess derived from the metamorphic rocks of Otago extends from north-eastern Otago to northern Southland. It contains roughly the same proportions of quartz and feldspar as the loess of Canterbury, these minerals together making up from 70 to 80% of the primary minerals. Mica and chlorite are more abundant than in the loess of greywacke origin and may amount to as much as 7% of the primary minerals. Minor accessory minerals consist of epidote (mainly clinozoisite), with rare zoisite and very rare piedmontite, tourmaline, zircon, amphiboles (green and colourless hornblende), sphene, and iron ores. It also contains plant opal and sponge spicules but much less volcanic glass than loess of greywacke origin. Near loess sources this loess also shows some variation from the above proportions.

(3) Loess of tuffaceous greywacke origin is confined to Southland. It is derived primarily from the volcanic greywackes of Southland and to a lesser extent from the granites, diorites, gneisses, mica schists, feldspathic greywackes, and possibly also ultrabasic rocks of western and northern Southland as well. It is much more variable in mineralogical composition than the loess of Otago or Canterbury and reflects to a large extent the lithology of locally outcropping rocks (Woods, 1957). Broadly, however, it differs from the loess of the two previous classes in its greater proportion of feldspar, which may exceed 60% of the primary minerals, and the more abundant amphiboles. Brown hornblendes are more abundant than green and colourless hornblendes, and together they may amount to as much as 2 or 3% of the total primary minerals. Magnetite is also an important accessory mineral and may amount to 2% or more of the primary minerals. Minor accessory minerals include mica, chlorite, zircon, tourmaline, augite, sphene, and rutile. Plant opal and sponge spicules are rare accessory minerals and volcanic glass is very rare.

In addition to the three regional classes of loess listed above, there is a small area of loess on the downs and hills flanking Tasman and Golden Bays in the Nelson district. This loess is mostly less than 18 in. thick and may have been derived largely from the floors of these bays during low Pleistoecne sea levels, for thickness increases towards the coast. Small areas of loess have also been reported from the West Coast of the South Island, from high terraces at Karamea and near Westport and bordering river floodplains near Hokitika (Mr C. Vucetich, pers. comm.). The Nelson loess is more strongly weathered than loess elsewhere in the South Island, the chief primary mineral being quartz.

Within each mineralogical province the loess is not entirely homogeneous in mineralogical composition. In some places it contains minerals from locally outcropping rocks, and there appear also to be minor variations in the alluvium derived from the major mountain catchments. The loess also varies in mineralogical composition from layer to layer and from one local site to another within the same layer. These variations apparently reflect changing circumstances of transport, as for example variations in wind direction, turbulence, and velocity, and possibly also variations in loess provenance. There appears also to have been some sorting of the various minerals during transport. Coarse-textured loess deposited within 5 miles of a source and within the medium and fine sand range contains abundant roughly equidimensional grains, and the dominant minerals are quartz, feldspar, and epidote. Zircon, which occurs mostly as euhedral grains of very fine sand and silt size, appears to have been transported beyond this zone. Among roughly equidimensional grains sorting depends on relative density. The deposit is thus enriched in epidote near the source, and the zircon content is low. At Gore, for example, where the loess is a fine to medium sand derived from the nearby floodplain of the Mataura River, it contains nearly 20% of epidote. At Otama, in the upper reaches of the same river and also close to the floodplain, it contains nearly 18% of epidote. In the Clutha valley adjacent to the floodplain (within 5 miles), most loess contains at least 17% of epidote. Loess in the Dunedin district remote from a major floodplain contains about 6% of epidote.

Fine sand and silt grains carried beyond 5 miles from the source and transported in suspension appear to be subjected to a different sorting process. Feldspar, amphibole, and epidote occur to a greater extent as cleavage flakes than as equidimensional grains, and fallout is enriched with the more dense and equidimensional zircon. In deposits 10 miles or more distant from a major source, zircon may amount to from 6 to 9% of the heavy mineral fraction. Within 5 miles of a major source zircon rarely exceeds 1% of the heavy minerals.

Minerals and Microfossils of Light Mineral Fraction

Particles of density less than 2·3 are referred to as the light mineral fraction. In most loess deposits this fraction amounts to less than 2% of the total mineral fraction, and in many it is less than 0·01%. It is composed chiefly of the following: secondary minerals, sponge spicules, volcanic glass, plant opal, diatoms, and charcoal.

Secondary minerals occur as stable aggregates of two kinds: aggregates of plasma from colloidal infilling of cavities, microfissures, worm channels, and root traces, and montmorillonised shards of volcanic glass. Plasma aggregates consist mostly of flakes and contain abundant primary mineral grains of quartz and feldspar. They show optical orientation and moderate birefringence, and have a refractive index range from 1·54 to 1·56. In slightly weathered loess they are honey yellow and in more strongly weathered loess yellowish brown to deep brown. Some deeper brown flakes from dry inland sites show distinct pleochroism and may be nontronite.

Flakes of altered volcanic glass show a wide range in degree of alteration, ranging from shards with sharply defined conchoidal fracture to shards with ill-defined fracture and slight to moderate birefringence. Strongly montmorillonised shards are difficult to distinguish from flakes of plasma.

Secondary minerals are more abundant in topsoils than in subsoils, and most abundant in the upper horizons of Loess No. 4 (Table 1).

Sponge spicules as broken fragments are widespread throughout loess of Last Glaciation age. They are markedly more abundant and larger near the coast than distant from it. Near the coast, as for example at Harrington Point on Otago Peninsula, they reach a length of 0·25 mm and a diameter of 0·04 mm. Twenty miles inland they do not exceed 0·08 mm in length. They appear to diminish in abundance up to a distance of about 20 miles from the coast and thereafter occur only sporadically. The content of spicules shows also some local variation, and the total content rarely exceeds a few parts per thousand. Some spicules are extensively abraded and appear to have been subjected to prolonged wear, either on the continental shelf or during reworking of shelf sediment.

Spicules appear to dissolve readily in soil solutions, for none have been recovered from the upper horizons of Loess No. 4 (the weathered horizons of the soil formed during the Last Interglacial), and in the lower horizons of this loess as well as the underlying layers nearly all spicules recovered were deeply pitted with solution pits (Fig. 2). A few well preserved spicules may, however, be found on the outside of prismatic subsoil columns of some of the underlying loess layers. These were most probably washed down joints from overlying younger loess layers.

TABLE 1—Loess Formation, Timaru, South Canterbury

Loess No. 1	10 in.	medium grey friable silt loam
	36 in.	compact yellow silt loam to heavy silt loam with coarse prismatic structure and prominent vertical joints; sharp boundary
Loess No. 2	10 in.	moderately compact to slightly friable yellow silt loam with many worm channels
	28–40 in.	compact brownish yellow silt loam with coarse prismatic structure, well defined joints, rare moa bones; sharp boundary
Loess No. 3	10–12 in.	moderately compact brownish yellow heavy silt loam with many worm channels; sharp boundary
Loess No. 4	8–12 in.	compact pale yellow silty clay loam, fine to medium subangular blocky structure, mottled rusty orange and grey; distinct boundary
	48–60 in.	compact brownish yellow to yellowish brown heavy silt loam with very coarse prismatic structure, rare worm channels; sharp boundary
Loess No. 5	7–11 in.	compact brownish yellow heavy silt loam with many worm channels, some containing well preserved casts, scattered moa crop stones 1 in. to 1·5 in. in diameter; sharp boundary
	36–48 in.	very compact yellowish brown silty clay loam with very coarse prismatic structure, rare worm channels; sharp to distinct boundary
Loess No. 6	8–12 in.	compact yellowish brown heavy silt loam with many worm channels
	24–60 in.	very compact silty clay loam with very rare worm channels, scattered angular basalt boulders, and extending without perceptible break into fissures and caves in the basalt below
		on basalt

Volcanic glass is widely but unevenly distributed throughout the loess. It is markedly more abundant in loess of Last Glaciation age than in older loess, and it is totally wanting in the weathered horizons of Loess No. 4. It also has a more complex regional distribution than the sponge spicules. It is least abundant in the south of the Island and increases in an approximately logarithmic manner northwards. Loess from Fortrose near Invercargill contains only rare grains, but in loess from Marlborough it dominates the light fraction in some samples. In loess from the Wairarapa in the southern part of the North Island it amounts to from 1 to 2% of the total mineral fraction. Glass also increases in abundance from the coast inland in Last Glaciation loess, but beyond a distance of about 20 miles from the coast it appears to be evenly distributed in an east–west direction.

The glass is colourless and acid ($n = 1{\cdot}48$ to $1{\cdot}50$) and shows increasing alteration downwards through the loess. In Loess Nos. 5 and 6 many altered glass shards can be identified only tentatively from surviving traces of flutings and conchoidal fracture.

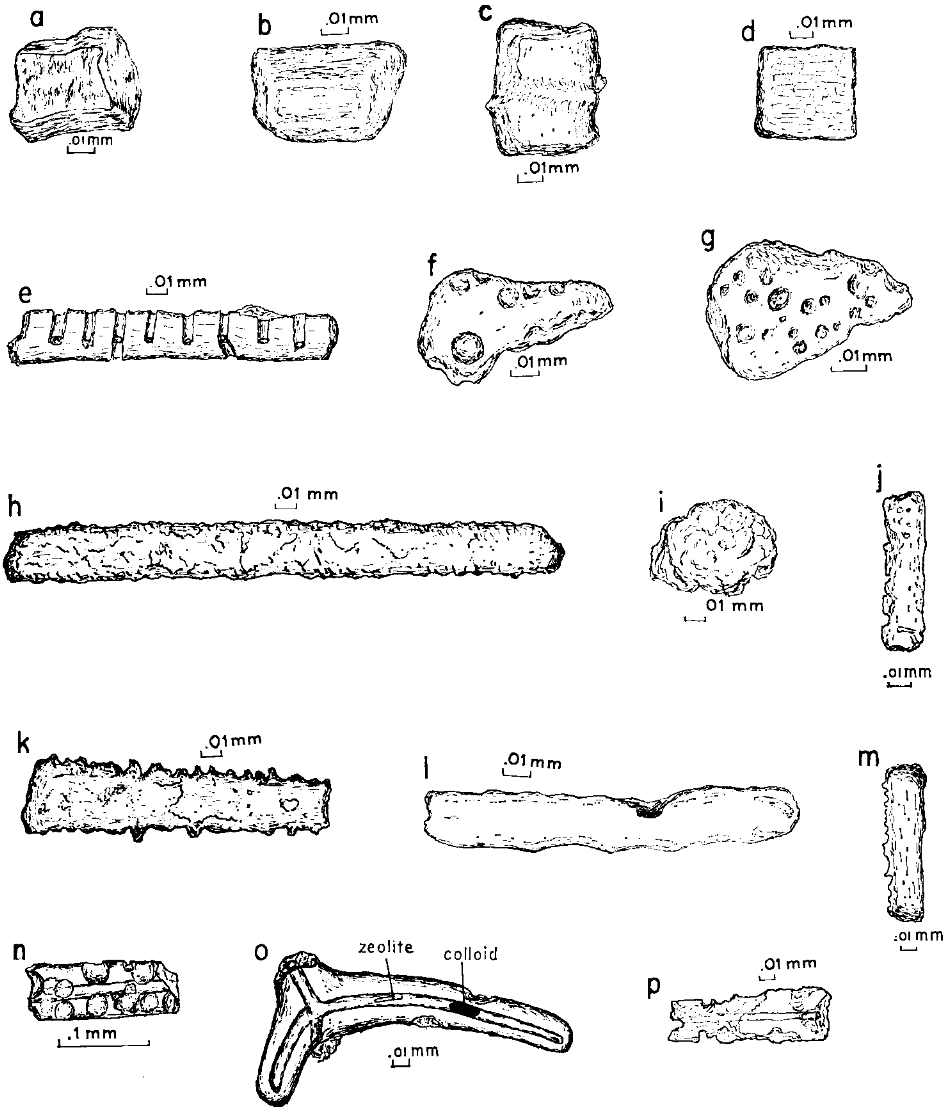

FIG. 2—Plant opal (*a–m*) and sponge spicule (*n, o, p*) forms from loess. (Various localities in the South Island.)

Plant opal is widely distributed but is most abundant in loess of Last Glaciation age. It is markedly more abundant in fossil topsoils than in subsoils, and totally wanting in the weathered horizons of Loess No. 4. In loess of Penultimate Glaciation age it is rare, and most grains are pitted and etched. Unlike sponge spicules broken fragments of plant opal are extremely rare.

Plant opal grains fall into two main classes of about equal abundance: (*a*) equidimensional grains and (*b*) rod-shaped grains.

(*a*) More or less equidimensional grains include irregular tabular grains (Fig. 2a, b, c), ridged grains (Fig. 2d), and pear-shaped forms, generally pitted (Fig. 2f, g), and approximately spherical grains with rough surfaces (Fi. 2i). All grains in this class are colourless, with refractive indices of from 1·42 to about 1·45, and a size range from 30 to 80 microns.

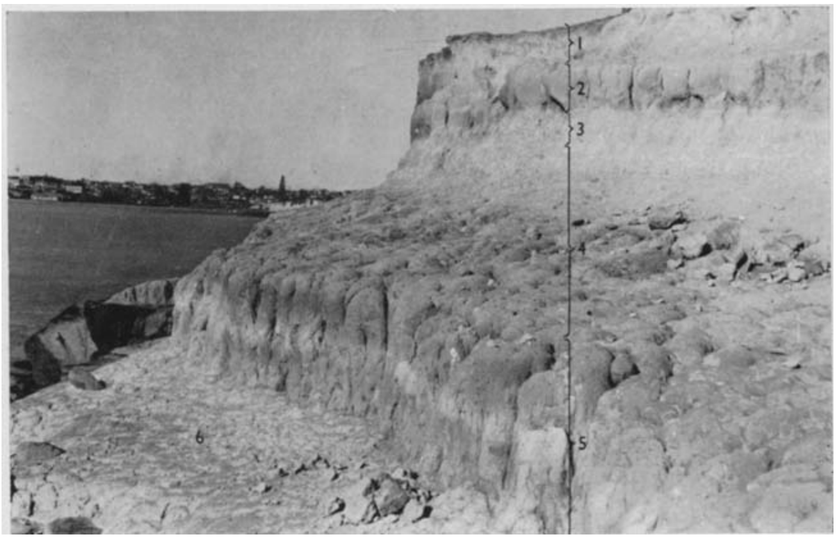

FIG. 3—Loess formation at Dashing Rocks, Timaru, South Canterbury. The pale band above the bench in the middle of the formation marks the upper horizons of the interglacial soil (formed on Loess No. 4). The lower bench is formed on Loess No. 6 at this point.

(*b*) Rod-shaped grains show a greater diversity of colour, size, and shape. They include smooth and rough approximately symmetrical rods with both rounded and tapered ends (Fig. 2h, l), asymmetrical rods wtih serrations (Fig. 2h, j, k, m), slightly curved rods, and rods with regularly spaced cylindrical cavities (Fig. 1e) resembling some species of the soil diatom *Navicula*, of which these could possibly be broken fragments. Rod-shaped grains range in length from 30 microns to more than 200 microns, and in colour from colourless to deep brown. A few rods contain needle-like crystals of authigenic minerals (Fig. 2j), and some contain roughly spherical cavities.

Diatoms occur very rarely as broken fragments in Last Glaciation loess. Some appear to be *Cymbella* and *Surirella* spp., but insufficient material was obtained to make accurate identification possible. No diatoms have been obtained from older loess. It is thought that the diatoms were deposited as broken tests, for surfaces are invariably sharp and show no evidence of solution. It is possible, however, that many diatoms have been destroyed by solution, to which they would be more subject than a fragment of plant opal because of their large surface area. The present distribution of diatoms in the loess may therefore be a doubtful guide to the original diatom content.

Charcoal is unevenly distributed through loess of all layers in grains ranging from 100 microns to more than 1·5 mm.

STRATIFICATION AND AGE OF THE LOESS

The loess shows distinct stratification in most places. It is most distinct in the driest part of the loess region and grows less distinct towards the wetter margin of the loess deposits. Each loess layer* has a fossil soil more or less clearly impressed on it, the contact between the surface of the fossil soil and the base of the next loess layer being generally sharp.

There appear to have been at least six phases of loess deposition, each followed by a period when no loess, or only an insignificant amount, was deposited. The periods of loess deposition and the intervening periods together cover without stratigraphic break the total time span embraced by the loess formation. Some of the loess layers were undeniably eroded in places, and in some localities the column is incomplete, but sufficiently well preserved sections are available to establish the stratigraphic sequence.

Timaru District

A complete section of the loess formation (Fig. 3) is exposed in the coastal cliffs at Dashing Rocks, just north of Timaru in South Canterbury (map reference S111/784540), and appears to be sufficiently undisturbed to serve as a type section (Table 1).

At this site the uppermost layer of loess, designated *Loess No. 1,* the youngest layer of the sequence, marks the closing phase of loess deposition, and is the parent material of the present soil (Fig. 4). At this site it is much reduced in thickness through erosion, but elsewhere reaches a thickness of more than 4 ft with topsoil from 7 to 10 in. thick. The sea breaks heavily against the basalt cliffs below the section, and the soil near the cliff edge is constantly receiving salt spray and will support only sparse salt-tolerant plants. There is much bare ground and layers of surface soil are constantly being lost through erosion. The topsoil is thin (less than 6 in.) and the subsoil is compact, strongly jointed, and separated by a sharp boundary from the underlying layer of loess.

*"Layer" is preferred to "horizon" to describe the various strata of the loess. "Horizon" is now an accepted term in pedological literature and denotes zonation within a soil profile. In this discussion the term "horizon" will be used in its pedological sense and "layer" to denote stratigaphic zonation.

FIG. 4—Loess layers 1, 2, 3, and upper part of 4 at same locality as Fig. 3.

Loess No. 2, from 4 to 5 ft thick, is strongly jointed by a system of well defined vertical joints outlining prisms from 8 to 10 in. in diameter (Fig. 4). The uppermost 10 in. of this loess layer shows traces of an original crumb structure. It is markedly less compact than the underlying horizons and contains abundant colloid-lined fossil worm channels with fossil worm casts and many fine root traces. Since the channels do not extend upwards into the overlying loess layer (Loess No. 1) worm activity would appear to have antedated the deposition of this later loess. The lower compact part of Loess No. 2 contains few worm channels and few root traces. This distribution of worm channels would be consistent with deposition of the loess under a grassland vegetation and a dry regime with subsequent soil formation under a moister regime. Small quartz crop-stones and rare moa bones occur in this layer.

Loess No. 3, from 10 to 12 in. thick, is separated from Loess No. 2 by a sharp boundary, showing that there was little or no worm mixing of the two layers (Fig. 4). It consists of a single brownish yellow horizon, moderately compact but still retaining indistinct traces of an original crumb structure, with abundant colloid-lined worm channels (up to 6 mm in diameter) and many fine root traces. None of the worm channels extend down into the underlying loess layer and only a few up into the base of the overlying Loess No. 2. During the accumulation of this layer worm activity was therefore at a minimum, rose to a maximum after the layer had accumulated, and ceased before the next layer began to accumulate.

Loess No. 4, from 4 to 8 ft thick, is yellowish brown and is separated from the overlying Loess No. 3 by a sharp boundary (Fig. 4). The uppermost 7 in. of this layer are distinctly humus-stained and mark a fossil topsoil that must originally have had a high content of stable humus. A strongly weathered subsoil, from 10 to 15 in. thick, is strongly gleyed, of heavy clay loam texture, and sharply defined medium to fine subangular blocky structure. The underlying horizons are compact and strongly jointed, and closely resemble the lower horizons of other loess layers except that the prisms outlined by the joints are much larger, reaching diameters of more than 24 in. (Fig. 5). Worm channels are wanting in the upper weathered horizons and sparse in the lower jointed horizons.

Loess No. 5, from 3 to 5 ft thick, is a yellowish brown silty clay loam, compact, with a coarse prismatic structure (prisms 7 to 9 in. in diameter) and well defined joints (Fig. 5). The uppermost 7 to 8 in. contain abundant coarse colloid-lined worm channels (average diameter 4 mm) and fine root traces. This horizon is also slightly less compact than the underlying horizons. Rare rounded boulders of basalt are embedded in the lower part of this layer and rest on the surface of the underlying layer (Loess No. 6). It contains sparse moa crop-stones from 0·75 in. to 1·5 in. in diameter.

Loess No. 6, from 3 to 5 ft thick, is a medium yellowish brown silty clay loam, compact, with a well defined coarse prismatic structure (prisms 8 to 9 in. in diameter), and well defined joints (Fig. 3). The uppermost 7 in. contains abundant colloid-lined worm channels (up to 4 mm in diameter) and fine root traces. Angular fragments of basalt are widely scattered throughout, many with their long axes vertical. Some of these

FIG. 5—Bench formed by compact lower horizons of Loess No. 4, overlying Loess No. 5, at the same locality as Figs. 3 and 4. Note difference in diameter of prisms of upper and lower loess layers. The basalt on which the loess rests appears at the right. Loess No. 6 is not apparent here.

appear to have been shed from ridges that remained bare of loess during this phase of deposition, but some may have been raised by freeze and thaw from the underlying basalt (Schönhals, 1957, quoting Poser*).

The basalt on which the loess formation rests is from 20 to 30 ft thick, strongly jointed, and at the site of the section forms steep cliffs against which the sea breaks heavily. The surface of the basalt sheet rises from below sea level to about 1,000 ft, covers a total area of 55 square miles, and extends some 10 miles inland. The surface is gently undulating and unweathered. (For a description of the basalt surface *see* Hardcastle, 1890.)

The basalt sheet rests on a deeply weathered eastward-tilted piedmont gravel plain. At the site of the section the gravels are exposed in a few places only at low water. No loess has been found under the basalt. Silts under the basalt were extensively exposed in the Timaru basalt quarry about the close of last century and were identified by Forbes (1890) as loess, but were shown by Hardcastle (1890) to contain greywacke pebbles of alluvial origin. Weathering of the gravel to a depth of 7 ft took place before the basalt was extruded, for the pebbles of a contemporary stream buried under the basalt (Hardcastle, loc. cit.) were fresh. From this it may be inferred that no weathering of the gravel took place after it was protected by the basalt. The gravel that was extensively exposed in the Timaru quarries is now inaccessible, but it was carefully described by Hardcastle, who appreciated that its advanced weathering must have required a prolonged weathering period apparently of interglacial rank.

Each of the six phases of loess deposition appears to have taken place in a similar environment, for the lower parts of each layer (with the exception of No. 3 which is here thin) are more or less similar in general morphological features. With the exception of No. 4 the upper parts of each layer are also more or less similar in morphology. Each layer appears to have accumulated under an environment that promoted only weak weathering of the accumulating loess, and encouraged only a sparse vegetation and a sparse worm population in which there were few large worms. These features of the loess would be consistent with a cool dry climate supporting a grassland vegetation. Each phase of loess deposition was followed by a period during which no loess, or at least an insignificant amount, was deposited; there was no obvious increase in the intensity of weathering, but there was an increase in the worm population and in the abundance of large worms. These features would be consistent with a wetter, but not excessively wet climate. Except for Loess No. 4 there was no marked increase in the intensity of weathering of the upper horizons of each layer and the change in rainfall and temperature must therefore have been small. The absence of forest traces, both of buried roots or root traces of large diameter, cannot be taken as conclusive evidence that during the warmer and damper parts of the cycle forest did not become established. Forest trees would be shallow rooted on these compact soils, and the high worm activity in the friable upper horizons could have obliterated forest traces.

The advanced degree of weathering of the upper horizons of Loess No. 4 argues either a period of more intensive weathering of comparable duration (that is, a period of higher rainfall and/or higher temperature), or a period

*POSER, H.; HOVERMANN, J. 1951: Untersuchungen zur pleistozänen Harz Vergletscherung. *Abh. Braunschw. Wiss. Ges. 3*: 61–115.

of weathering of comparable intensity to those responsible for the alteration of the overlying and underlying layers but of longer duration. There is no evidence that the climate was either wetter or warmer, for there is no trace of the increased weathering and leaching in the joints of the lower horizons of Loess No. 5 that would be expected. Moreover, the minor features of the lower horizons (worm channels with worm casts, and root traces) are still perfectly preserved. Provisionally, therefore, it is assumed that the weathering interval between the deposition of Loesses Nos. 3 and 4 was broadly similar in intensity to the weathering and soil-forming periods 2/3 and 4/5 but was of much longer duration.

Loesses Nos. 1, 2, 4, 5, and 6 are of comparable dimensions and are comparable also in morphology. Loess No. 3 marks a depositional period of shorter duration, at least in this locality. Interdepositional periods are of two ranks, one of short duration to which periods 1/2, 2/3, 4/5, and 5/6 belong, and one of long duration to which period 3/4 is assigned. The former are regarded provisionally as of interstadial rank and the latter as marking an interglacial period. If this view is correct, Loesses 1, 2, and 3 would be assigned to the Last Glaciation and Loesses 4, 5, and 6 to the Penultimate Glaciation.

The weathering to a depth of 7 ft of the piedmont gravel underlying the basalt expresses a much greater degree of weathering than that separating Loesses 3 and 4. Small greywacke crop-stones embedded in the upper horizons of Loess No. 4 are only pitted. The deep weathering of the piedmont gravel is accordingly thought to have taken place in the Penultimate Interglacial. Since there is no discernible break in the stratigraphic continuity the deeply weathered gravel must be assigned to the later stages of the Antepenultimate Glacial (Table 2). Absence of appreciable weathering on the surface of the basalt indicates that it was extruded sufficiently late in the Penultimate Interglacial to have escaped weathering. Loess No. 6 would effectively protect it from subsequent weathering.

Loess deposits extend to sea level on the South Canterbury coast south of Timaru, but there is no evidence of marine erosion of the formation by the high sea levels of the Last Interglacial. It would seem, therefore, that there has been a downward movement of this part of the coast of at least 45 ft during the Last Glaciation. It is likely that this was accompanied by tilting as well. The surfaces of alluvial sedimentation assigned to the Postglacial, the Last, the Penultimate, and the Antepenultimate Glaciations show increasing eastward tilt (20, 35, 80, and 100–135 ft per mile, respectively).

Dunedin District

Sections of the loess formation similar in principal features to the section at Timaru occur also at Waikouiti and Fairfield in eastern Otago. At Fairfield the loess rests on gently tilted Tertiary rocks on the summit of a small hill isolated by late Pleistocene dissection. The base of the section consists of phonolite boulders and stones derived from a nearby outcrop to the north-west, set in a matrix of reworked Tertiary sandstone and loess, and resting on an old base level, possibly part of an ancient flood plain. It corresponds with a surface regarded by Ongley (1939) as "the base level of an old cycle" which occurs at between 120 and 160 ft above sea level near the coast between the mouth of the Taieri River and Green Island. The dissection that has taken place since the deposition of the loess greatly exceeds what could be plausibly accommodated in the Last Glaciation, and suggests that this old base level is of Antepenultimate Glacial age.

TABLE 2—Upper Pleistocene Succession in South Canterbury

Sequence of Depositional and Soil-forming Periods	Glacial Stages	Tentative Correlation (Gage, 1961)
Present period of accelerated weathering and soil formation	Postglacial period	
Loess deposition with some weathering and soil formation (No. 1)	3rd ice advance	
Accelerated weathering and soil formation	2nd ice retreat	Otira Glaciation
Loess deposition (No. 2)	2nd ice advance	
Accelerated weathering and soil formation	1st ice retreat	
Short (?) period of loess deposition (No. 3)	1st ice advance	
Long period of accelerated weathering and soil formation	Last Interglacial	
Loess deposition (No. 4)	3rd ice advance	
Accelerated weathering and soil formation	2nd ice retreat	Waimaunga Glaciation
Loess deposition (No. 5)	2nd ice advance	
Accelerated weathering and soil formation	1st ice retreat	
Loess deposition (No. 6)	1st ice advance	
Extrusion of basalt at Timaru	Close of Penultimate Interglacial	
Prolonged period of weathering and soil formation in piedmont gravels	Penultimate Interglacial	
Deposition of piedmont gravels	Antepenultimate Glaciation (last phase)	Porika Glaciation

No loess has been found that antedates the Penultimate Glaciation. This would have to be sought on surfaces antedating the Antepenultimate Glaciation to which loess could be supplied by actively aggrading surfaces of Antepenultimate age. A section of mixed loess and solifluxion* detritus in the Dunedin district indicates, however, that solifluxion deposits older than the Penultimate Glaciation do not contain loess. This section is described below.

Solifluxion appears to have been active during the Pleistocene in the Dunedin district, partly because of its latitude (ca. 46° S) and partly because of the proximity of the Silver Peaks mountains and the Maungatua uplands. Stratified slope deposits are therefore widespread on the flanks of the Dunedin hills. They consist of angular fragments of the local rocks set in a matrix of weathering products of these rocks, and loess derived from the metamorphic schists of Otago, and resemble in origin and morphology the solifluxion deposits described in the Wellington district by Cotton and Te Punga (1955a and 1955b) and Stevens (1957). Successive layers terminate in shaved surfaces; boulder-filled gullies are widely distributed through the deposits; and there has been some inversion of relief. Solifluxion has been sufficiently active in this district to strip the mantle of weathered rock from the upper slopes of ridges and transport it to the lower slopes, in some cases into the drainage system and into Otago Harbour.

A succession of layers of mixed loess and solifluxion detritus that appears to embrace a time span comparable with that embraced by the Timaru loess section is exposed on the old northern highway near Mt Cargill (Fig. 6).

Fresh Tertiary basalt outcrops at the base of the section. Overlying this is a mantle of weathered basalt from 2 to 4 ft thick terminating in a shaved surface. In the northern part of the section a tongue of solifluxion detritus resting on this shaved surface consists of angular partly altered fragments of phonolite (derived from an outcrop further upslope) in a matrix of weathered basalt. The close similarity in colour, texture, and consistency between the matrix and the underlying undisturbed weathered basalt suggests that this matrix contains little (if any) weathered phonolite.

Five distinct layers of solifluxion detritus rest on the shaved surface of the basaltic and phonolitic layer. The base of each layer contains a high proportion of angular fragments of phonolite up to 12 in. in diameter, set in a fine-textured matrix. In the lowermost solifluxion layer this matrix consists chiefly of weathering product of phonolite with less than 20% of loess. The proportion of loess increases towards the top of the section, the closing layer consisting almost entirely of loess with only sparse phonolite fragments near the base of the layer. In each layer the proportion of phonolite fragments decreases towards the top of the layer, and the uppermost few inches of each layer consists largely of loess.

*Solifluxion has been used here *sensu lato* to denote downslope movement of the soil mantle by the agency of freeze and thaw irrespective of whether this occurs in or near or even beyond the region of the permafrost, or in the *regio alpinum*, or in a strictly periglacial environment. An adequate supply of soil water and a sufficient frequency of freeze and thaw are the controlling factors for this kind of downslope movement. The term *soil creep* is conveniently used to designate downslope movement of the saturated soil mantle where the soil is not subject to freeze and thaw.

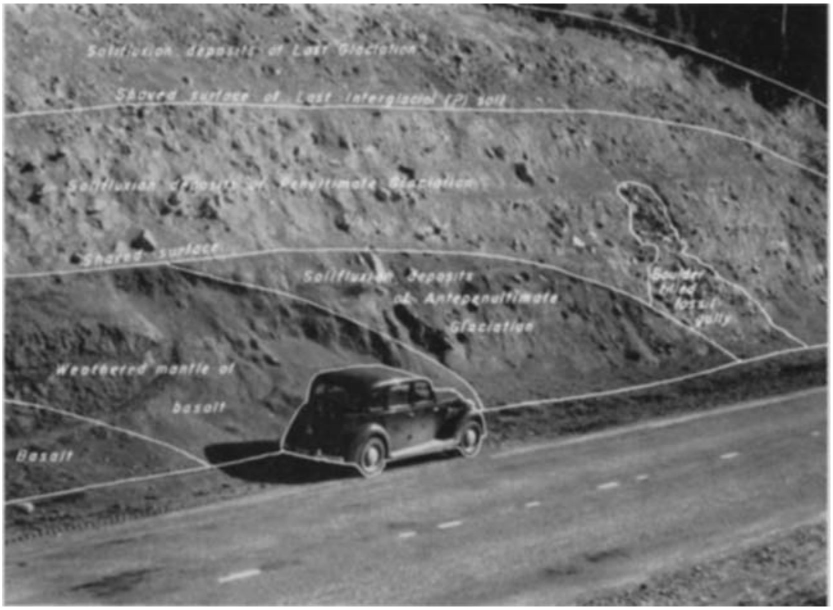

FIG. 6—Solifluxion deposits on Mt Cargill, Dunedin.

A soil profile has formed on each layer, the soils on each resembling the present yellow-brown earths on the closing layer. The soil on the third layer from the surface, however, appears to be more strongly weathered than the others, and to have a greater proportion of free iron, which has stained the soil profile a medium red-brown colour. Detailed study of the fossil soils, however, is greatly hampered by truncation of profiles by overlying solifluxion layers.

The sequence shows, nevertheless, that loess was accumulating during each period of solifluxion and continued to accumulate to some extent after solifluxion virtually ceased. This could be taken as somewhat slender evidence that loess deposition continued through the period of ice advance into the period of retreat but cannot be regarded as conclusive, although the undisturbed nature of the closing layer of loess could be confirmatory evidence of the deposition of loess during the retreat phase of the cycle. Solifluxion detritus, however, provides rather dubious stratigraphic evidence, because the deposition on any particular site is only the tail end of the stream of detritus of which it once formed a part and marks the situation only at the close of the solifluxion period.

These considerations, however, do not affect the broader implications of the section. Periods of solifluxion and loess deposition clearly alternate with periods when the surface deposits remained stable and soil processes took place without interruption. The weathering and soil-forming intervals separating periods of solifluxion consist of two intervals of major rank and three of minor rank. The first weathering interval of major rank follows the deposition of the basal layer of coarse phonolitic detritus and weathering product of the basalt. Prior to this weathering period only fresh phonolite was exposed. During it the phonolite was sufficiently deeply weathered for weathering products of the phonolite to be available throughout almost the whole of the remainder of the Pleistocene, and argues a prolonged period of weathering. This period has accordingly been equated with the Penultimate Interglacial, and the accumulation of the basal basaltic slope deposit with the closing stages of the Antepenultimate Glacial. The five overlying layers of solifluxion detritus have been assigned to the remainder of the Upper Pleistocene, the lower two to the Penultimate and the upper three to the Last Glaciation.

ORIGIN OF LOESS

Loess appears to have been derived from several source areas. Precise thickness gradients are difficult to establish because the loess fell on undulating and in some places hilly surfaces on which the mantle varied in thickness. Much erosion took place both during and after the deposition of each layer. A few broad trends in thickness can, nevertheless, be discerned. The deposits thicken markedly near the major rivers in much the same manner as reported by Péwé (1951 and 1955) for the loess of Alaska. Much of the loess in the immediate neighbourhood of the east coast rivers undoubtedly came from their floodplains. In addition to the thickening of the mantle in the immediate neighbourhood (within 7–10 miles) of the rivers, the loess shows also an appreciable thickening towards the coast. Remote from sources of abundant alluvial loess (e.g., more than 20 miles distant from alluvial plains), the loess remains more or less constant in thickness parallel with the present coast. Between the Waitaki and Clutha Rivers, for example, the youngest loess layer has an average thickness of about 3 ft. Loess appreciably thicker than this occurs only on the flanks of Otago Peninsula and near the estuary of Blueskin Bay. On the seaward margin of Banks Peninsula, however, slopes sheltered from inland sources of loess have thick deposits, in some places exceeding 25 ft.

It would appear, therefore, that some loess was derived from sources located on the continental shelf during the sea-level recessions of the Pleistocene. In the Last Glaciation the accepted maximum recession of 300 ft would have extended the present shoreline by approximately 30 miles in South Canterbury and about 20 miles near Oamaru on the Otago coast (Admiralty Chart No. 2532). Practically the whole of Pegasus Bay, north of Banks Peninsula, has a present average gradient of less than 5 ft per mile (N.Z. Chart No. 10) for a distance of about 30 miles from the shore. South-east and south of the Peninsula the shelf is also of gentle gradient. It is likely that the physiography of the shelf was much the same, or at least differed only in minor respects, during the Last Glaciation, and possibly in broad features in the Penultimate Glaciation as well. If this is so, it would be expected that the aggrading Pleistocene rivers would follow meandering and braided courses over the gently sloping parts of the shelf during periods of low sea level in the upper Pleistocene, and their broad flood plains would be able to furnish abundant loess to the adjacent plains and downlands. The present Canterbury Plains consist mainly of the apexes of the great Pleistocene alluvial fans, that is, the parts of the fans on which the coarsest detritus was deposited. The toes of the fans, where the finer detritus was deposited, lie below sea level on the present continental shelf. During low Pleistocene sea levels, therefore, an abundant supply of fine detritus would be available from these now submerged parts of the fans. It is possible in fact that the toes of the fans were the richest sources of loess. A sample of fine sandy silt from an almost flat part of the shelf in 36 fathoms (obtained through the courtesy of the Navy Department from the site of the *Holmglen* wreck in Lat. 44° 33′ 42″ S, and Long. 171° 43′ 30″ E) contained 80% of fine sand and silt. All the coarse and medium sand consisted of Foraminifera and shell fragments. Reworking of such a deposit during a sea-level advance or retreat, or while it was spread over a flood plain would provide abundant loess.

There is, however, no evidence at present available from which the proportions of loess derived from flood-plain detritus and from reworking of shelf deposits can be computed. Some of the loess at least appears to consist of reworked shelf detritus. Loess within 20 miles of the present coast contains small amounts of sponge spicules, which decrease in abundance and size from the coast inland. Loess more distant than 20 miles from the coast contains only rare spicules.

The major source of loess, however, was probably the flood plains of the major rivers draining the mountain catchments along the whole length of their courses, across the exposed continental shelf as well as across the present plains. Minor amounts of loess were probably derived from reworking of the shelf deposits during advancing and retreating sea levels. It is possible that in a few isolated localities loess was derived primarily from reworking of estuarine and shelf deposits. The loess deposits on Otago Peninsula, in particular those near Harrington Point, were probably derived from the shallow estuary of Otago Harbour and the flattish part of the shelf in about 10 fathoms, just offshore of Harrington Point. Much of the loess on the Otago coastal hills from Otago Harbour to Waikouaiti may have been derived from the gently sloping shelf offshore and from Blueskin Bay, a shallow estuary exposed at present at low water.

LOESS DEPOSITS AND PLEISTOCENE TERRACE SEQUENCES

The chronology of the loess should provide a useful approach to the dating of Pleistocene terraces: it should be possible to date terraces from the number of loess layers deposited on them. A discussion of terrace chronology is beyond the scope of this paper and only a single example of a tentative dating will be given. The high terrace that borders the Opihi River in South Canterbury and extends from Temuka some 10 miles inland is covered with loess of Last Glaciation age only and is regarded therefore as a late Penultimate flood plain.

Dating of terrace treads should be largely independent of whether the degradation that isolated the terrace tread from further aggradation was due to climatic oscillation or whether it was of tectonic origin. If the terrace was of climatic origin, that is, if the treads were part of prior flood plains formed by aggradation when abundant waste was available, and streams entrenched themselves when the proportion of waste to water declined, the aggradation phases would be assigned to glacial stadials and the degradation phases to interglacial or interstadial periods. Since phases of loess deposition correspond also with glacial stadials, and phases of non-deposition with interglacials (or interstadials), a possible mechanism of loess accumulation and terrace formation might be summarised as follows:

Stage 1. Aggradation of flood plain takes place during period of ice advance. Loess is supplied to older land surfaces.

Stage 2. Entrenchment of drainage system in flood plain during interglacial or interstadial period and widening of rejuvenated valleys by lateral corrasion.

Stage 3. Aggradation accompanying fresh ice advance supplies loess to higher land surfaces including isolated remnants of flood plain of Stage 1, now a terrace tread.

CORRELATION WITH NEW ZEALAND GLACIAL CHRONOLOGY

In the previous sections of this paper the terms Last, Penultimate, and Antepenultimate Glaciations have been preferred for the major divisions of the Pleistocene, and the sequence of major and minor events has been given more emphasis than details of relative chronology.

The loess deposits described lie beyond the Pleistocene periglacial zone and express the resultant of a more complex set of factors than strictly glacial deposits. They reflect the availability of fine-textured sediments vulnerable to wind transport, and the circumstances that make such detritus available may not correspond with those that produce a maximum advance of an ice front; and the culmination of a particular set of physical factors in a catchment need not necessarily coincide with the onset or cessation of loess deposition or the period of maximum accumulation of loess. Although it is generally accepted that loess deposits accumulate during glacial stadials and cease during ice retreat, the period when the rate of loess accumulation is a maximum may not correspond with the period of maximum ice advance, and may in fact correspond with the period of maximum aggradation, which could well be the early stages of ice retreat. It seems desirable, therefore, to work out the mechanics and chronology independently of other Pleistocene processes, and until these are well founded to attempt only tentative and provisional correlations with other Pleistocene events.

With these reservations, therefore, the broad subdivisions of the Pleistocene inferred from the loess succession may be said to correspond in some respects with the subdivisions based on glacial events (Table 2). The Last Glaciation, as expressed in the loess succession, may be correlated with the Otira Glaciation, and the three advances referred to by Gage (1961) may possibly correspond with the three phases of loess deposition. Similarly the Penultimate loess may be assigned to the Waimaunga Glaciation, though the detailed correlation is less satisfactory.

The surface on which the loess formation rests in South Canterbury and eastern Otago would be assigned to the last phase of the Porika Glaciation.

The deep weathering of the Porika–Waimaunga interglacial surface in South Canterbury may correspond with the deep weathering during this interval cited by Gage (1961) and Gage and Suggate (1958).

Until some absolute dating of loess deposits is possible, long-range correlation of loess deposits with those of other parts of the world must remain on a very uncertain basis. The work of Schönhals (1950, 1951a and 1951b, and 1957) and the general summary of Wolstedt (1960) show, however, that the sequence of fossil soils formed on Pleistocene loess in Germany is in general agreement with the sequence described above. Three phases of loess deposition are described for the Würm Glaciation, and the loess succession is regarded as largely confined to the Riss and Würm Glaciations. There is still, nevertheless, some difference of opinion about the detailed interpretation of European loess deposits.

LOESS DEPOSITS AND YELLOW-GREY EARTH SOILS

Loess deposits in the South Island are the dominant parent materials of two major soil groups of the New Zealand classification (McLintock, 1959)—a large area of yellow-grey earths and a smaller area of yellow-brown earths in regions of higher rainfall. The yellow-grey earths in the South Island appear to be mainly confined to loess deposits, and for some time it has been thought that the clue to their morphology might lie in the history of their parent materials.

Morphology of Yellow-grey Earths

A conspicuous morphological feature of yellow-grey earths of the South Island derived from loess is a compact, well-jointed "pan" referred to as a "fragipan" (Taylor and Pohlen, 1962). This feature of the soil stands out as a prominent shelf in weatherbeaten roadside cuttings. The pan is also an important practical feature of the soils. It affects both the moisture regime and the depth to which roots can penetrate freely. When the soil is dry the pan shrinks, the system of permanent joints opens up, and in the early stages of wetting, before the whole mass has absorbed enough water to close the joints, drainage water percolates down the joint network bypassing the prisms outlined by the joints and delaying the wetting of the soil. When the soil is wet the pan swells, the joints close, the pan becomes an effective barrier to downward percolation, and the soil waterlogs readily.

The pan has been treated as a lower B horizon by some workers, assuming that it is a morphological feature imposed on the parent material (loess) during the process of soil formation. This implies either that the pan is still developing or has developed as a product of a pedological process. This concept of the pan, however, cannot be reconciled with its detailed morphology.

The lower boundary of the pan is generally sharply defined, and in the soils studied marks the contact between the surface of a fossil soil formed on an underlying layer of loess and the base of the overlying loess layer. In these soils the lower boundary of the pan is thus a stratigraphic boundary and not a pedological one.

FIG. 7—A yellow-grey earth soil (Warepa silt loam) at Berwick, western Taieri Plains (near Dunedin), showing advanced disintegration of the compact horizons.

Throughout most of the yellow-grey earth zone the upper part of the pan is more or less fragmented and its upper boundary is ill-defined (Fig. 7). The pan is apparently being destroyed from above downwards rather than being developed by a current pedological process. The depth and extent of fragmentation increase with increasing rainfall and mark the extent to which a current destructive process (destructive in the sense that it destroys the well defined prismatic and coarse blocky structure of the pan) has been superposed on an earlier regime that was responsible for this structure. In a few coastal sites exposed to the prevailing north-easterly winds and receiving much salt-laden spray, the pan generally exhibits a sharply defined prismatic structure, with well defined hexagonal cross sections, and sharply defined and generally domed tops to the columns. In these situations the superposition of a saline regime (from input of cyclic oceanic salts) has accentuated swelling and shrinking, and the soil profile simulates the morphology of a solodised solonetz soil. The primary origin of the pan, however, is identical with that of the remainder of the yellow-grey earths, and these soils should be regarded as coastal variants of the yellow-grey earths rather than associates of the solonetz soils.

Formation of Yellow-grey Earth on Loess

Two distinct processes may therefore be discerned in the history of the yellow-grey earth pan. The first process produces a loess deposit with a strongly jointed structure and a high degree of compaction. The second destroys this feature from above downwards to a greater or less extent according to the nature of the present climate, except where a new factor is introduced, an input of soluble salts.

Earlier in this paper loess deposition and subsequent soil formation and weathering were referred to as separate processes for convenience of exposition, but this is not strictly true. Loess is a terrestrial deposit and soil formation takes place continuously both during and after its accumulation. Soil formation has in fact been continuous throughout the whole period embraced by the loess formation, but it has varied in intensity and therefore in the kind of impress it has left at various levels in it. Variations in intensity were more or less periodic, and the whole formation can be treated as the product of a series of cycles, each consisting of a phase of loess deposition followed by a phase of weathering and accelerated soil formation. Each cycle may be said to have begun with the onset of a phase of loess deposition and to have closed with the onset of the next phase of deposition. During the phase of loess accumulation the climate was dry and cool, vegetation was sparse, and the rate of weathering, intensity of biological activity (measured by abundance of worms) and intensity of soil formation (measured by the capacity of the whole organic cycle to produce a friable soil structure) were at a minimum. In the succeeding phase when no loess fell and the climate was warmer and wetter, the vegetation was more abundant, and biological activity, weathering, and soil formation reached a maximum. During this period, friable humus horizons were developed that were abundantly populated by worms, and the upper soil horizons were weathered to a greater or less extent according to the duration of the weathering period. Throughout each cycle, therefore, changes in rate of loess accumulation on the one hand, and in intensity of soil formation and weathering on the other, took place reciprocally.

Each layer of loess thus comprises a lower group of horizons characterised by well defined jointing and compaction, and an upper group of horizons with less sharply defined joints and distinctly more friable. The whole layer has previously been regarded as the soil profile, but it might be better treated as forming a *soil system* that expresses the end-product of a cycle of events.

During the first part of the cycle, when weathering and biological activity were at a minimum, the accumulating loess acquired a high bulk density, sufficient colloid being released by weathering to stabilise contemporary morphological features such as root traces and worm channels and enclosed worm casts by cementation of mineral grains. The survival of these features in fossil soils shows that climatic fluctuations throughout the history of the formation had only a limited range. No doubt the sealing effect of each succeeding layer of loess would also help to preserve the underlying fossil micromorphology. The system of joints that intersects each layer of loess could also be regarded as a fossil feature preserved in this way.

During the second part of the cycle, when deposition of loess virtually ceased, the increased biological activity and more abundant vegetation led to the development of a friable humus horizon that extended downwards at the expense of the compact jointed loess through the agency of roots and the mixing accomplished by worms. The loess that retained its initial compaction is in fact the so-called "pan" of the yellow-grey earths. The process that characterises the second part of the cycle is thus one of pan destruction rather than pan construction.

It is possible that some minor illuviation was taking place throughout the cycle. Some clay shift has, in fact, been observed in loess deposits of recent age, as for example at Barrhill on the south bank of the Rakaia River. This would be expected to be least during the first phase of the cycle and to be appreciable only in the second phase, but because of the low permeability of the loess the translocated colloid would be deposited near the top of the subsoil, in joints or on the surface of the major prisms. Only minor modification of the pan would be expected in this phase. Some iron oxides would probably also be deposited on the surface of the major structural units, and leaching of the loose material in joints would also take place.

According to this view of the origin of the yellow-grey earth morphology, the present soil—that in equilibrium with and a true expression of the present soil-forming environment—could be regarded as embracing only those horizons overlying the pan, and the pan itself could be treated as the parent material for the last phase of the pedological cycle.

If the yellow-grey earths are looked at in this way, the question arises whether the pedological process of the second phase of the cycle can be equated with an already defined pedological process other than the yellow-grey earth process. In the wetter half of the yellow-grey earth zone the soil profile may be divided into two distinct parts, an upper part resembling a yellow-brown earth and a lower jointed part in process of disintegration, the remains of the compact layer inherited from the first phase of the cycle. In the drier parts of the yellow-grey earth zone, however, there is much less apparent affinity between the soil profile above the pan and the yellow-brown earths, and the friable horizons above the pan are generally thinner. Moreover, in this part of the yellow-grey earth zone the superposed soil has generally been truncated by erosion.

The extensive development of yellow-grey earths on loess deposits is due primarily to the environment in which the loess accumulated. This was sufficiently dry to produce the depositional and pedological cycle described above. Where loess accumulated in a wet environment the sequence of events during the cycle was somewhat different. Instead of the alternate swelling and shrinking in alternately wet and dry seasons, the soil was predominantly wet. A friable structure developed instead of a joint system and prismatic structure, and much less compaction took place. In the wettest part of the loess zone of Southland the loess is friable and moderately soft and the soils formed on it belong to the yellow-brown earth group.

In intermediate situations, where loess accumulated under a sufficiently dry climate for compaction and well defined joints to develop, but where the climate of the last phase of the cycle was damp, though not damp enough to destroy the inherited structures, profiles that can be equated with the yellow-brown earths rest on a subsoil with marked compaction and distinct joints. With increasing rainfall the yellow-brown earth soil becomes more strongly impressed and extends deeper into the compact subsoil until finally all trace of compaction and joint system disappears. The threshold at which all trace of compaction and joint structure disappears can mark, therefore, either a climatic boundary that existed when the loess was accumulating, and separated an environment that promoted compaction and a joint structure from one that promoted a friable structure, or a boundary that defined the limits of a climatic zone that permitted destruction of inherited compaction and joint patterns during the period of accelerated soil formation.

Classification of Soils on Loess

These considerations concerning the origin of the pan and the relation between yellow-grey earths and yellow-brown earths on loess deposits are relevant to the classification of these soils. If the pan is properly regarded as an integral part of the yellow-grey earth profile, and not as parent material, a boundary between yellow-grey earths and yellow-brown earths developed on loess merely marks where all trace of the pan finally disappears. The soil on both sides of the boundary is in fact a yellow-brown earth. The question can reasonably be asked whether this is an adequate distinguishing character at great group level. It could be argued that it is not strictly a zonal boundary but a distinction at a much lower level of classification. Although the distinction is a convenient practical one it may be more genetically correct to consider the yellow-grey earths as a subdivision of the yellow-brown earths.

Loess is a widespread deposit in many countries and it might be expected that yellow-grey earth soils would also be widely distributed. Much of the loess of China (Barbour, 1930), Argentina (Frenguelli, 1955; and Teruggi *et al.*, 1957), and North America and Europe, however, is calcareous, and the characteristic joint structure is less strongly developed, although still perceptible, for the presence of free lime appears to reduce the degree of compaction. The soils with the closest affinities to some of the yellow-grey earths of New Zealand appear to be the pseudo-gley soils of Europe formed on non-calcareous loess (Laatsch, 1957; Altemüller, 1957; and Kubiena, 1953). These soils appear to stand *mutatis mutandis* in much the same relation to the leached brown earths of Europe as the yellow-grey earths do to the yellow-brown earths of New Zealand.

The genetic considerations outlined above are essential to a proper interpretation of analytical data obtained for yellow-grey earth soils. Both physical and chemical studies must take into account the fact that the relation between the A horizons and the pan is not of a simple A/B nature where the pan is the product of illuviation from the A horizon or of compaction during the progress of contemporary soil formation. It is doubtful, indeed, whether the use of the term "pan" without qualification can be justified as a satisfactory designation for the compact jointed horizon. The term "hard pan"* would be more acceptable than "clay pan", the horizon being one of compaction rather than illuviation, but the term implies that the compaction is a current pedological phenomenon. The fossil nature of this horizon, however, is of prime importance in interpreting soil studies, and it would be desirable to distinguish it by a qualifying term that conveys this difference. Perhaps it might be desirable to designate it a *fossil pan*, a *C. pan*, or perhaps more explicitly a *loess pan*.

*The term "hard pan" is applied in most countries to a horizon of compaction, e.g., the *Verdichtungshorizont* of Germany, and the *horizon endurci* or *compacifié* of France.

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