Made in United States of America

Reprinted from Soil Science
Vol. 45, No. 2, February, 1938

THE RECLAMATION OF THE DUTCH SALINE SOILS (SOLONCHAK) AND THEIR FURTHER WEATHERING UNDER THE HUMID CLIMATIC CONDITIONS OF HOLLAND[1]

D. J. HISSINK

Institute of Soil Science, Groningen, Holland

Received for publication August 6, 1937

MUD DEPOSITS, KWELDERSOILS

The Dutch saline soils occur on the seacoast. The sea deposits are brought in by the recurrent tides against the sea dikes. They vary from very sandy to heavy clayey soils; the reclamation of the latter only is discussed here.

The sea deposits contain the salts of the sea water, and of the exchangeable bases, the MgO and the Na_2O are more prominent than the CaO. These deposits contain approximately[2] 25–40 parts CaO, 45–30 parts MgO, 8 parts K_2O, and 20 parts Na_2O per 100 parts exchangeable bases and are therefore to be regarded as magnesium-sodium clay soils. The chief feature of these saline clay deposits is their muddy structure, or rather their lack of structure, which is directly related to the very high content of water. Whereas the normal older clay soils in the wettest condition contain no more than about 50 gm. H_2O per 100 gm. clay substance,[3] the mud deposited by the sea water against the dikes contains about 175 to 350 gm. H_2O per 100 gm. clay-substance. This mud is characterized by its dark color, due to the presence of ferrosulfide (FeS), which has been formed from the $CaSO_4$ of the sea water and the Fe_2O_3 of the soil. When in contact with air, the FeS oxidizes to $FeSO_4$, which is immediately converted by the superabundant $CaCO_3$ into $CaSO_4$ and $FeCO_3$, and the $FeCO_3$ then oxidizes to Fe_2O_3. The dark color changes during this process to a gray tint.

Because of continuous accretion, the mud deposits gradually accumulate, until they are too high to be covered by the normal summer tides. It is obvious that the reclamation of these Dutch saline soils has, in the humid Dutch

[1] A few papers on this subject have already appeared (10, 12, 13, 14, 16), some in English, some in German, and some in Dutch, which are not readily accessible to most American readers. After discussing the matter, Doctor Lipman and I came to the conclusion that it might be useful to publish this paper in Soil Science.

[2] The method for the determination of the exchangeable bases in saline soils which also contain calcium carbonate has not yet been accurately fixed. I have endeavored to indicate an approximate method (9, 11), but I am quite willing to admit that there is much to criticize in this method, by which the given figures have been obtained.

[3] By "clay-substance" is understood fraction I + II, that is, particles smaller than 16μ in diameter. The settling velocity of these particles is 10 cm./450 seconds. According to Stokes' formula $V = 34720\, r^2$, therefore, the diameter $(2r) = 0.0016$ cm. $= 16\mu$.

climate, a somewhat different aspect from that of similar reclamation in semi-arid and arid regions, such as those of Hungary, southern Russia, and California. The annual rainfall in the Netherlands is sufficient entirely to wash out the salts within a few years, provided the drainage conditions are otherwise good. When the muddy deposits have accumulated sufficiently to rise above the normal summer tides, the salts are consequently washed out of the upper 20 to 30 cm. of the muddy deposits by the summer rains to such an extent that the original salt vegetation (Seaweed, Salicornia, etc.) gives way to a grass flora. These grass-grown deposits are called "kwelders"; they are covered only by the high tides, especially in winter. When the kwelder is high enough a dike is built to keep out the sea water; the kwelder is now transformed into a young sea-polder.

The muddy deposits are therefore to be regarded as the first step in the formation of marine clay soils, which are well known to be the most fertile soils in the Netherlands, both from a chemical and from a physical point of view. For many decades the young marine clay soils yield abundant crops, without the use of any fertilizer, and even at a great age (200 to 400 years) they are regarded as among the most valuable arable lands. It is therefore obvious that the study of the transition from muddy deposits to fertile land and of the further weathering of the young marine clay soils is worthy of the interest of Dutch soil scientists.

RECLAMATION OF THE SALINE MUD DEPOSITS

The first soil-forming process of the saline mud deposits is that of drying, which takes place as early as the kwelder period, thus while the land is not yet diked but already bears a grass flora. It is obvious that this drying process takes place from the upper layer, because of the action of the sun and the wind. Gradually the deeper layers—also under the influence of the grass flora—also dry up.

As a result of the high content of water the mud deposits have a very low volume-weight [weight of 1 cc. dry matter (105°C.) in grams]. The volume-weight of the mud deposits was found to range from 0.43 to 0.81, depending on the water content; that of the upper layer of the kwelder soil was about 0.87; that of the upper layer of the 6-year-old new polder soil was about 0.97; and that of the oldest polder soils was 1.35. During the drying process, therefore, a large number of fissures are formed, at first in the upper layer. The muddy mass, which at first is virtually impermeable to water, gradually becomes permeable and attains solidity, or structure.

After the formation of fissures the rain water is able to penetrate into the soil and to wash out the salts of the sea water, at first, it is true, only out of the upper layer. The air, too, penetrates into this upper layer. Oxidation processes take place; the sulfur-iron compounds are converted into iron oxide (Fe_2O_3) and sulfuric acid (H_2SO_4). As $CaCO_3$ is present, gypsum ($CaSO_4$) and calcium bicarbonate, two calcium salts soluble in water, are formed, and these change the sodium-magnesium-clay-humus substance into calcium-clay-humus substance. This part of the soil-forming process will be treated in detail below.

For the rapid course of this exchange process it is of importance that the exchange products, and especially the sodium salts, should be removed from the soil as quickly as possible. A thorough and rapid draining of the rain water from the upper layer into the ditches and canals is therefore necessary.

It is of great importance that the soil become permeable to water before the end of the salt period, that is, while the soil still contains salts which prevent the peptization of the sodium-clay-humus substance. If the soil has become sufficiently permeable to water before the end of the salt period, the salts, and later the products of the exchange process also, and especially the sodium salts, can be rapidly carried off. The peptization of the clay-humus substance, which will unavoidably occur after the washing out of the salts, naturally somewhat reduces the permeability of the soil for a time. The already fairly permeable soil can, however, afford this luxury. If, on the other hand, the washing out of the salts from the soil occurs in the muddy period, the soil may, because of the peptization, become almost impermeable to water.

It is a fortunate circumstance that the soil—at any rate, that in the upper layer—dries somewhat during the kwelder period, its structure becoming such that the soil is more or less permeable to some depth, and at the same time the base equilibrium shifts from the Na side in the Ca direction. Thereby the soft skeleton of the young sea-soil is somewhat solidified.

For the formation of a good structure it is therefore essential that two processes take place, one physical, the other chemical. The muddy mass must dry, and the exchangeable sodium (and magnesium) must be largely replaced by calcium. Neither of these processes is in itself sufficient for the formation of a good structure. Both the sodium-clay substance and the sodium-humus substance disintegrate again or become soft when, after drying, they again come into contact with water. And as long as the calcium-clay-humus substance remains more or less soft, it does not form a good material for a strong soil-skeleton. According to various investigators [among others, Sokolovsky (19)] a difference occurs in this respect between the clay and the humus substance. It is claimed that the calcium clay, after drying, remains a fully reversible colloid; the dried calcium humus, however, is a partly irreversible colloid. The dried irreversible humus does not peptize, even when part of the lime is washed out.

In this connection it is of importance to note the possibility of a rather close connection between the organic and the inorganic adsorbing complexes. According to Gedroiz (4) and others (1) it is possible that in soils these two parts form, not a mechanical mixture, but something more intimate. Humus, as a colloid of high dispersivity, binds the soil particles together, even when there is but a small percentage of it.

In the structure-forming process of the muddy deposits it is therefore essential that both the clay and the humus substance dry and the excess of exchangeable sodium (and magnesium) be replaced by calcium. I am convinced, although I cannot prove by submitting figures, that the old grass flora in the kwelder period has a very great influence on the formation and strengthening of the structural solidity of the young kwelder soil. From the soil science point of view the kwelder period is to be considered as an extremely useful preliminary period for the future polder soil. During this kwelder period the foundation is laid for the excellent structure of our marine clay-polder soils, a structure which remains unchanged for centuries. Williams (3, 20) long ago pointed out the great importance of a durable structure in all soils for all soil processes. On the basis of his studies of the natural soil-formation processes, Williams considers that structure in soil is the product of meadow formation and results from the anaerobic decomposition of organic residues, and that the creation of durable structure in arable soils can be accomplished only by meadow-forming plants, that is, in the turf stage of soil formation. Since newly formed structure is inevitably lost, Williams advises that arable soil be periodically subjected to the influence of perennial meadow plants as a part of the process of cultivation.

After a sufficiently long kwelder-period the young polder, immediately after being diked, can be cultivated as arable land. With proper drainage the salts are washed out in one winter to a sufficient depth. The chief requisite in the cultivation of the young polder soils is that the structure formed during the kwelder period should not be destroyed. The main point here is that the working of the soil should at first be only very superficial and that it should not go any deeper than the drying process, that is, than the depth to which the formation of structure has progressed. More especially the soil should not be worked in a wet condition. Care must further be taken that the water be rapidly led away; pools of water must not occur. It must constantly be borne in mind that this is still a young soil, which is more rapidly peptized by water than is an old soil.

As the young polder soil ages, drying—with the consequent formation of fissures, to which must be added worm and root holes—gradually occurs to a depth of more than 1 meter. During this process, soils of extraordinarily great permeability are formed to a great depth. As a result of cultivation, the upper layer gradually becomes less permeable; under the upper layer in many places is a thin layer which is fairly impermeable to water (Pflugsohle). In soil profiles of this nature the rain water will take the shortest way through the fairly permeable upper layer (0 to about 20 cm.); the movement of water will here be directed almost vertically downward. In the very permeable lower layer (from 20 to 100 or 150 cm.) the rain water has a chance to flow away very rapidly to the open ditches or to the drainpipes.

I have been able to observe this great permeability of the lower layers very well on a plot in a polder 163 years old. The plot is 43.5 m. wide and is drained by two side ditches about 1.5 to 2 m. deep; further drainage by means of open ditches or drains is not provided. Nevertheless this piece of ground never suffers from an excess of water.

As the soil ages still further the permeability of the deeper layer gradually decreases, and consequently drainage becomes necessary.

RECLAMATION OF THE NEW ZUYDER ZEE SOILS

A dam, 30 km. long, has been built from the coast of the province of Noord-Holland, by way of the island of Wieringen, to the coast of the province of Friesland. In 1932, when this dam was completed, the Zuyder Zee was transformed into a lake with an area of about 335,000 hectares. It is now intended to dike within this lake four polders, of respectively 20,000, 55,000, 95,000, and 55,000 hectares, an area equal to 7 per cent of the total area of Holland and to 10 per cent of the area now available for cultivation. In 1930 a dike from Medemblik to the island of Wieringen was completed, enclosing an area of about 20,000 hectares. The water was pumped out of this enclosed area, this process being finished in September, 1930; the new polder is known as the "Wieringermeer polder." The new soils vary from very sandy to heavy clay soils; the reclamation of the latter only is discussed here.

Immediately after being freed from the sea water these soils presented the same picture as do the muddy deposits when these are formed on our coasts: a muddy mass, virtually without structure, very rich in salt water and free from any vegetation. These new soils were very quickly covered with the usual salt flora (seaweed, salicornia, sea aster, etc.).

For these soils, too, the first soil formation process to be undergone is that of drying. They have to get rid of their surplus water, and so dry, form fissures, and become permeable to water; in a word, as a result of this process of drying, the originally structureless soil is changed into one with structure. For the carrying-off of the surplus water, canals and wide ditches have to be dug, and the water is removed from the smaller plots by means of open ditches and drains.

It would be best to leave these new Zuyder Zee soils for a decade or two as meadowland; in other words, to let them, like the muddy deposits along our coasts, remain for a sufficiently long time in the kwelder stage. This is necessary to give firmness to the mineral and organic soil colloids and thus to render the soils more capable of resisting the peptizing action of the rain water. As long as sodium comprises 15 to 20 per cent of the exchangeable bases, the risk of peptization is very great, and even after this sodium is nearly washed out and replaced by CaO, the new soil for a time remains liable to peptization by water.

RECLAMATION OF THE FLOODED OLDER POLDER SOILS

From time to time a sea dike gives way, and the polders behind it are flooded with the salt sea water, with which they then remain for some time in contact. After the dike has been repaired and the sea water has been expelled, a soil saturated with salt water is left behind, and moreover part of the exchangeable calcium of the soil has been replaced by sodium from the sea water. The salts of the sea water are rather quickly washed out, but the conversion of the sodium clay into calcium clay may sometimes take several years longer. The older polder soils differ chiefly in two respects from the young kwelder soils. First, the upper layer of the older polder soils is already well packed and has a high volume-weight. When drying takes place, fewer fissures are formed, and consequently the upper layer remains for a long time fairly impermeable to water and therefore also to air. This latter factor also results in a diminished production of carbonic acid, so that little calcium bicarbonate is formed. Secondly, the older polder soils lack sulfur-iron compounds. No $CaSO_4$, therefore, is formed, and the conversion of the sodium clay into calcium clay depends entirely on the calcium bicarbonate.

The best remedy for the sick older polder soils is to leave them as grassland for several years. More than a hundred years ago this procedure was recommended and applied by practical agriculturists (18).

TRANSFORMATION OF THE MAGNESIUM-SODIUM CLAY SOILS INTO CALCIUM CLAY SOILS

Both the deposits on our coasts and the new Zuyder Zee soils are rich in $CaCO_3$. When air penetrates into the soil, the FeS oxidizes into $FeSO_4$, which with $CaCO_3$ forms $CaSO_4$, and calcium bicarbonate is also formed. These two salts are soluble in water and convert the magnesium-sodium clay into normal calcium clay.

The rapidity with which this process takes place can be seen from tables 1, 2, and 3. These tables give the figures for soils taken from the following four polders: the experimental polder near Andijk, diked in 1927; the Carel Coenraad polder, the youngest polder in the Dollard region on the east coast of the province of Groningen, diked in 1924; the Reiderwolder polder, the youngest but one in the Dollard region, diked in 1862; and the Wieringermeer polder, diked in 1930.

The course of the transformation can easily be followed. The greater part of the exchangeable sodium is very quickly washed out and replaced by CaO from the $CaCO_3$. There is some difference between soils 5 and 6, both taken from the upper layer of the Andijk polder and both taken at the same time, viz., 8 years after diking. Soil 5, which is taken from a plot favorably situated with regard to drainage, has a relative proportion of $77 + 18 + 4 + 1 = 100$ (see table 3), whereas the relative proportion of soil 6, which is unfavorably situated in that respect, is of $61 + 29 + 5 + 5$. The exchangeable magnesium is much more strongly bound by the clay-humus substance (5); consequently even the soil of the most favorably situated plots contains 17 to 18 per cent MgO.

As is seen by soil 8 (table 3), the magnesium content of the 70 year old Dollard soil from the Reiderwolder polder has been reduced to the minimum

TABLE 1

Origin and age of soil

SOIL NO.	ORIGIN AND FURTHER PARTICULARS	AGE OF SOIL FROM DATE OF DIKING
		years
1	Andijk; the original black mud	0
2	Carel Coenraad polder; the layer from 40 to 50 cm. beneath surface, just free from water-soluble chlorides and sulfates; taken in 1930	6
3	The upper layer (0–14 cm.) at the same spot as no. 2, taken at the same time	6
4	Andijk; the upper layer of a plot situated very favorably in respect of the draining-off of water; taken in 1933	6
5	Andijk; the same plot as no. 4; upper layer (from 0 to between 10 and 33 cm.); taken in 1935	8
6	Andijk; the upper layer of a plot situated very unfavorably in respect of the draining-off of water; taken in 1935	8
7	Wieringermeer polder; average of several light clay soils, upper layer (0–10 cm.); taken in 1935	5
8	Reiderwolder polder; upper layer; taken in 1932	70

TABLE 2

*Content on $CaCO_3$, humus, clay, and sand; values S, V, and pH**

SOIL NO.†	PERCENTAGES CALCULATED ON DRY MATTER (105°C.)						S PER 100 GM. CLAY (+HUMUS)	V	pH
	$CaCO_3$	Humus	Clay	Sand	Clay (+ humus)	S			
1	11.6	5.7	63.1	17.5	89.0	27.4	30.8	....	
2	10.0	3.8	66.1	20.1	83.4	31.5	37.8	43.4	8.3
3	8.7	5.5	56.4	29.4	81.4	29.3	36.0	42.3	7.7
4	11.5	4.6	50.4	33.5	71.3	26.2	36.7	....	
5	10.8	5.2	57.2	26.8	80.8	30.0	37.1	....	
6	8.2	4.0	54.4	33.4	72.6	26.9	37.1	....	
7	11.0	1.7	17.4	69.9	25.1	9.85	39.3	....	
8	8.1	3.5	66.8	21.6	82.7	30.4	36.8	45.4	7.7

* Clay = fraction I + II, particles smaller than 0.016 mm. (settling velocity 10 cm./450 seconds); sand = particles from 0.016–2 mm. Clay (+ humus) is calculated by multiplying the humus by 4.545 and adding this to the clay; in this calculation the base-adsorbings capacity of the humus substance has been estimated as being 4.545 time greater than that of the clay substance. *S* value = sum of exchangeable bases ($CaO + MgO + K_2O + Na_2O$) in milligram equivalents; *V* value = the degree of saturation according to Hissink (baryta method). The pH value is determined in water suspensions by the quinhydrone method.

† See table 1.

value (relative proportion 86 + 9 + 4 + 1 = 100). How long is required for this replacement of exchangeable MgO by CaO under Dutch climatic conditions is unknown and will be determined during further investigation of the young polders.

FURTHER WEATHERING OF THE CALCIUM CLAY SOIL

After several decades the Dutch salt clay soil thus becomes a normal calcium clay soil, rich in $CaCO_3$ and with a relative base proportion of about 86 + 9 + 4 + 1 = 100. In the course of centuries this soil undergoes great changes. As with all investigations, so, also, in this case it is of great importance to find a good object of study. So far as the investigation of the process of weathering of the Dutch sea-clay deposits is concerned, the soils of the successively diked Dollard polders (Dollard region on the east coast of the province of Groningen) provide an ideal object of study. These polders were

TABLE 3

Exchangeable bases, relative proportion

SOIL NO.*	EXCHANGEABLE BASES IN MILLIGRAM EQUIVALENTS PER 100 GM. CLAY (+ HUMUS)					RELATIVE PROPORTION OF EXCHANGEABLE BASES PRESENT PER 100 PARTS EXCHANGEABLE BASES			
	CaO	MgO	K_2O	Na_2O	*S*	CaO	MgO	K_2O	Na_2O
1	7.3	14.9	2.6	6.0	30.8	24	48	9	19
2	15.9	11.3	2.6	8.0	37.8	42	30	7	21
3	23.8	9.2	2.3	0.7	36.0	66	26	6	2
4	27.9	6.3	1.6	0.9	36.7	76	17	5	2
5	28.6	6.6	1.5	0.4	37.1	77	18	4	1
6	22.7	10.6	2.0	1.8	37.1	61	29	5	5
7	28.6	6.7	1.9	2.1	39.3	73	17	5	5
8	31.6	3.3	1.5	0.4	36.8	86	9	4	1

* See table 1.

diked after the formation of the Dollard in the year 1277; the oldest polder dates approximately from the year 1550, and the youngest Dollard polder—the Carel Coenraad polder—was diked in the year 1924. The soil of the entire complex of Dollard polders is of a fairly homogeneous composition, consisting of very heavy clay soil containing little humus. Weathering has proceeded far enough to a fairly great depth. All stages are found, from the young soils, well-saturated with bases and rich in $CaCO_3$, of the young polders, to the very old soils, in which not only the calcium carbonate has disappeared, but in which the adsorbing clay-humus complex has also already lost a considerable amount of its bases, so that the soil now has an acid reaction. The soils of this latter stage are nearly 400 years old.

In this paper only a summary of a few results of the investigation of the surface of soils (from 0 to 20 or 25 cm.) of the Dollard polders is given (tables 4, 5, and 6).

TABLE 4

Origin and age of the soils of the Dollard polders

SOIL NO.	SOIL SAMPLE	NAME OF POLDER	YEAR IN WHICH THE POLDER WAS DIKED	AGE OF POLDER IN THE YEAR IN WHICH SAMPLES WERE TAKEN (1930, 1932, OR 1933)
				years
1	3648	Carel Coenraad polder	1924	6
2	5546/47	Reiderwolder polder	1862	70
3	5268/69	Finsterwolder polder	1819	113
4	5560/61	Oostwolderpolder	1769	163
5	5574/75	Het Nieuwland	1701	231
6	6181/82	Het Oud Nieuwland	1665	268
7	5588/89	Het Oudland	1626	306
8	3423	Polder Simson	1550	380

TABLE 5

Content on $CaCO_3$, humus, clay, and sand; values S, V, and pH—Dollard polders

SOIL NO.*	PERCENTAGES CALCULATED ON DRY MATTER (105°C.)						S PER 100 GM. CLAY (+ HUMUS)	V	pH
	$CaCO_3$	Humus	Clay	Sand	Clay (+humus)	S			
1	9.4	4.8	57.5	28.3	79.3	30.1	37.9	42.3	7.8
2	9.3	3.3	68.9	18.5	83.9	31.3	37.3	45.7	7.7
3	7.5	3.4	71.9	17.2	87.4	32.2	36.9	46.6	7.7
4	6.9	3.3	68.8	21.0	83.8	30.5	36.4	45.2	7.7
5	3.0	3.6	76.8	16.6	93.2	35.8	38.4	46.8	7.7
6	0.2	3.6	70.6	25.6	87.0	33.0	37.9	44.5	7.2
7	0	3.6	71.4	25.0	87.8	34.0	38.7	45.3	7.4
8	0	4.8	68.4	26.8	90.2	27.1	30.0	32.1	5.9

* See table 4.

TABLE 6

Exchangeable bases, relative proportion—Dollard polders

SOIL NO.*	EXCHANGEABLE BASES IN MILLIGRAM EQUIVALENTS PER 100 GM. CLAY (+HUMUS)					RELATIVE PROPORTION OF EXCHANGEABLE BASES PRESENT PER 100 PARTS EXCHANGEABLE BASES			
	CaO	MgO	K_2O	Na_2O	S	CaO	MgO	K_2O	Na_2O
1	22.5	10.5	2.2	2.7	37.9	59	28	6	7
2	31.7	3.9	1.4	0.3	37.3	85	10	4	1
3	32.9	3.0	0.9	0.1	36.9	89	8	2.5	0.5
4	31.6	3.1	1.5	0.2	36.4	87	8	4	1
5	34.0	2.9	0.9	0.6	38.4	88	8	2	2
6	30.3	6.9	0.6	0.1	37.9	80	18	1.5	0.5
7	31.3	6.3	0.7	0.4	38.7	81	16	2	1
8	21.2	7.3	0.6	0.9	30.0	71	24	2	3

* See table 4.

As van Bemmelen has already pointed out, the content of $CaCO_3$ decreases with the age of the soil; van Bemmelen found that approximately 1 per cent $CaCO_3$ was washed out from the soils of the Dollard polders in about 25 years (2). The humus content of the kwelder soil, when the latter is grown with grass, is 5.4 per cent. After diking, the pasture is converted into arable land, and the humus content diminishes to about 3.5 per cent, after which it remains practically constant. I may add here that at the same time the nitrogen percentage of the humus rises from about 5.4 to about 6 or 6.5, and that the P_2O_5 content is rather high, about 0.2 per cent, but decreases in the older polders (0.17–0.13 per cent).

From tables 4, 5, and 6 we see that the upper layer of the young normal marine heavy clay soils of the Dollard region, from perhaps a few decades after their diking, are characterized by the following figures: a humus content of about 3–3½ per cent, or 5 gm. humus per 100 gm. clay substance; an S value of about 37–38 m.e. per 100 gm. clay (+ humus); a V value (according to Hissink) of about 42–47; and a pH of about 7.7; and the average relative proportion of the exchangeable bases is $87 + 8 + 4 + 1 = 100$. At first (soil 2, Reiderwolder polder) the $CaCO_3$ content is 9–10 per cent (9.3 per cent). As is well known, the $CaCO_3$ decreases until, after about 250 years, it is washed out of the upper layer. As long as the soil still contains $CaCO_3$, the values S, V, pH, and the relative proportion remain nearly constant, the average values in this period, from about 50–250 years, being S(per 100 gm. clay + humus) = 36.9, $V = 45.8$, pH 7.8 to 7.7, and the relative proportion $87 + 8 + 4 + 1 = 100$. A consideration of the figures of the following polders (soil 6, 268 years old, and soil 7, 306 years old) shows that something very remarkable takes place. The $CaCO_3$ is entirely or virtually washed out of the upper layers of these polders. As I had anticipated, the content of exchangeable CaO decreases in this period, but the remarkable thing is that this loss of CaO is compensated for by a rise of the content of exchangeable MgO, with the result that the values, S, V, and pH remain practically unchanged in this period. In the upper layer of the 306-year-old polder, soil 7, that is, about 50 years after the disappearance of the $CaCO_3$, S is still = 38.7, $V = 45.3$, and pH = 7.4. The exchangeable MgO increases, however, so that the average relative proportion in this stage becomes $81 + 16 + 2 + 1 = 100$. In this stage of the weathering process the exchangeable CaO washed out seems to be replaced by MgO. It is necessary to inquire where this exchangeable MgO comes from. In my paper of 1920 (6, 7), I pointed out the possibility of the change of the bases from the acid-soluble form into the exchangeable form. In that paper I also pointed out that among the acid-soluble bases of the Dutch marine clay soils magnesia ranks first. I found an average of 0.08 gm. exchangeable MgO and 1.34 gm. acid-soluble MgO per 100 gm. soil. In 1920, I suggested two possibilities for the transition of MgO from the acid-soluble form into the exchangeable form, viz., the grinding of the soil particles, resulting in an increase of surface, and a slow diffusion from the interior of the soil particles towards the surface. In the case of the old Dollard soils I am inclined to think rather of this latter alternative.

With further weathering in still older soils (see soil 8, 380 years old), the content of exchangeable CaO falls still farther, and a further slight increase in the MgO content occurs; but the loss of exchangeable lime is greater, so that the S, V, and pH values now decrease ($S = 30.0$; $V = 32.1$; pH = 5.9). The relative proportion now becomes $71 + 24 + 2 + 3 = 100$.

Soils older than no. 8 (380 years) have not yet been so thoroughly investigated. As far as is known, however, pH values below 5 seldom, if ever, occur in older soils of this type.

THE MINERAL ADSORBING SOIL COMPLEX

Finally, I would point out that during this entire weathering process of the Dollard clay soils over a period of nearly 400 years in the temperate, humid Dutch climate, virtually no change takes place in the mineral adsorbing soil complex. In the oldest marine clay soils this complex still has practically the same composition as in the youngest polder soils. I consider myself justified in ascribing this to the lack of appreciable quantities of acid humus substances, that is, the substances, which, in the cold and temperate humid climates, attack the mineral adsorbing soil complex. As a result of the leaching of the soil water containing acid humus, the constituents Al_2O_3, SiO_2, and Fe_2O_3 of the mineral adsorbing complex are carried off and only the practically unweatherable minerals—quartz and mica—remain (15).

CONCLUDING REMARKS

The foregoing discussion in no way exhausts the subject. Important investigations have been carried out on such phases as the transformation of the humus substance, on the availability of the nitrogen compounds and the P_2O_5 compounds in the youngest soils, and the decrease of the P_2O_5 content and the K_2O content in the oldest soils. Even a brief mention of these questions is impossible within the scope of this article. I will conclude with a remark of a practical nature. Liming tests on the oldest Dollard soils (table 4, soil 8) have shown that of the excess lime applied only enough is adsorbed in exchangeable form to raise the S, V, and pH values to about 40, 43, and 7.4, respectively. With presscake[4] this takes place very soon after fertilizing, that is, in about one year; burnt lime took about 2 years. Higher values than these are not reached, in spite of the fact that there is still an excess of lime, which excess changes in the soil into $CaCO_3$ (8, 17). During the adsorption of the calcium, only hydrogen, and not exchangeable magnesium, is replaced by the calcium. Should, therefore, the occurrence of exchangeable MgO in quantities such as those observed in soils 6, 7, and 8 (table 6) be detrimental either to the soil structure or to the plant growth, the soil must be

[4] A by-product of sugar refining, called, in German, *Kreideschlamm*.

limed before the increase of exchangeable MgO begins; that is, while the soil still contains small quantities of $CaCO_3$.

REFERENCES

(1) Barbier, G. 1935 Influence des colloides humiques sur certaines propriétés physiques et chimiques des terres argileuses. *Ann. Agron.* (*n. s.*) 5: 765–780.

(2) Bemmelen, J. M. van 1863 Bouwstoffen tot de kennis van de kleigronden der provincie Groningen. *Scheik. Verhandl. en Onderzoek.* 3 (2).

(3) Bush, A. J. 1935 William Robert Williams as revolutionist in soil science and agriculture. *Pedology* 5/6: 710–733.

(4) Gedroiz, K. K. 1933 *Trans. First Comn. Internatl. Soc. Soil Sci. Soviet Sect.* A(I): 34–111.

(5) Hissink, D. J. 1919 Over de bindingssterkte van den bodem voor adsorptief gebonden basen. *Chem. Weekbl.* 16: 1128–1146 [Abs. in *Internatl. Mitt. Bodenk.* 10: 20–23 (1920)].

(6) Hissink, D. J. 1920 De methode ter bepaling van de adsorptief gebonden basen in den bodem en de beteekenis van deze basen voor de processen, die zich in den bodem afspelen. *Dept. Binnenland. Zaken. en. Landb.* [*Netherlands*] *Versl. Landbouwk. Onderzoek. Rijkslandbouwproefsta* 24: 144–250.

(7) Hissink, D. J. 1922 Methode zur Bestimmung der austauschfähigen oder adsorptiv gebundenen Basen im Boden und die Bedeutung dieser Basen für die Prozesse, die sich im Boden abspielen. *Internatl. Mitt. Bodenk.* 12: 81–172.

(8) Hissink, D. J. 1926 What happens to the lime when soil is limed. *Trans. Second Comn. Internatl. Soc. Soil Sci.* A: 174–197.

(9) Hissink, D. J. 1929 *Trans. Second Comn. Internatl. Soc. Soil Sci.* A: 119–121.

(10) Hissink, D. J. 1932 The reclamation of a part of the Zuyder Zee. *Proc. Sixth Comn. Internatl. Soc. Soil Sci.* A: 177–187.

(11) Hissink, D. J. 1932 Die Methode zur Bestimmung der austauschfähigen Basen in der holländischen Böden, welche mit Seewasser getränkt sind und $CaCO_3$ enthalten. *Proc. Second Internatl. Cong. Soil Sci.* (1930) 5: 333–334.

(12) Hissink, D. J. 1933 Die Salztonböden und die Alkalitonböden in den Niederlanden. *Verhandl. Zweiten Komm. u. Alkali-Subkomm. Internatl. Bodenk. Gesell.* 1933 (A): 185–189.

(13) Hissink, D. J. 1933 The course of the weathering processes in the marine clay deposits of Holland. *Mezögazdasági Kutatások* 6: 467–474.

(14) Hissink, D. J. 1935 De bodemkundige gesteldheid van de achtereenvolgens ingedijkte Dollardpolders. *Dept. Binnenland. Zaken en Landb.* [*Netherlands*], *Verslag. Landbouwk. Onderzoek. Rijkslandbouwproefsta.* 41: 1–126.

(15) Hissink, D. J. 1935 Der Basenaustausch im Boden. *Trans. Third Internatl. Cong. Soil Sci.* 2: 60–74.

(16) Hissink, D. J. 1937 Die Kultivierung der jungen Zuidersee-Böden vom bodenkundlichen Standpunkt aus betrachtet. *Deut. Landw. Rundschau* 6: 35–41.

(17) Hissink, D. J., and Spek, J. van der 1926 Verslag van het bekalkingsproefveld op perceel 11, enz. van de proefboerderij "Jacob Sypkens' Heerd" te Nieuw-Beerta (Provincie Groningen).

(18) Ponse, H. 1808 Kleine verhandeling over de beste middelen om de met zout water overstroomd geweest zijnde gronden tot hunne vorige vruchtbaarheid te herstellen. Rotterdam.

(19) Sokolovsky, A. N. 1933 The problem of soil structure. *Trans. First Com. Internatl. Soc. Soil Sci. Soviet Sect.* A(I): 34–111.

(20) Williams, W. R. 1935 Theses of tenacity and cohesion in soil structure. *Pedology* 5/6: 755–762.