Chapter 7

Physical Disequilibrium and Transportation of Soil Material

Introduction

Surface movement of geological materials is a very important factor in interpreting clays at the surface. Much of what we see today at the surface has been displaced from its initial position of contact with the atmosphere to the site where it is now. This is in fact one of the major problems of interpreting soils and soil clay relations and has been known and studied for many years by pedologists. Multi cycle surfaces are very often sites of human activity. For example, the initial great civilizations were produced on sites of fluvial transport. Ancient Egypt was renowned for the Nile River and its regular flooding and subsequent fertile renewal of surface soils. The Tigris and Euphrates flood plains were sites of soil renewal. The Ganges flood plain is continually fertile. Xian in the old cradle of Chinese civilization was at the same time subject to active loess deposition and river flooding. It seems that early city dwelling could be sustained for man if he lived and profited from surface clay renewal.

However not all displacement gives a happy ending and some movements of Earth materials can be considered to be catastrophic. Landslides and tsunami are not all that welcomed. The interesting point in catastrophic events (flooding especially) is that they are periodic and the greater events are always on the time scales of hundreds of years (see Smith and Ward 1998 for example). Thus strong displacement is a rare but extremely important event whereas yearly river overflow or loessal deposition is more regular and can be handled more easily by farmers. It is interesting to consider that flooding for example has no geographic limits, flooding occurs in arctic climates, mountains, temperate zones, tropical forests and deserts. By contrast, massive land slides are more contained to regions of steep relief. However they can be a major part of surface displacement and geomorphological processes (see Evans and Van de Graff 2002).

In all of these displacements clays of surface origin are put into new chemical contexts where they will react with their silicate surroundings and the chemical forces imposed by plants. New alteration profiles are produced after transport events.

7.1 Slope Effects and Physical Disequilibrium

7.1.1 High Slopes in Mountains

In looking at topographic maps of the different parts of the world, it is clear that the exposed continental surfaces are rather flat. For example strong, high mountain relief in the Western Hemisphere is relegated to about one third of North America and one fifth of South America. The African continent is rather flat for the most part as is Australia. One finds high mountains around the Mediterranean Sea the Middle East and along the giant Himalayan Tibetan massif. However, these massifs present a very special type of erosion and displacement of soils.

High mountains show rock faces which give them esthetic interest. However these cliffs basically indicate that the alteration mantle once developed has been displaced. One can look for it at lower altitudes. Again looking at high mountain topology, one can see that ice has been a major vector of transport in a classical glacial displacement system, with deposition at lower altitudes, and also one can see the results of deposition fans due to more recent landslide events (see Evans and Van de Graff 2002). It is probable that most present erosion (quantitatively) occurs through these catastrophic events. Small stream transportation is most likely of minor importance. The end result of landslide events is to mix altered material with rocks that are less in equilibrium with rainwater. One has a mixing of the different parts of an alteration profile into one more or less homogeneous structure which will gradually come back into chemical equilibrium with alteration processes. However, boulders are mixed with clays and gravel in a random manner which involves local chemical re-equilibration. Essentially landslides move large amounts of material and create new soil and alteration profile development. However some of the silicates in the fine fraction have already come into equilibrium with plant and alteration chemistry.

Lower mountain relief often indicates more regular events which move material in a slightly less catastrophic way. In such events, more akin to flooding events, one finds that the finer materials are sorted from the coarse and one develops depositional fans which grade out from the high relief as a function of grain size. This is especially true in drier mountain areas. One must remember that flooding can occur in any climate regime. In dry inter mountain basins the finer materials are spread and sorted by grain size and hence by chemical reaction zones corresponding to the amount of interaction with plants and water hydration alteration. Thus one finds a sort of banding of coarse grained (boulder and gravel) zone at mountain bases with more fine grained material found along river and sheet food surfaces grading into more arid zones. These distributions are still subject to movements through catastrophic events by flooding. However a non negligible amount of material in the flat intermountain areas can be moved by wind erosion if vegetation is sufficiently sparse; this is the loess transport mechanism.

7.1.2 Moderate Slopes

Geomorphological forces, slopes and water movement, create disequilibrium at the surface by displacing material from its equilibrium chemical environment. In cases of transport, clays which have come into equilibrium with water and chemical flux are abruptly put out of equilibrium through surface movement. Such change creates catena or sequences of soils and soil types depending upon the surface structure or their place in a landscape. In such situations where transportation of clays occurs due to water transport, new and unstable material is added to the soil surface and it interacts with the plants present (Fig. 7.1). In such situations there can develop a new set of chemical

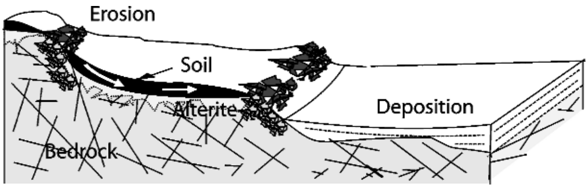

Fig. 7.1. Major vectors of soil clay displacement on slopes in temperate climates. Alteration creates a plane of mechanical weakness between rock and alterite on slopes which fosters landslides and the displacement of altered, clay-rich material

constraints which develop new equilibrium between clays and plants. Movement of clays from the surface a given site in a profile contributes to its shortening and a disequilibrium. In general, profiles which are being eroded are thin and immature where the saprock zone is minimal. A significant portion of fine grained material can move within the soil profile down slope. This material can accumulate in the level, flat lying soils or be transported further to be deposited in flat basins.

Birkeland (1984, p. 246–257) indicates that movement of fine grained material is very frequent on sloped soil sequences (catena). At the base of slopes one finds thick layers of very clay-rich materials. In temperate climate landscapes one can often observe that flat inter hill zones are more clay rich and that the soils are decidedly deeper in color if not black. When one sees such a topographical sequence one should think of lateral clay migration and accumulation. Birkeland's analysis demonstrates the fact that soils showing clay accretion will have mixed mineral assemblages, i.e. those with clays from the alterite, portion of the alteration sequence where they are not in equilibrium with the surface. Alteration sequences (vertical) will show regular transitions of clay minerals from unaltered material to that reacting with plants in the soil zone. Zones of accumulation at the base of slopes will show mixtures of clays having come from different chemical systems.

7.1.3 Wind and Water

One can divide transport systems into perhaps three broad types:

1. slope movement and local deposition of clays at the foot of the incline.
2. water born deposition of material along the edge of a river or stream and deposition by tidal and storm action into marshes along a coastline
3. movement by wind

In the second and third situations, the input material is largely dominated by clay sized material usually of 40% or more <2 µm size material. Slope movement (case one) can give fines and more coarse material to a deposit depending upon the slope grade and the material present. Slumping will bring all material to the bottom of a slope in a chemically "disordered" state where new soil parameters must be established and new plant regimes formed. Gradual runoff will give a deposition of fine clays to the down slope catchment area. Deposition along rivers (case two) is the most variable where the energy of the flow in the river determines the size material which will be deposited. Wind deposition (case three) will transport the fine sized materials. The physical process of particle transportation are detailed in Allen (1997).

Movement Vectors

Some of the effects of geomorphology on soil clay mineral sequences has been outlined by Birkeland (1984). He develops the concept of soil chains depending upon the catena in which they are found. Paquet (1977) has gone further in attempting to identify the clay mineral changes induced by topographical effect. This is of course dependent upon climate which dictates the types of vegetation and the development of clays in the soil horizons. However emphasis is placed upon lateral movement of clays and ions in solution.

What are in fact the specific consequences of such translocation of material from one soil profile to another, or the introduction of sediments into and onto a soil? Initially it is clear that the clay minerals stable in a previously established soil profile will become unstable when moved into a new, disturbed environment. First the soil chemical regime will be different due to the new plant regime which imposes new chemical equilibria. Second, the new environment can have different hydric constraints, some hydromorphic periods, for example. Changes in pH and oxidation potential can strongly affect clay mineral stabilities. Further, addition of new clay resources can stimulate or enhance plant growth, due to different potassium availability for example. It is well known that alluvial plains along rivers give high productivity due to a good availability of water and renewed clay-organic resources. Such places are typically where vegetable gardens are placed and have been for many thousands of years. In all situations, new chemical equilibria will effect changes in clay mineralogy.

Surface material becomes inherently unstable as alteration proceeds and it becomes more and more fine-grained. Such alterite absorbs large quantities of water, shrinks and expands with wetting and drying, and tends to desolidarize with the rock strata upon which it is formed. Such situations lead to land surface instability and massive movement of material down slopes. It is probable that most erosion removal in mountains is through such a mechanism. The surface soil is generally held in place by plants, roots are a good insurance against massive failure of surface materials. However despite the stabilization by plants there is nevertheless movement of the finer material within runoff water movement or within the soil itself. As water follows the down the general slope in the porous soil medium clay is moved also. Figure 7.2 indicates such a situation.

River to Sea Transportation

The ratio of fine-grained material in soil and surface erosion movement depends upon the slope and intensity of rainfall. When sufficient water is moving, sediments are carried to a river outlet and move along its course. Eventually they get deposited along the edges of the river in flood plains. Further movement brings the fine-grained material to the ocean and it can be re-deposited along the coast by re-deposition in salt marshes. In each of these transportation steps the material is of smaller grain size and the clay fraction increases in the deposited material. Thus the material deposited by water action is more and more concentrated with soil clays which were formed under surface alteration conditions. As the proportion of clay increases the materials should be more and more in equilibrium with the surface environment. Less old, unstable material such as mica, feldspar or pyroxene will be present. However the unstable, high temperature mineral material will tend to alter more rapidly due to its small grain size and hence great surface area per mass. The large flood plains are traditionally areas of fertile soils. They are essentially zones of transported soil clay. Coastal areas frequently accumulate sediment through tidal action where the clay-rich material is flocculated and re-deposited in marsh zones. These areas are frequently poldered and used for their relatively high fertility. (Fig. 7.3)

In each of these situations clay-rich material due to alteration processes is exposed to plant/clay interaction since the areas of deposition are normally in temperate climate zone where plant colonization can occur. New plant regimes can change the clays in these soil zones. However, in zones of continual deposition, the new materials are exposed to the new plant/soil regime for a relatively short period of time, being buried by the accumulation process in play. If the sedimentation is interrupted or slowed, one finds an accumulation of organic matter in a "static" situation forming a soil sequence (A, B and "C" horizon). When sedimentation resumes this static situation it is buried and is identified as a paleosoil. In such situations of river and marsh accumulation, one should remember that the C horizon material has already passed through the plant/soil zone to be eventually buried. Hence it is not a representation of the initial stages of water/"rock" interaction as found in normal alteration profiles where the source material is reacting with aqueous solution when the upper material is reacting with plant regimes.

Another, very important but often neglected source of displacement of fine-grained material is wind transport creating loess deposits. This material is taken off of scarcely or un-vegetated areas during periods of dry weather by wind storms. Such events can now be followed and monitored by satellite imagery. We can determine with precision the direction, time of flight and deposition area of such material. At present most wind born material originates in desertic areas, especially the Sahara and Gobi-Asian pla-

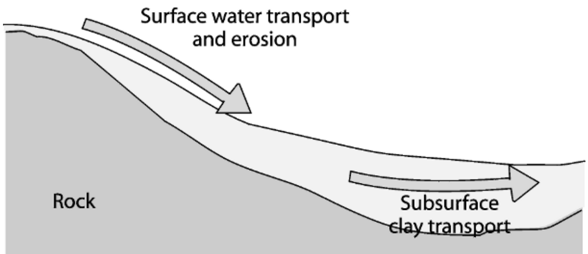

Fig. 7.2. Movement of clay particles on soil profiles (erosion) and in soil profiles (elutriation) along slope planes with the result of deposition at the bottom of the slope on or within the soil profile at the base

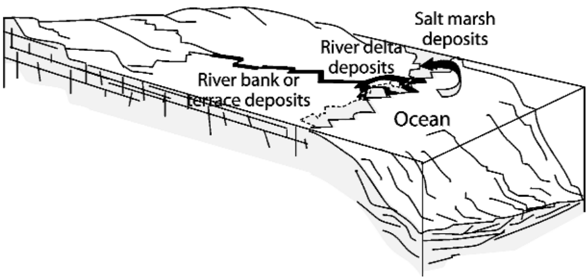

Fig. 7.3. Displacement of fine sediment by river transport into oceans and resulting re-deposition in coastal salt marshes

teau areas. However in the past a great source of dust movement as air-born material occurred at the front of continental glacier masses. This was not necessarily in desert or dry climate areas but those which had a sufficiently high deposition rate from glacial deposit to prevent significant plant growth. Thus fine-grained material was present on glacial outwash plains which could be eroded by wind movement.

In each of these environments the fate of clays and unstable materials depends upon the existence or not of plants which can rapidly transform the fine grained material into clay minerals. We will investigate these different situations as a function of plant interaction.

7.1.4 Movement of Coarse Grained Material

Displacement of surface clays is a very important feature of geomorphologic and geologic action. Any slope upon which soil is formed has a tendency to move fine particles laterally. Erosion is the general term for such movement. Usually the finer material is moved but at times landslides can occur moving all loose material, especially when the topographic relief is great. One could expect that a large part of erosional displacement in high mountain terrains is by landslide movement.

Landslides and desert wash formation suggest massive, rapid transportation of rock and altered material. Essentially all materials in different sites of equilibrium with water/rock interaction and soil plant/silicate interaction are mixed together and taken out of their chemical context. Here all is to be done again. The gradual implantation of plant communities will occur in a sequential manner and water-rock/rock alteration will begin again. However, these chemical forces will acct on heterogeneous materials some of which have already come into equilibrium with surface chemical influences and others are untouched by such action. Hence resulting clays will be highly dependent on local conditions and the origin of the materials. In the case of landslides in humid environments, one can expect a change due to plant interaction as well as water interaction. However under dry conditions, the change of the material will occur much more slowly if at all. With low residence time of water, and low plant occupation of the surface chemical change will be difficult to attain. Deserts retain the imprint of the material moved into their basins.

Mountain landslide materials are much more active chemically due to higher rainfall and plant activity. In fact much mountain slope material is in constant re-equilibration as movement is frequent. The further one moves up onto the mountain, the younger the soils are, i.e. the less clay material present and they become less deep. Nevertheless, such young soils can come to a chemical equilibrium as seen by the change in soil clay and soil clay mineralogy (see Chap. 3).

7.2 Fine Grained Material

Massive transport of fine grained material is effected by two main agents, wind and river transport.

7.2.1 Wind Transport and Loess

Loess Deposits

However another category of fine grained geologic material, which is moved laterally is the result of the action of wind. This is loess. The origin of loess deposits is generally considered to be from wind ablation of relatively flat zones of sediment accumulation of fine materials. The North American continent and Europe are examples of what are considered to be peri-glacial accumulations of fine material moved by wind (see the review by Catt 1988). The fine grained material would have been deposited on outwash plains from peri-glacial torrents which dry periodically and wind action transports the fines to be deposited at greater distances, usually several hundreds of kilometers. Grain size studies show diameter/distance relations indicating air born transport. It is generally assumed that the outwash plains were not covered by vegetation. One then has the deposition of the fine fraction of glacial, moraine material at various distances from the retreating glacier front. In some areas the accumulation of loess is very thick, tens of meters. However, the possibility of secondary accumulation of loess material should be entertained. For example if one compares the loess thickness of the Peoria unit in Illinois to the old river channels, there is a strong thickening at their edges (Lineback 1979; Fehrenbacher et al. 1984, p. 68). One can suspect secondary accumulation by surface water effects after wind deposition. A Schematic description of this process is given in Fig. 7.4.

Loess deposits in China, active today, seem to be still accumulating from the large Gobi desert region (Zhang et al. 1991). In this situation it is clear that there is no plant/soil interaction at present on the loessal materials. It is logical that plants be almost absent otherwise wind action could not ablate large quantities of fine-grained material. Loess deposits in Central China appear to be dominated by detrital chlorite and high temperature (2M) muscovite micas (Li and Chen 1999).

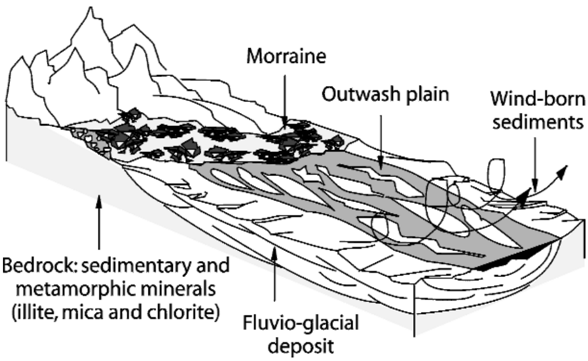

Fig. 7.4. Situation of glacial deposit on outwash plains and subsequent air born transport of the fine fraction by wind. The major cause of this transport is the high sedimentation rate and consequent lack of vegetation which could stabilize the sediment

Clays in Glacial Loess and Related Deposits

Loess has been derived from till materials in the large European and North American deposits. (Catt 1988). The clay sized material in till deposits as we see them now are typical of soils, i.e. interaction of plants and alteration products. They are composed mostly of vermiculite, S/I and I/S clays; and kaolinite. Silt sized fractions in loess contain illite and chlorite plus some kaolinite in French deposits (Hardy et al. 1999; Jamagne 1973) while tills in the American Mid-West show indications of weathering mineralogy although illite-chlorite is frequent (Willman et al. 1963, 1966; Hensel and White 1960). Most often these soil clay types are found to great depths, tens of meters just to the underlying rock substrate. The question is: why and how do soil clay minerals form these thick wind-transported deposits?

In general loess is found to be relatively homogeneous as far as grain size and clay mineralogy are concerned throughout its thickness except at the present day plant/soil interface where clay assemblages are found to change at the surface (Kuzila and Lewis 1993; Burras et al. 1996 for example). Loess clays are smectite-rich in North America and contain high amounts of soil vermiculite-S/I in Western Europe, at least France (conclusions based upon published XRD spectra by Jamagne 1973; and discussion by Hardy et al. 1999). Loessic soils on the Russian Steppes appear to contain I/S and S/I minerals (Reichenbach and Rich 1975). Kaolinite is present in most loess materials, especially in the upper portions of profiles (for example Frye et al. 1960, 1962, 1968). The S/I and I/S assemblages suggest plant/soil interactions in that these minerals are found in soils and not in the water/rock interaction alteration zones.

If we take the case of Illinois glacial deposits studied in detail in the period 1960–1975, in the tills one finds mainly illite and chlorite except for the oldest, Kansan till deposits where mixed layered clays, typical of weathering are found (Willman et al. 1966). Weathering produces the mixed layer minerals along with soil vermiculite. In the youngest till (Woodfordian) illite-chlorite content is highest. One can imagine that the tills represent the glacial material transported to the glacier front which is sifted by water transport and re-deposited on the outwash plains in front of the glaciers. It would expected that the till material is mostly unweathered rock ground from the shield substrate by glacial action. Since much of the Canadian shield or basement is of greenschist facies rocks, illite (muscovite)-chlorite would be a major component of the fine-grained fraction of such actions. Such clay fraction minerals are in fact dominant in unweathered till in Illinois.

7.2.2
Reaction Rates due to Plant/Loess Interaction

Loss of Chlorite

If illite-chlorite is transported into a climate where plants establish themselves quickly, how long does it take to alter them in the soil (plant/silicate) zone? In other words, could one expect plants to change clay mineralogy in depositing loess regimes? Transformation of illite-chlorite fine grained fractions to smectites is known in soils based on periglacial sediments in Denmark (Moberg 1990) Norway (Teveldal et al. 1990) and Finland (Gillot et al. 1999). The vegetation cover of the soils in these reports is conifer forest for the most part. The weathering reactions, illite + chlorite to soil vermiculite and S/I take several thousands of years in northern climates when developed on tills but Gillot et al. (1999) indicate that soils based on sands show much more rapid development of smectite, on the order of 1 200 years. One should note that the soil/plant interaction zone is smectite-dominated in the soil clay fraction while deeper in the profile, below the soil plant interaction zone HIV, chlorite, and micas are more dominant. However, we know that illite-chlorite is highly unstable in salt marsh (Spartina grass) prairies (Velde and Church 1999) being transformed into S/I assemblages in several years time in the plant/soil interaction zone. From these observations it appears that climate (temperature and rainfall), and perhaps vegetation type, could influence the reaction rate of formation of the soil clay minerals.

If we consider the estimations of time necessary to form smectite from illite + chlorite in moraine materials to roughly 80% completion, Egli et al. (2002) indicate a 3 000 year period for high altitude mountain glacial moraine soils. Gillot et al. (1999) indicate 1 200 years for alteration of moraine materials in Finland and Velde and Church (1999) 4 years or so in Delaware Bay salt marsh sediments of glacial origin. If we consider that reaction progress is related to temperature as $1/T$ (Ritchie 1966, p. 14), we can plot the time necessary to complete 80% reaction against the temperatures. In the case of high mountain climate, average temperature is not a very significant number in that all of the temperatures below zero are equivalent. Let us assume half of the year under ice and 10 °C average for the others which gives a value of near 5 °C. For Finland the temperature is certainly higher for non sub zero days, and one can estimate an average for all non-iced days to be near to 9 °C. The Delaware Bay, a very temperate climate probably has a 15 °C average value. Given these estimations and the determined values for reaction progress to completion by the different authors one can plot $1/T$ against reaction time (Fig. 7.5). The values align very well, but given the probable errors in the estimated temperatures and times, the relations are probably less well aligned than in the figure. However, it is clear that the differences of 3 000 years reac-

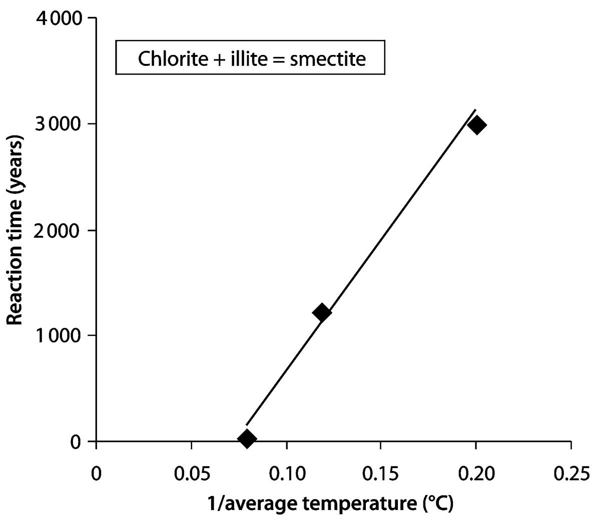

Fig. 7.5. Relation of chlorite transformation into a mixed layer mineral as a function of temperature. The stage of 80% reduction of chlorite content was observed in three situations, Delaware salt marsh, Finland till deposits and high Alpine tundra sequences on till deposits. The linear relation of reaction time vs. temperature^{-1} suggests a strong thermal relationship which would govern biological activity which enhances the reaction rate. Data from Egli et al. (2002), Gillot et al. (1999) and Velde and Church (1999)

tion times can largely be accounted for by differences in average temperature (climate). This analysis confirms that under temperate climates, one should see illite-smectite being transformed into smectites rather rapidly.

Given the possibility of a rather rapid rate of transformation under favorable conditions (repeated tidal flooding), one could expect that plant action at the surface of a soil could rapidly efface the initial illite-chlorite mineral of fine clay materials. However, if the burial rate is great enough, basically unaltered loess materials would be deposited and buried without mineral change. If this is the case, loess should be essentially illite-chlorite bearing. If it is not, at least as it seems in Illinois and France, soil clays dominate. Jamagne (1973) finds the typical soil clay mineralogy in French loess in all but one of his carefully studied profiles. At the Picardie ouest site, the deepest sample (4 m) is illite/chlorite-bearing. But in general, the loess soils under prairie or deciduous forest situations show a soil clay mineralogy to great depths, illite, S/I and soil vermiculite, kaolinite. Potassium exchange treatment closes significant portions of the smectite or soil vermiculite (14.2 Å spacing) materials suggesting smectite and HIS components of the clays.

Clay Mineral Formation in Loess Materials: Gain of Mixed Layered Minerals

Let us look again at the dynamics of clay mineral transformation in the cases loess and till examples cited. In the soil clays of the Scandinavian forests (till and outwash materials), the top most layers contain smectites. As one goes downward the illite-chlorite mineralogy becomes rapidly dominant, especially in the youngest soil profiles. However, smectite mixed layer minerals are dominant in the top most part, where the plant/clay interaction is the most intense. In the till profile the material treated by plants is fixed in place and alteration proceeds from the top downwards. Now, considering the salt marsh example where the clays are transformed rapidly, they are changed in the upper most part of the profile, where sediment accumulation occurs. Each year fresh unstable illite-chlorite is deposited mainly in the winter and during the growing season, plants interact with it. The action is through a relatively thin layer of material (several centimeters). Below this interaction level the clays change but little. This is the reverse of a soil profile developed upon a static deposit of glacial material where the plant interaction must penetrate into the profile.

Clays and Loess Deposition Rate

The case of loess accumulation and soil development is more similar to that of the salt marsh than it is to till weathering. In loess deposition, new material is layered onto the surface each year. If plants are present, probably prairies near the glacial interface, they will interact each year. Should burial be reasonably rapid, the typical characteristic of a soil (humic accumulation, clay mineral translation, etc.) will probably not be visible to any great extent in the burial sequence. In order for the deposition process to appear to be homogeneous, the upper layers of the deposit which have interacted with the plants need to be buried and new interaction take place in a new upper horizon upon further loess accumulation. If the loess transformations take place as rapidly as those in the salt marsh, 3–4 years are necessary to accomplish the formation of the typical S/I and I/S soil clay assemblage.

The reaction rates at 15 °C can be sufficiently high to produce such an effect. If the material is buried at a sufficient rate, there will be little development of typical soil features such as clay migration, development of a stable humic layer, etc. The buried clay mineralogy will represent that of the soil plant interaction. Lateral movement of surface horizons by water transport will concentrate the upper most portion of the clay profile. The deep loess horizons along major rivers in the United States are probably the result of such transport/deposition actions. This means that the soil materials in the sequences of one to several and tens of meters of loess in North America and northern Europe have been strongly affected by plant interaction.

A preliminary investigation by BV of soil clays in the Xian loess deposits and those in the Yangtze delta region showed that they are dominated by illite-chlorite with less important amounts of interlayered minerals. The interlayered mineral appears to be illite/chlorite most often. As the accumulation rate in Xian is very high (2 mm yr^{-1}) the relatively unaltered mineralogy of the soil clays could reflect high burial rate where the interaction of plants is not rapid enough under the reigning climatic conditions.

Paleosols seen in loess sequences must then represent pauses in the sedimentation of the fine grained material. Under such conditions there is a tendency to form a strong humic layer and to allow clays to migrate downward in the soil sequence as stated by Catt (1988). Since burial occurs after a resumption of sedimentation the soil profile is preserved as a paleosol.

Present Day Plant/Clay Interactions in Loess

Various investigations show that the soil clays are not greatly different in the different parts of the profile. Burras et al. (1996) find that the smectitic clays are quite similar in B and C horizons in soils based upon Peoria loess in western Ohio. Ransom et al. (1988) find that the highly smectitic clays in the B-C horizons are partially transformed into HI minerals (soil vermiculites with exchangeable aluminum in potassium solutions) in the A horizon of Peoria loess soils and Frye et al. (1968) show X-ray spectra indicating a strong increase in illite content of the S/I minerals in the upper soil horizons of an Illinoian Woodford loess. In these studies it is clear that the present day plant/soil interaction does not favor the S/I mineralogy that was produced in the loess materials upon their initial sedimentation.

Given that most of the clay minerals deposited from desert outwash plains, in China for example, have clay mineralogies representing the high temperature phases of the rocks from which they were derived, it seems logical to ascribe the typical soil clay mineralogy of European and North American loess deposits to soil clay interaction after deposition. Hence the soil clays found today are due to interaction between today's plants with minerals developed in old plant/soil interaction zones. In other words we see today the influence of new climatic and plant regimes on clays developed under other climates. Given the similarities between high plain grassland mineralogies in present soils (Birkeland et al. 2003 and Velde 2001) one would be tempted to attribute the clay mineral assemblages reported in deep loess as those formed on the dry steppe lands several tens of thousands of years ago (Fitzpatrick 1983, p. 52; Bridges 1978). Here the clay assemblages are dominated by the smectite, illite mixed layered and illite 2:1 clay minerals. The changes in present day non-deposition regimes are those of new plant regimes engendering formation of HI, and illite due to the installation of forest biotopes replacing the drier prairies.

If sedimentation of loessal material resumes, the present day soil profiles will become paleosols fixing indices of climate change in the clay mineral cortege present in the upper, humic zones.

7.2.3 River Transport and Salt Marsh Sediments

Salt marsh sediments usually are fed by river transported materials which are deposited on shallow shelves of the Continental Plateau and remobilized during storm event. The material is usually in equilibrium with terrestrial plants, having come from soil environments. Salt marsh vegetation is frequently dominated by grasses, Spartina, and can contain some broad leaved types of plants and very low shrubs. Broadly one can describe salt marsh vegetation as a type of prairie.

An example of salt marsh interaction has been reported above (Velde and Church 1999). In this instance one finds that unstable glacial flour sediments composed of mica and chlorite react quickly to the plant regime in the soil zone. A period of 4 years is all that is necessary to transform the unstable high temperature minerals into a largely new clay assemblage. Sedimentation quickly buries these materials and they do not change significantly in their composition after they leave the soil zone. This is shown in Fig. 7.6a. In the upper centimeter the clay assemblage is illite-chlorite. Chlorite represents 27% of the peak surface areas. The illite WCI peak is very sharp (*WHH* = 0.3 °2theta). In going down the profile, one sees an initial appearance of highly smectitic S/I minerals and then the formation of a slightly more illitic mineral. Eventually an I/S mineral is present also. Chlorite content drops by 80%. In a core taken along a small river, tributary to the Bay, where no plants are present on the mud banks, one finds a sequence of S/I-rich clays of similar composition to different depths. The similarity of these clay assemblages with the initial stages of transformation (Figure 7.6b) suggests that the river edge sediments are in fact due to a re-working and transportation of the uppermost layer of the salt marsh clay assemblage. Local transportation produces a homogeneous clay assemblage buried rapidly and not subject to plant-soil interaction.

This analysis demonstrates a rapid interaction of plants with new highly unstable phyllosilicate materials which produces a new clay assemblage at a rate great enough to mask the initial sedimented material. We see that a transportation of the surface material and subsequent deposition without plant interaction leaves the new soil clays unchanged. The contrast in soil clay mineralogy is very great as is the difference below the root/clay interaction zone. Essentially the climate and vegetation is the same whereas the sedimented material is quite different, one much more reactive than the other is closer to the equilibrium imposed by the plants.

In salt marsh sediments one finds that transportation and deposition initiate an interaction between plants and sediment, as in the case of loess deposition. The initial stage is a chemical equilibration with plants at the air/water interface which determines the clay mineralogy. If reaction is rapid, the imprint of the plants will be very important. Burial essentially freezes the mineralogy determined at the surface interaction zone. If great chemical disequilibrium between plant and silicates exists, clay mineral change will be significant but if the sedimented clay material is not significantly out of equilibrium little change will be observed.

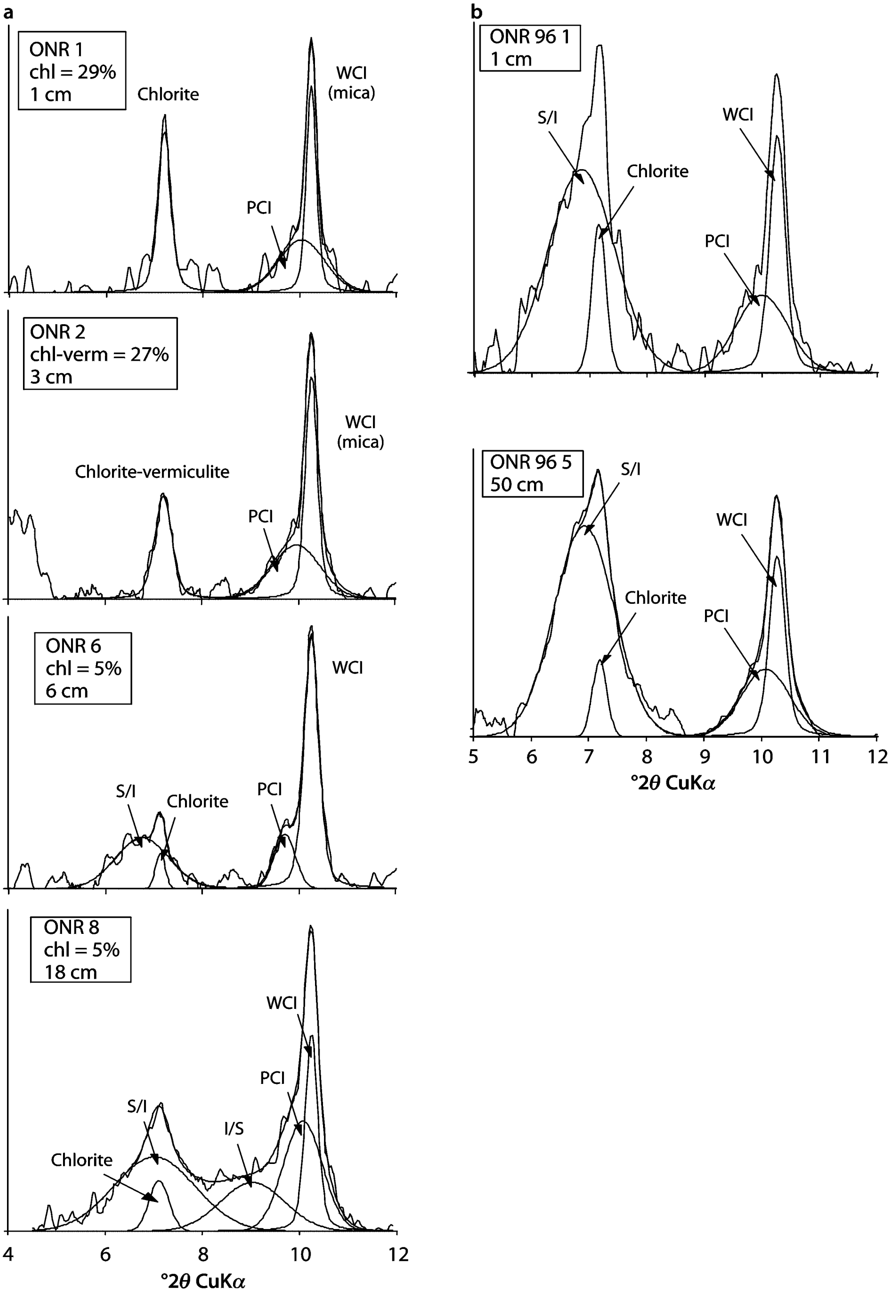

Fig. 7.6. Clay mineralogy of Delaware Bay sediments in a salt marsh core (**a**) and river bank sediment (**b**). These XRD patterns indicate that the re-mobilization of the salt marsh material through surface activity brings a relatively mature (altered) clay assemblage into re-deposition. However significant sediment is included, indicated by the presence of chlorite. This example can also be used as a model for loess transformation and re-deposition

7.3
Catena Movement of Fine Grained Material on Slopes

7.3.1
Topographically Controlled Soil Sequences

Most treatises on soil formation deal with alteration profiles that are on flat land, i.e. where little or no movement of material occurs in a lateral direction. The movement of clays and dissolved matter is assumed to be vertical. However, in many areas of land surface there is a distinct slope which moves material, either on the surface or within the alteration profile towards a lower altitude. The importance of this concept has been emphasized by Millot (1964) and Birkeland (1984) who followed studies of soils as a function of their geomorphological situation. Two things happen under such circumstances: first, material is moved by water flow to the lowest local topography and second, the plant regime usually changes from high plateaus, down slopes to more hydromorphic sites. Combination of both strongly affects, in many cases, the clay minerals formed and forming in the alteration and soil zones. Some examples are given below.

7.3.2
Slope and Smectite Genesis (Catenas)

Tropical Soils in Tchad

Bocquier (1973) reports on two toposequences from Tchad formed under tropical conditions. The overall dimensions, or relative dimensions, of the different soil profiles in the sequence are quite striking as outlined in Fig. 7.7. The granite source rock is biotite-rich, providing a clay mineralogy of kaolinite plus detrital biotite in the zones of high slope. Down slope movement of clays gives a strong concentration in the B horizon which rises almost to the surface on the toe slope region. A thin surface zone of transported clays is present there. However at shallow depth one finds some interstratified minerals and almost exclusively kaolinite and a large amount of smectite at some depth. The high slope part of the sequence is covered by a treed savannah with a decrease in trees in favor of grasses in moving down slope.

The smectite is considered by the author to be formed in the soil and subsoil. The soil sequence from high slope to toe slope is one of tropical drained red soils to black vertisols. The movement of material is accompanied by a change in mineralogy, where the silica-poor 1:1 mineral kaolinite is replaced by the more siliceous smectites.

Here it is clear that an increase in active silica (higher activity in soil solutions) is the cause of mineral change. One finds a notable thickening of the B clay-rich horizon at the expense of the more clay-poor A horizon. Since there is significant movement by erosion and some by transport of clays within the soil itself, one can pose the question of the circulation of materials with respect to the plant cover (savannah prairie type). Bocquier (1973) and other authors have argued for the accumulation of dissolved ions in solution which are concentrated upon evaporation. If the majority of the material displaced arrives from erosion deposit, then the soils are developed from the top downward, i.e. with successive deposits gradually incorporated into the

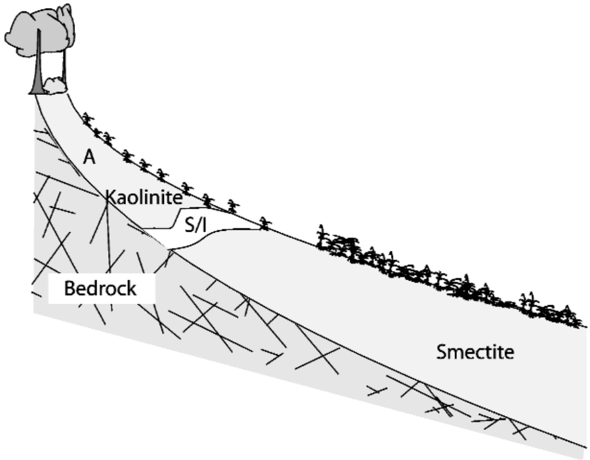

Fig. 7.7. Description of the clay facies in the catena described by Bocquier (1973) for a tropical drained soils on a slope with black soil, saturated (hydrologically) soils at the toe of the slope where smectite is found. The influence of slope on clay mineralogy under similar climatic conditions in more than evident

soil plant/silicate interaction zone from above. If this mechanism is dominant, the clays in the developed soil and alteration profile are largely of depositional origin and will have been affected by plant interaction before burial. This is a similar situation to that of loess deposition, except that the transport medium is water and not air.

Paquet (1977) insists on the importance of montmorillonite (smectite) formation at the lower portions of slopes in arid to semi-arid climates due to the accumulation of dissolved ions through capillary action to the surface under strong evaporative conditions. Her extensive research and observations under these climates at sites in Lebanon, Morocco and Tchad indicate the prevalence of the 2:1 expanding mineral at the base of slopes and their presence on outwash plains or flat basins. She felt that the explanation for this mineral, and its "invasion" of the soils under these climates was due to a concentration of dissolved elements which concentrate under conditions of lower water flow. In fact she sees a relation between these smectites and the formation of sepiolite and palygorskite in truly arid soils. This is possible, but there is perhaps another, more simple explanation related to plant/silicate relations. In the situations of slopes in semi-arid climates, there seems to be a tendency to form sparse forests on the upper portion or the plateau part of the slope. On the slope itself one finds scrub growth. In the lower portion or on the outwash zone, one finds grasses, the savannah. In each portion of the catena, different plants dominate. At the bottom of the slope prairie forms and this is where one finds smectites.

We know that grasses are good sources of phytoliths (amorphous silica) and that the savannah plant occupation of the surface is more dense that the more sparse vegetation of the treed savannah regime. One can expect that the movement by chemical uplift of silica in grasslands in such a situation would be greater than that of the sparse shrub lands of the higher slopes. It will be longer lasting in that the slope is low and the effect of uplift will be longer lasting than on a slope where erosion occurs. Hence a chemical pressure (activity of silica) would be applied by the grasses to form a more silica-rich mineral than the 1:1 mineral kaolinite in the soil (plant/silicate interaction) zone. Thus we can imagine a sequence of kaolinite-rich sediments which react with silica brought to the surface through the action of grasses in the form of highly reactive phytoliths. One should remember that, as Paquet suggests, the soil solutions flowing into the basin will concentrate silica also.

In such a situation, there is a continuous importation of soil clay minerals, dominated by 1:1 types and oxides. These will be brought into the upper, soil (plant/clay interaction) zone. Although the rain events are periodic, they are regular when considered on a year to year basis. Thus one finds a renewal of clays at the surface formed under different conditions from those of the prairie. It is highly possible that the plant/clay interaction, essentially one of the introduction of silica through phytoliths, can change the 1:1 clay mineral type into a more silica-rich 2:1 mineral type, smectite. Each yearly input will be fully or partially transformed into this new phase and subsequently buried by the continued input from upslope. Transfer of fine-grained material by gravity movement effects a change in mineralogy through the uplift of silica by plants to the surface where it is combined with a silica-poor clay mineralogy to produce smectite. In this way one can explain the high clay content profiles in the flat basins remarked by Paquet (1977) and demonstrated by Birkeland (1984, p. 238) where there is a concentration of fine material at the foot of slopes (Fig. 7.8). This fine material is sedimented, and the soil profiles formed are renewed from the top where plant/clay interaction is predominant. One can propose then that a least a part of the smectite forming vertisols under semi-arid climates is due to down slope transportation of clay material and interaction with plants.

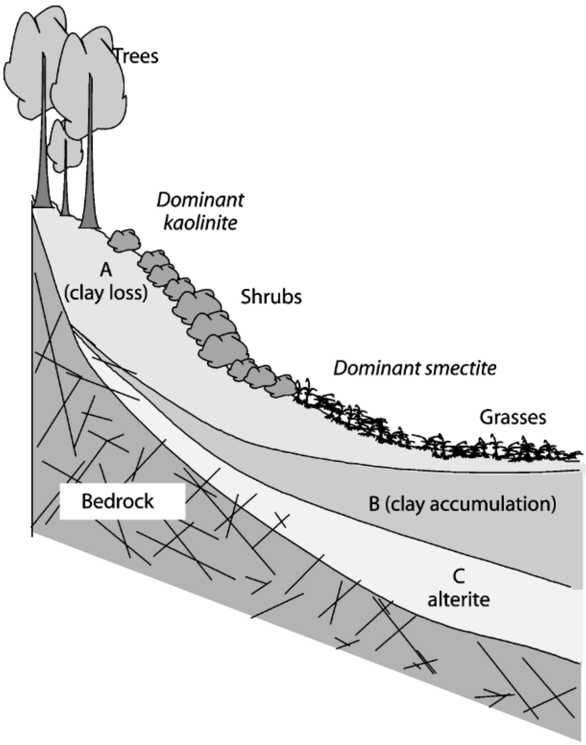

Fig. 7.8. Illustration of the relations of clay minerals assemblages as a function of position on a slope in alteration under a contrasted climate regime. High slope and low plant cover produce kaolinite, scrub produces kaolinite and lower slope prairie type vegetation results in a smectitic mineralogy (data after Paquet 1977). The change in mineralogy is essentially due to two factors, one is better drainage and low transit times of water in the soils (low concentration of dissolved ions in solution) and low vegetal activity and low input of translocated elements. Toe slope environments show higher plant activity and an accumulation of transported clays with the result that water transits more slowly and is more saturated with the elements present in the clays. Plants translocate K and Si to the surface

Red and Black Soils

A special case, at least from a soil color point of view, is found in the red-black soil sequences. These soil types, or the association of these soil types, are well known in savannah climates where soils are formed on basalts on slightly hilly terrain (Herbillon et al. 1981; Bühmann and Grubb 1991; Vingiani et al. 2004). Basically one finds kaolinite-iron oxide soil clay assemblages at the top of the plateau and slope alteration profiles developed from basalt. In the lower portions (alteration zones) smectite is common (nontronite) which is gradually replaced by kaolinite towards the surface. The plateau and slope soils tend to be sandy and red with a thin A horizon whereas the toe slope soils have a deeper brown to black color and a more strongly developed A and B horizon with more clays present. The clays in the lower toe slope zone contain smectite and kaolinite/smectite interlayered minerals. The soil color is deeper and one finds a change from hematite in the slope soils to goethite in the toe slope soils. Relative proportions of elements in the clay fraction do not seem to change much, however the oxidation state of iron does change following the color. The smectite in the lower, more reduced soil zones in the landscape is largely nontronitic, i.e. containing high amounts of Fe the majority of which is Fe^{3+}.

Undulating hills form local zones of clay accumulation and this is expressed as the black part of the red-black sequence. However the plant regime changes some, with more hydromorphic plants in these shallow basins. Hence one can suspect that the reduction in iron is to a large extent driven by increased plant activity and accumulation of organic matter. The impact of this reduction in oxidation state is to favor smectite, containing some ferrous iron. Thus one goes from a kaolinite-hematite oxidized assemblage on the slopes to one of a more reduced kaolinite/smectite plus or minus an independent smectite phase in the depressed zones. The clays at the very surface of the profiles, those of most recent migration, tend to be kaolinite and hematite rich. In the B horizon one finds the mixed layered and smectite mineral associations.

Basically, one finds that smectite (nontronite type) forms upon alteration of basalts and is gradually replaced by kaolinite and iron oxides in alteration and soil profiles on well drained sites. These are the red soils. However, in poorly drained sites the tendency is to find kaolinite/smectite minerals and even smectite (nontronite and iron beidellite, Vingiani et al. 2004) in the zones of clay accumulation. It appears that the reaction smectite to kaolinite + iron oxide is reversed in poorly drained areas. The transformation of kaolinite to smectite occurs through an interstratified mineral.

Here we can see the impact of topography on clay minerals at the surface. One can imagine, though most papers published on the red-black sequences do not mention the plant regime, that the lower, dark soil areas indicate an increase in prairie plant activity and development of a stable humic layer which favors the reduction of iron from hematite to ferric forms. Since ferrous iron is not stable in solution in the presence of silicate minerals, one finds that kaolinite is transformed to smectite in a mixed-layer phase. In better drained sectors, on slopes or plateau zones oxidation is stronger under the conditions of a savannah (contrasted season) climate. Again, in the more reduced soils, increased plant activity might bring an increase in phytoliths with a resulting increase in silica activity.

Red-black soils sequences demonstrate the importance of slope and most likely plant regime. The clay minerals change rather rapidly, since they follow the influx of eroded material (either by surface action or within the profile itself) rather closely.

In these examples we have seen that lateral movement of soil clay material and eventual deposition in low lying areas often produces a smectite mineralogy. Smectites are the most silica-rich of the soil clays and hence need an abundant source of silica to maintain their presence. This source is most likely that of plant phytolith deposition at the surface. In clay-rich sediments, little clay movement can be expected by elutriation or vertical water movement within the soil and hence the clay assemblage will be stable as it is continually buried by further sedimentation due to down slope movement.

7.4 Summary

Movement of surface materials is very important in understanding soils and their clay mineralogies. Transport of fine grained material can change the surface layers, or in fact much of a soil sequence if the material is deeply buried. In such instances the clay mineralogy is relatively static having come to surface chemical equilibrium. Should the plant regime change, one would expect to see changes in clay mineralogy in the soil zone. Chemical loss by water-silicate dissolution is minimal, compared to that which occurs when water is in contact with highly unstable high temperature minerals which transform into clays. In such situations one could even propose that there is a high proportion of chemical transport that occurs through plant chemical uplift.

Much of human activity has been centered in the areas where clays have been transported and concentrated, in the presence of water or not. Initially, of course the necessity of transportation and water resources for a population invited grouping of people around rivers or delta areas. The population concentration occurred largely because early on men began to get along poorly with their neighbors and needed to build protective systems for their well being. This led to concentrations of population within the protective walls even though overall the population density of an area was small. In any event, water resource became important. Transportation by water rapidly became important also as trade in needed external resources became evident. With the advent of agriculture, given a concentration of habitation on local sites, one needed a close source of fertile soil. River and lake or sea side sites were extremely well adapted in that soils, frequently with humic material, were deposited in such sites, soils which were adapted to grain growing. Further, if a water source were sufficiently important one could correct for nature's forgetfulness in times of drought by irrigation. As a result of these causes, people used the renewable resources of river and peri-maritime transportation of fine grained alteration products to the benefit of developing mankind.

If one wishes to understand the reasons for the presence of vertisols at the base of long slopes in semi-arid climates, it is probably in the relations between clay mineral transport and the development of prairie ecosystems. Certain positions in the landscape are conducive to the formation of smectitic minerals. Observations of mineralogy and site in the landscape were often made without the insight concerning plant ecosystem relations. If one combines the physical transportation of a specific type of mineral with the impact of plant interaction one can easily conclude concerning the origin of the clay minerals observed. Reading the landscape involves both vegetal and mineral elements.

Suggested Reading

Allen PA (1997) Earth surface processes. Blackwell Science, 404 pp
Birkeland PW (1984) Soils and geomorphology. Oxford University Press, 372 pp
Fitzpatrick E (1983) Soils. Longman, London, 353 pp
Millot G (1964) Géologie des argiles. Masson and Cie, Paris, 499 pp (English translation 1970: Geology of clays. Springer-Verlag, New York, 429 pp)
Smith K, Ward R (1998) Floods: physical processes and human impacts. John Wiley and Sons, New York, 382 pp