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Use of clay minerals in reconstructing geological processes: recent advances and some perspectives

J. ŚRODŃ

Institute of Geological Sciences PAN, Senacka 1, 31-002 Kraków, Poland

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ABSTRACT: This article reviews that clay literature from the last ten years, which is devoted to the applications of clay minerals in the interpretation of geological processes in sedimentary basins. The results, selected by the author as being of particular interest, are presented, arranged according to the successive phases of the rock cycle.

The research field defined in the title has expanded significantly over the last decade. The number of articles has at least tripled in the period 1992–96 compared with 1986–91, the trend characterizing both publications, *Clay Minerals*, and *Clays and Clay Minerals*. Current advances are largely due to widespread use of radiometric dating, stable isotopes, electron microscope techniques and basin modelling software. The fundamental particle model of Nadeau *et al.* (1984) inspired different lines of mineralogical research which will soon find geological application.

Diagenesis remains the most intensely studied domain of clay geology. Research interests centre on sandstones as opposed to shales, which were more widely studied in the pioneer period of clay diagenesis. The most complete information was accumulated from the North Sea region, as opposed to the Gulf Coast, which originally provided classic data on shale diagenesis.

The state of knowledge in the field of clay geology has been summarized in detail in books by Chamley (1989) and Weaver (1989). This article presents recent advances in clay science applied to solving geological problems, selected by the author as being of particular interest. They are arranged according to the successive phases of the rock cycle. Metamorphic and hydrothermal processes are not discussed.

WEATHERING

Studies of weathering throughout the last decade were dominated by applied, environmental research. Nevertheless, important advances in understanding natural processes were made in this period.

Kaolinite

Studies of kaolinite seem the most advanced. Chivas & Bird (1995) summarized results of stable isotopic studies in the southern hemisphere (former Gondwanaland). In Australia, stable isotope data for kaolinite from weathering profiles ranging in age from Permian to Recent were correlated with the continent's migration toward the equator. This correlation can now be used for approximate dating of soils of unknown age and for estimation of palaeoaltitudes of dated soils. Australian data were confirmed by data from India and South America (Chivas & Bird, 1995). They all document widespread cold climate kaolinitic weathering. Permian kaolins of Australia are interpreted as having formed by glacial meltwaters. The presence of kaolinitic weathering crusts can no longer be interpreted as an indicator of tropical weathering, without stable isotope data. It is suggested that the high-latitude kaolinitic weathering crusts of the northern hemisphere were destroyed by glaciation.

Mizota & Longstaffe (1996) also inferred a cold climate origin when studying stable isotopes of thick Cretaceous and Oligocene kaolinite deposits of Japan. Kaolinitization reactions were studied intensely using transmission electron microscopy (TEM) (e.g. alteration of biotite: Ahn & Peacor, 1987; Fordham, 1990). Alteration of kaolinite to halloysite in lateritic profiles was documented in great detail (Singh & Gilkes, 1992). Such TEM studies may aid genetic interpretation of kaolin minerals in sediments.

Arenes

Sequeira Braga *et al.* (1990) summarized studies of coarse granitic saprolites ('arenas') of Europe, from Portugal to Scandinavia. They proposed the term 'arenization' as a name for a third major weathering process, in addition to kaolinitization and smectitization, which can be distinguished by its textural and mineralogical characteristics (abundant coarse-grained primary minerals plus very low clay content). Arenes of Europe show climatic zonality of the weathering products, related to temperature and not to rainfall: from vermiculite and mixed-layer minerals in Scandinavia to kaolinite and gibbsite in Portugal and Spain. Arenes can be used in palaeoclimatic reconstructions. Their geographic relation to cold climate kaolins, detected by stable isotope studies, remains unclear.

Soil vermiculite, a characteristic component of arenas, was studied in detail as an indicator of acid rain impact (Bain *et al.*, 1990). They concluded that the amount of hydroxy-Al interlayers is pH dependent. This finding is useful for palaeoclimatic reconstructions based on palaeosoil studies.

Smectite and illite-smectite

Wilson (1987) reviewed studies of soil smectite, stressing the differences of soil smectites with respect to bentonitic smectites. Soil smectites are typically Fe-rich beidellites. Hydroxy-Al interlayering is common at low pH. Anomalously high basal spacings are sometimes recorded, due to other types of interlayering (organic?). Righi *et al.* (1997) summarized their recent work on smectites from Vertisols (basic pH) and from eluvial E horizons of Podzols (highly leached, acidic environments). They found that in both cases, low-charge beidellite is the most stable smectite, forming at the expense of montmorillonite in Vertisols and at the expense

of high-charge beidellite or vermiculite in Podzols. The processes of smectite formation were stated to occur within a few thousand years. These findings are useful in the interpretation of the origin of smectite in marine sediments (see below).

As opposed to soils, the composition of smectites in weathering crusts does not show such a clear pattern. Detailed studies using analytical electron microscopy (AEM) indicate that under the same weathering conditions, smectites of different chemical composition may crystallize locally in microenvironments, from different parent minerals (e.g. Aoudjit *et al.*, 1995). A similar variation in smectite chemistry, reflecting chemical gradients developed during alteration, rather than parent rock bulk chemistry, was documented in bentonite deposits (Christidis & Dunham, 1993).

Isotope studies of soil smectites seem less numerous than those of kaolinite. The power of this approach was demonstrated by Stern *et al.* (1997), who presented a stable isotope study of smectites developed in soils on Himalayan molasse. They found that smectite probably crystallizes during wet seasons and calcite in dry seasons. A parallel shift of the stable isotope compositions of smectite and calcite shows major climatic change in the region (either increased aridity or more marine-sourced precipitation).

Illitization of smectite in weathering environments remains a big unsolved problem of clay geology, and is very important for evaluating the detrital input into sedimentary basins. Wetting and drying cycles, in particular under basic conditions, were suggested as the possible illitization mechanism (Eberl *et al.*, 1986 and literature cited therein). So far, the most convincing evidence of this process actually taking place in nature was provided by Righi *et al.* (1995), who detected progressive illitization in polders of the Atlantic coast of France, reclaimed from the sea over the last 350 years. More evidence was presented by Berggaut *et al.* (1994) who detected randomly interstratified illite-smectite as a major component of a Quaternary regolith developed on pyroclastics of basalt composition in the Golan Heights. The origin of illite-smectite is attributed to alteration during long dry seasons. Both studies point to wetting and drying as the illitization mechanism, but both are lacking the ultimate proof, i.e. ruling out the aeolian input of illite-smectite (e.g. by K-Ar dating: older than the stratigraphic ages expected in case of aeolian contamination).

It seems clear that the alteration of illite in the weathering environment is not a simple reversal of the smectite illitization reaction (Wilson, 1987). In particular, ordered mixed-layer minerals are not being encountered as alteration products. A study by Elsass *et al.* (1997) indicated a mechanism proceeding on crystal-by-crystal basis and producing very heterogeneous expandable material.

SEDIMENTATION AND EARLY DIAGENESIS IN CONTINENTAL ENVIRONMENTS

The most interesting recent developments in this field came from a study of the Recent sediments of saline alkaline lakes of Eastern California and the Eastern African rift zone, and ancient sediments of the Mediterranean region (Spain, Turkey, Morocco). These studies, published in English, provided more detailed analyses than previously available for the clay neof ormation phenomena described from French Tertiary basins during the 1950s (see Millot, 1970).

Of particular importance is the study of a 700 m core from Searles Lake by Hay *et al.* (1991). Clastic sediments of this lake undergo little alteration apart from crystallization of small amounts of clinoptilolite if the pH of the interstitial water does not exceed 8. In the pH range 9–10, up to 70% of the sediment is recrystallized into an authigenic Fe-illite, Mg-smectite, K-feldspar and analcime assemblage. According to stable isotope evidence, playa oxidizing conditions favour precipitation of Fe-illite and K-feldspar, and open-water reducing conditions promote crystallization of Mg-smectite. This paragenesis can then be used as indicator of shallow alkaline lake and playa environments. Deconinck *et al.* (1988), who studied Fe-illites from the Swiss and French Jura, suggested a similar interpretation for the environment. The conditions and mechanisms of formation of lacustrine Fe-illite, and its chemical composition, are clearly different from that of both glauconite and burial-diagenetic illite. Recently, abundant Fe-illite of approximately syndimentary K-Ar age was documented in the European Permo-Triassic, but interpreted as being of pedogenic origin (Jeans *et al.*, 1994). Some Fe-illites produce stratigraphic K-Ar ages (e.g. Deconinck *et al.*, 1997), but sometimes detrital contamination is present and cannot be removed (e.g. Le Puy illite; Clauer & Środoń, unpublished data).

Numerous recent studies characterize Mg-clays in lacustrine sediments, usually confirming earlier findings. Sepiolite and palygorskite are firmly established as indicators of arid climatic conditions (sabhka, saline lakes, caliche). These results are summarized in a monograph by Jones & Galán (1988). New findings were presented by Hay *et al.* (1995) who investigated Recent sediments of Eastern African lakes. They documented $\delta^{18}\text{O}$ evidence of evaporation controlling kerolite vs. stevensite crystallization.

The phenomenon of mechanical clay infiltration, well recognized in soil profiles, was stated as occurring on a large scale in coarse fluvial deposits under conditions of arid/semi-arid climate, owing to a lowered water table. The SEM criteria for distinguishing infiltrated clays were proposed (Moraes & Ros, 1990).

SEDIMENTATION AND EARLY DIAGENESIS IN MARINE ENVIRONMENTS

Green marine clays

These clay minerals were the first to be recognized as clearly authigenic in the marine environment. Current knowledge of these clays has been summarized in an excellent monograph edited by Odin (1988), based mostly on the studies of Recent sediments. Four distinct sedimentary facies containing Fe-clays have been characterized: verdine, oolitic ironstone, glaucony and celadonite.

The verdine facies is known only from Recent deposits and is characteristic of tropical, very shallow (5–60 m) marine waters close to a major supply of iron (river mouth or outcrops of volcanic rocks). Such a restricted occurrence makes this facies an excellent environmental indicator. With depth, the verdine facies may evolve into the glaucony facies. Mineral components of verdine are interstratified clays composed of 7 Å, 14 Å and smectitic (swelling) layers, called phyllite V and C by Odin (1988). Å di-trioctahedral 7 Å clay mineral (odinite) was defined by Bailey (1988). Amouric *et al.* (1995) documented an interstratification of Fe-kaolinite and Fe-serpentine by a HRTEM study of similar material.

The mechanism of formation of verdine clays is interpreted as neof ormation in a confined environment (pores and cracks in substratum) at the sediment-water interface. A silicate precursor is

not needed and verdine minerals can also crystallize on a carbonate substratum.

Oolitic ironstones are not known from Recent sediments and are interpreted as diagenetically altered clays similar, but not identical to, the verdine facies. This interpretation is based on similar mineral composition (7 and 14 Å clays). Recently, Hornibrook & Longstaffe (1996) documented a transition of grain-coating and pore-lining berthierine into chamosite below 70°C. They inferred, from oxygen isotope data, a brackish-freshwater composition for the original crystallization environment.

The glaucony facies is defined by the presence of mineral glauconite, which crystallizes by neof ormation on different substrata at the seawater-sediment interface. It became evident that a silicate precursor is not necessary. Contemporary glauconitization is known from open-sea continental margins at low and moderate latitudes and at a range of depth from 60 to 1000 m, most often between 60 and 550 m. A prerequisite for glauconitization is a porous substratum residing for prolonged periods of time at the sediment-water interface. The presence of glauconite is then an indicator of a sedimentation hiatus, the length of which can be estimated from the stage attained by the glaucony grains. Glauconitization of a substratum characteristic of very shallow depth (e.g. shell bioclasts) is a record of marine transgression.

Mineralogically, glauconitization is a process analogous to illitization: gradual alteration of neof ormed Fe-rich smectite into Fe-illite similar to celadonite, through intermediate mixed-layer phases. Simultaneously, substratum minerals gradually dissolve. Complete glauconitization, whereby expandability disappears and K₂O increases to 9%, requires ~1 Ma. It is estimated that, at a stage of 7% K₂O, substratum minerals are totally dissolved, and such glauconite grains should yield correct stratigraphic ages (Odin, 1988).

A very detailed study of the glauconitization of nontronite that crystallized in the Galapagos Spreading Centre mounds has been presented by Buatier *et al.* (1993). Transition from the verdine to the glaucony facies was documented by Amouric *et al.* (1995). Using HRTEM they discovered the following alteration sequence: Fe-kaolinite-berthierine-glauconite.

Numerous studies of celadonite in ODP materials have confirmed that celadonite is chemically different from glauconite (more Si, Mg and K)

and indicative of submarine alteration of basalt. As a neof ormed mineral, carrying no detrital signature, it offers an excellent opportunity for dating the basalt alteration events (Odin, 1988).

Palygorskite and smectite

The authigenic vs. detrital origin of palygorskite and smectite in the Atlantic sediments has been debated vigorously. Thiry & Jacquin (1993) observed a lack of smectitic-type weathering in the Cretaceous of Europe and a lack of palygorskite in the Cretaceous of onshore Moroccan basins. They concluded that smectite in the Atlantic Cretaceous sediments must be authigenic, produced by recrystallization of detrital silicates, and palygorskite must be also authigenic, crystallized from sinking brines.

Deconinck & Chamley (1995) presented evidence of three varieties of smectite present in Cretaceous sediments: (a) soil-derived Fe-Al smectites; (b) recrystallized smectites, distinguishable by idiomorphic shapes using electron microscopy (Steinberg *et al.*, 1987), and characteristic of low sedimentation rate; and (c) Cheto-type smectites produced by alteration of pyroclastic input. On the other hand, in the Gulf Coast bottom sediments deposited at high sedimentation rate, Yeh & Eslinger (1986) were unable to detect an authigenic clay component by stable isotope techniques.

Based on particle morphology observed by SEM and TEM, Pletsch *et al.* (1996) described two types of palygorskite in onshore Moroccan basins: authigenic in the Atlas Mountains, and reworked in locations close to the present-day shoreline. They concluded that deep-sea Atlantic palygorskites are detrital, transported mostly by SW winds from nearshore shallow African basins into the ocean. Thus they confirmed palygorskite as an unambiguous indicator of shallow-water saline environments and arid climate.

BURIAL DIAGENESIS

Burial diagenetic processes are controlled predominantly by the bulk composition of the rock. As a result, illite is the most common diagenetic product. Formation of kaolinite and chlorite as dominant diagenetic minerals requires special conditions (high fluid/rock ratio or uncommon composition of the parent rock). Reactions involving all three minerals were studied extensively in the last decade and used to interpret geological processes.

Illite

Mechanism of illitization. The single most important development in illite studies was the interpretation of mixed-layer minerals in terms of fundamental particles and interparticle diffraction, initiated by McHardy *et al.* (1982) and developed by Nadeau *et al.* (1984). This new concept implied that the entities which evolve during illitization are not mixed-layer crystals but fundamental particles, and an understanding of the mechanism of illitization should evolve from fundamental particle studies. Indeed, Inoue (1986) stated that fundamental particles grow simultaneously in three dimensions (3D), changing their shape from irregular flakes to laths and hexagonal plates. A similar trend was described by Lanson & Champion (1991). Recently, Środoń *et al.* (1997) confirmed a 3D growth pattern. They found that the thickness distribution of fundamental particles of illite-smectite is strictly lognormal and follows a unique evolution pattern. This finding permits refinement of the well-known Kubler crystallinity index measurement into a precise measurement of mean crystallite thickness (Drits *et al.*, 1997).

The mechanism of illitization in bentonites was identified as the growth of fundamental particles (simultaneous nucleation and growth was excluded) by K-Ar dating of classes of fundamental particles separated by ultracentrifugation: thinner particles gave older ages (Clauer *et al.*, 1997). This technique offers an opportunity to determine the duration of illitization events, as demonstrated by timing the duration of thrusting in the Montana disturbed belt (Clauer *et al.*, 1997).

The lognormal distribution of the thickness of fundamental particles does not support the concept of Ostwald ripening suggested earlier as an explanation of the illite crystal growth mechanism (Eberl *et al.*, 1988; Inoue *et al.*, 1988).

Controls of the illitization reaction and palaeotemperature interpretation. Discussions concerning thermodynamic vs. kinetic control of smectite illitization in shales started with Eberl & Hower (1976), and continued during the past decade (review in Essene & Peacor, 1995). It is largely agreed that the reaction is kinetically controlled. Several kinetic equations have been proposed and used to model the evolution of expandability with depth in different basins in order to test computer models of basin evolution, in the same way as vitrinite reflectance data are being used. The

proposed formulae take into account only time-temperature effects (Velde & Vasseur, 1992) or include pore-water chemistry (Pytte & Reynolds, 1989; Huang *et al.*, 1993) and chemical heterogeneity of the parent smectite (Wei *et al.*, 1996).

Critics of the kinetic approach point out that none of the published equations is capable of modelling basins of diverse history (Elliot & Matisoff, 1996). In particular, for old basins the modelled degree of illitization is always highly overestimated. The fit would become even worse if the recent findings of Small (1994, 1995) were taken into account. He found experimentally that carbonate and organic anions (oxalate, acetate) buffer aK^+/aH^+ in the mica stability field, and the rate of illitization increases by several orders of magnitude. On the other hand, quite expandable illite-smectite persists even in Precambrian sediments if the burial history did not include an elevated temperature event (Price & McDowell, 1993).

An alternative viewpoint is held, e.g. by Pollastro (1993) and Środoń (1995), who concluded from analysing expandability data and thermal histories of basins ranging from Precambrian to Quaternary that the expandability of I-S in shales is controlled by, and indicative of, the maximum palaeotemperatures, other factors being negligible. Such an approach was used to interpret K-Ar data, producing results consistent with a basin history model (Clauer *et al.*, 1997). It is believed to apply only to shales, where K supply is not the rate-limiting step. Additionally, NH_4 becomes available during shale diagenesis and its level in illite is indicative of the intensity of organic diagenesis (Lindgreen, 1994 and literature cited therein).

In bentonites, which are K-deficient rocks, illitization is controlled by the kinetics of K migration from outside the bed, as evidenced by %S zonation and K-Ar dates (Altaner *et al.*, 1984; Clauer *et al.*, 1997). As a result, illitization in bentonites lags behind shales (Šucha *et al.*, 1993).

In sandstones, the degree of illitization may reflect the temperatures of migrating fluids rather than the burial temperatures of the entire basin. An example of such a relationship was presented by Whitney & Northrop (1987). Analysis of the chemical composition of illite and chlorite coexisting in sandstones led Jahren & Aagaard (1992) to conclude that these minerals crystallize and recrystallize in near equilibrium conditions.

Dating diagenetic events. Reliable dates are currently available only from bentonites and some

types of sandstones (aeolian, beach), free from detrital mica contamination. Shales produce mixed detrital/diagenetic ages even in the finest ($<0.01 \mu\text{m}$) separable fractions (Clauer *et al.*, 1997). Attempts to extrapolate diagenetic and detrital ages by quantifying these components in shale samples were presented (Mossman, 1991; Pevear, 1992) but they seem to be of only very restricted use because quantification is often next to impossible.

Illite dates were used to interpret ages of various diagenetic processes. Most often, these are ages of maximum palaeotemperatures related to burial (e.g. Elliot *et al.*, 1991; Barnes *et al.*, 1992; Clauer *et al.*, 1997). However, K-Ar dates of filamentous illites from the Paris Basin are incompatible with burial history and indicate a major heating event of Liassic age (Mathieu & Velde, 1989; Mossman *et al.*, 1992) and accompanying hot-fluid flow (Platt, 1993). A heating event of similar age was detected by Clauer *et al.* (1996) in the Rotliegendes of Alsace and N. Germany and was also related to hot fluid flow along major fault lines. Recently, the Liassic heating event, much younger than the maximum burial of the basin, was dated in the Carboniferous of the Upper Silesia Coal Basin (Banaś *et al.*, 1997). Similarly, K-Ar dates of filamentous illites in the Rotliegende and Jurassic of the North Sea are interpreted as ages of hot fluid flow and hydrocarbon emplacement (Ziegler *et al.*, 1994 and literature cited therein). Hay *et al.* (1988) interpreted their K-Ar data for illite-smectite from Ordovician tuffs in the Mississippi Valley area in terms of regional flow of basinal brines.

The K-Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ dates of illite were also used to evaluate the duration of thrusting (Altaner *et al.*, 1984; Clauer *et al.*, 1997) and age of stylolitization (Thomas *et al.*, 1993).

Chlorite

Studies of chlorite, in particular of authigenic chlorites in sandstones, have expanded rapidly in the past decade. Attempts were made to apply chlorite as a palaeothermometer, utilizing the evolution of its chemistry, polytype, interlayering and morphology during diagenesis and metamorphism. Reviews of this literature were presented recently by de Caritat *et al.* (1993) and Walker (1993).

Cathelineau (1988) presented a strong linear relationship between tetrahedral Al in authigenic chlorites and present-day temperature for two active

hydrothermal systems. Studies of diagenetic materials confirmed an ^{14}Al increase with temperature but did not confirm the unique relationship, indicating that the temperature-composition trend is affected by the bulk composition of the system (Jahren & Aagaard, 1989, 1992; Hillier & Velde, 1992; Spotl *et al.*, 1994).

According to the reviews of de Caritat *et al.* (1993) and Walker (1993), no simple relationship exists between chlorite polytype and temperature, although generally *Iib* is the higher temperature polytype. Spotl *et al.* (1994) documented a gradual *Ib-Iib* polytype transition in Fe-chlorites from sandstones of the Arkoma Basin, Oklahoma, well correlated with changes in crystal morphology from small thin plates into bigger and thicker plates. They estimated the lower limit of chlorite *Iib* appearance as 150–180°C. Very similar data were presented by Hillier (1994).

Problems of chemical and polytype chlorite palaeothermometry were explained by Curtis *et al.* (1985) and Hillier (1994) who proposed diverse origins for chlorite coatings in sandstones. According to the latter author, Fe-rich chamosite comes from a berthierine (serpentine) precursor and Mg-rich clinocllore, from trioctahedral smectite. The Mg-chlorites have lower ^{14}Al content than Fe-chlorites. The polytype of Fe-chlorite evolves with temperature from *I* to *Iib*, whereas Mg-chlorite crystallizes directly as *Iib*. The model of Curtis *et al.* (1985) is even more complicated, including direct precipitation of chlorite from solution as a product of several mineral reactions. In any case, these models imply that the chemical composition of grain-coating chlorite reflects the sedimentary environment. Further refinement of the model was presented by Hillier *et al.* (1996).

Diagenetic evolution of chlorite is complicated by interstratification. Interstratification with smectite and/or vermiculite was recognized in the 1960s. It differs from the pattern of illite-smectite interstratification through the exceptional stability of the regular 1:1 phase corrensite. According to data summarized by Hillier (1993), estimates of the temperatures of appearance of corrensite range between 60 and 160°C. Corrensite is then a late diagenetic mineral, unknown from surface environments. The transition of corrensite to chlorite was documented in detail from TEM studies by Jiang & Peacor (1994).

Reynolds *et al.* (1992) and Hillier & Velde (1992) recognized interstratification of chlorite with serpen-

tine and proposed XRD techniques for quantification of such mixed-layering. Hillier (1994) presented data indicating that the serpentine component has a berthierine composition and that it decreases gradually with increasing temperature and disappears entirely at temperatures between 150 and 220°C.

Kaolinite

Most new information on diagenetic kaolinite has come from studies of reservoir sandstones in the North Sea (summary in Bjorlykke, 1992). Early diagenetic kaolinite results from flushing sandstones with meteoric water flow; thus maximum development of kaolinite is indicative of the proximity of shoreline, the continuity of sandstone bed, and the sea level changes. In the absence of flushing, the kaolinite + feldspar assemblage is stable until 120–140°C, and then reacts forming hairy illite. Experiments of Huang *et al.* (1986) confirmed the role of fluid/rock ratio in altering feldspar into kaolinite or illite. According to Osborne *et al.* (1994), early diagenetic kaolinite crystallizes at different temperatures with different habits: vermiform between 25 and 50°C and blocky between 50 and 80°C. However, morphological changes may be related to the degree of supersaturation rather than directly to temperature.

Ehrenberg *et al.* (1993) recognized and documented a kaolinite-dickite transition at ~120°C in the Triassic and Jurassic of the North Sea. Polytypic transition is reflected in morphology changes from vermiform to blocky crystals. McAulay *et al.* (1994) estimated the transition temperature as 80–110°C. This reaction was documented also by Ruiz Cruz & Andreo (1996) from Permo-Triassic rocks of Spain and by Lanson *et al.* (1996) from the Rotliegend of the North Sea.

Late diagenetic (telogenetic) kaolinite develops in sandstones flushed by gravity-driven meteoric waters after the tectonic inversion of a basin. Longstaffe (1992) reviewed the abundant stable isotope data on kaolinite from the Western Canada Sedimentary Basin. Baker & Golding (1992) used $\delta^{18}\text{O}$ values of such telogenetic kaolinite to date the uplift of an Australian basin by the technique of Chivas & Bird (1995).

PERSPECTIVES

Development of new techniques for solving geological problems using clays depends to a

great extent on the progress made by clay mineralogists. New measurable parameters or smaller size of measurable objects make new applications possible.

Current developments in clay structure modelling, such as turbostratic and/or rotational disorder combined with *cis*- and/or *trans*-vacant unit-cells (Drits *et al.*, 1993, 1996; Reynolds, 1994; McCarty & Reynolds, 1995; Moore & Reynolds, 1997) and clustering of cations in the octahedral sheet (Dainyak *et al.*, 1992) should stimulate systematic studies aimed at correlating these features with the conditions of clay formation and alteration. These techniques of studying bulk properties of clays will be aided by TEM studies of individual clay particles, in order to evaluate the dispersion of bulk properties. New tools for reconstruction of geological processes may emerge from such studies.

New horizons for isotope studies will appear when isotope information becomes available from individual crystals (like AEM analyses at the present time) and if a single-clay geothermometer becomes a reliable tool (Bechtel & Hoernes, 1990; Delgado & Reyes, 1996). Clay-water fractionation equations have been refined recently (Sheppard & Gilg, 1996). We will observe expansion of isotopic studies in the domain of weathering, in particular applied to smectite weathering products, and to the processes involving evolution of illite, both neoformation and alteration.

The Bertaut-Warren-Averbach technique allowing rapid XRD analysis of crystal thickness distribution (MudMaster program, Drits *et al.*, 1998) will be used to trace the evolution of crystal size in the course of geological processes. It will help in refining quantitative clay mineral analysis and clay XRD peak decomposition techniques. Perhaps, detrital vs. authigenic fractions of different clay components of sedimentary rocks will become distinguishable by this technique. For illite-smectite, it offers the possibility of measuring directly the thickness distribution of illite fundamental particles (Eberl *et al.*, 1998).

Hydrothermal experiments, such as those of Huang (1990) and Small *et al.* (1992), may provide clues for interpreting pore-fluid composition from clay crystal morphology.

When the mechanism of illitization and its controls become better understood, the process will be modelled properly and this model will be integrated into basin-modelling software as an additional constraint. Hopefully, rapidly expanding

studies of diagenetic chlorite will succeed in providing another reliable tool for the reconstruction of different aspects of the history of sedimentary basins. The ultimate input of clay science into basin modelling studies will be realized if the ages of diagenetic illite can be extracted from shales.

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