

SUMMARY OF RECOMMENDATIONS OF NOMENCLATURE COMMITTEES  
RELEVANT TO CLAY MINERALOGY: REPORT OF THE ASSOCIATION  
INTERNATIONALE POUR L'ETUDE DES ARGILES (AIPEA) NOMENCLATURE  
COMMITTEE FOR 2006

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Brindley *et al.* (1951) reported the earliest efforts to obtain international collaboration on nomenclature and classification of clay minerals, initiated at the International Soil Congress in Amsterdam in 1950. Since then, national clay groups were formed, and they proposed various changes in nomenclature at group meetings of the International Clay Conferences. Most of the national clay groups have representation on the Nomenclature Committee of the Association Internationale pour l'Etude des Argiles (AIPEA, International Association for the Study of Clays), which was established in 1966. The precursor committee to the AIPEA Nomenclature Committee was the Nomenclature Subcommittee of the Comité International pour l'Etude des Argiles (CIPEA, International Committee for the Study of Clays). The AIPEA Nomenclature Committee has worked closely with other international groups, including the Commission on New Minerals and Mineral Names (CNMMN) of the International Mineralogical Association (IMA), which is responsible for the formal recognition of new minerals and mineral names, and the International Union of Crystallography (IUCr), which considered extensions to the nomenclature of disordered, modulated and polytype structures (Guinier *et al.*, 1984) published earlier by a joint committee with the IMA (Bailey, 1977). In contrast to the other national clay

groups, however, The Clay Minerals Society (CMS) Nomenclature Committee, which was established in 1963 at the same time as the CMS and predates the AIPEA Nomenclature Committee, remains in existence and occasionally produces recommendations. The precursor to this committee was the Nomenclature Subcommittee, which was organized in 1961 by the (US) National Research Council. The Chair of the AIPEA Nomenclature Committee is a standing member of the CMS Nomenclature Committee so that the committees are in close contact.

The purpose of the AIPEA Nomenclature Committee has been to make general and specific recommendations concerning: (1) definitions of mineralogical and crystallographic clay-related terms; (2) classification and terminology of clays, clay minerals and related terms; (3) standardization of structural and descriptive terms; (4) the establishment of procedures/criteria for determining species; (5) the emphasis (or re-emphasis) of the proper use of terms; and (6) any additional aspects relating to nomenclature. Approximately 12 published reports have been presented since the 1950s. However, an additional 12 unpublished reports have been archived, and many committee papers have been written by guest members asked to join the committee to help resolve a specific issue or by committee members to help lead the discussion of a specific topic. Although the latter papers have not been published, many illuminate the rationale behind recommendations. In addition, they may also show insight in areas still in need of additional research. In general, the committee is not expected to provide research to reach a recommendation. Instead, where

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sufficient data are unavailable, the committee may (or may not) note the insufficiency and postpone any further comment. Thus, extensive committee papers may have been written, only to conclude that comment should be deferred.

Clays are fine-grained and are generally impure, and clay minerals have variable degrees of perfection. Therefore, clay minerals represent a group of minerals that pose special problems in identification and detailed characterization. Because of these problems, nomenclature issues are more numerous than in most other mineral groups. Although the general crystal structures of the phyllosilicates were deduced by 1930 (Pauling, 1930), it was not until the period from the 1950s to the 1970s that details in structure started to become available by using X-ray diffraction techniques. Since the 1970s, the revolution in new or more refined current techniques, such as spectroscopy (*e.g.* infrared, Raman, Mössbauer), new optical and diffraction equipment (*e.g.* transmission electron microscopy, synchrotron), nuclear and isotope technology, and advances in computing, have made problems in nomenclature more tractable.

Because of the relatively large number of recommendations, presented over many years, a summary document would be useful. The purpose of the present report is to summarize by category and to comment on these recommendations, especially for the earlier reports in light of new progress. In some cases, the recommendations are not only valid, but also succinctly written, and there is no reason to rephrase the recommendation(s). Thus, some portions of the present report are reprinted from the originals. Other portions have been re-worked from the original and may include information that was not made available previously, from unpublished internal committee papers. Whenever possible, current usage is given, although the original citation may not have followed such usage. Some reports have typesetting errors that may have changed the meanings of some aspect of the report, and these have also been corrected (unless the item is within quotations, although these are minor and do not significantly change the meaning). Finally, in some cases, primarily in the more recent reports that are more readily available, the rationale and/or historical background for the recommendations have been limited or omitted. This paper also includes relevant terminology from non-AIPEA reports.

## RECOMMENDATIONS

### *Definitions and terminology for minerals, phyllosilicates, clays and clay minerals*

The CNMMN (Nickel, 1995) defined the term 'mineral' as follows in general terms: "a mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes". 'Crystalline' is considered to be a material

with sufficient atomic ordering such that a (X-ray, electron, neutron, *etc.*) diffraction pattern containing well defined maxima can be indexed using Miller indices. A mineral forms by a naturally occurring process (*e.g.* 'geological' process); phases formed by the interaction of individuals (even if outdoors under conditions not fully controlled by the individual) are not minerals. Nickel (1995) discussed exceptions to the requirements, such as the equivalence of extraterrestrial and 'geological' processes, metamict (non-crystalline) minerals, mercury (a liquid mineral), and others. The term 'crystalline' is discussed further below as it relates to clay minerals and remains consistent to the CNMMN nomenclature.

To describe better the chemical variation of minerals, the CNMMN had previously approved the use of Schaller-type adjectives, such as ferroan (for Fe<sup>2+</sup>) or ferrian (for Fe<sup>3+</sup>) and other terms that end in -oan and -ian. These modifiers, however, were found to be inadequate by most mineralogists. Bayliss *et al.* (2005) reported that CNMMN now recommends the use of chemical-element symbols or the name of the chemical element together with the descriptive term as an adjectival modifier, *e.g.* Mg-rich, Fe<sup>2+</sup>-poor, Na-exchanged, H<sub>2</sub>O-saturated, *etc.* to describe chemical compositions.

For phyllosilicates, the CMS Nomenclature Committee (Brindley *et al.*, 1968) and the AIPEA Nomenclature Committee (Brindley and Pedro, 1972) agreed that the terms "planes", "sheet" and "layer" cannot be used interchangeably and that they refer to specific parts of the structure, with atomic arrangements that increase in thickness. Thus, a 'plane' of one or more types of atoms (*e.g.* a plane of Si and Al atoms, a plane of basal oxygen atoms) can occur; a 'tetrahedral sheet' or an 'octahedral sheet' is composed of "continuous two-dimensional corner-sharing tetrahedra involving three corners and the fourth corner pointing in any direction" or edge-sharing octahedra, respectively; and a 'layer' contains one or more tetrahedral sheets and an octahedral sheet (Table 1). The tetrahedral sheet has a composition of T<sub>2</sub>O<sub>5</sub> (T = Si, Al, Fe<sup>3+</sup>, Be, B...). There are two types of layers, depending on the ratios of the component sheets: a '1:1 layer' has one tetrahedral sheet and one octahedral sheet, whereas a '2:1 layer' has an octahedral sheet between two opposing tetrahedral sheets. 'Interlayer material' separates the layers and generally may consist of cations, hydrated cations, organic material, hydroxide octahedra, and/or hydroxide octahedral sheets. In certain cases (*e.g.* talc, pyrophyllite), there is no interlayer material, and thus an empty interlayer separates the layers. A 'unit structure' is the total assembly and includes the layer and interlayer material. Thus, it is inappropriate to refer to a 'tetrahedral layer' or an 'octahedral layer', although these incorrect terms are commonly found in the literature even today. Other terms that are not suitable

Table 1. Structural terms of reference and their equivalents in different languages (modified from Bailey, 1989).

English	French	German	Spanish	Italian	Russian
plane	plan	Ebene	plano	piano	плоскость
sheet	couche	Schicht	capa	strato	сетка
layer	feuillelet	Schichtpaket	lámina o estrato	pacchetto	слой
interlayer	interfoliaire	Zwischenschicht	interlaminar	interstrato	межслоево промежуток (межлой)
unit structure	unité structurale	Struktur Einheit	unidad estructural	unità strutturale	пакет

for usage include a 'talc layer' and 'brucite sheet', both because the minerals talc and brucite do not allow for suitable substitutions that are found in many phyllosilicates (especially components of the chlorite structure where Al is a common constituent) and because it is inappropriate to conceive of a 'mineral' as being part of the structure of another mineral. Alternative, and proper, terms to use are '2:1 layer' instead of 'talc layer' and 'interlayer sheet' or 'hydroxide sheet' instead of 'brucite sheet'. In the ideal case, the smallest structural unit contains three octahedra. If two such sites are occupied with cations and one site is vacant, then the octahedral sheet is considered 'dioctahedral'. If all three sites are occupied, the sheet is considered 'trioctahedral'. If the dioctahedral or trioctahedral aspects are being emphasized and an alternative term is desired, such terms may be 'brucite-like' or 'brucitic' (trioctahedral) and 'gibbsite-like' or 'gibbsitic' (dioctahedral).

The family of phyllosilicate minerals (Brindley and Pedro, 1972) is based on the silicate parts of the structure, although previous to 1972 the nature of interlayer bonding and certain resultant physical properties were part of the definition. The definition presented by Brindley and Pedro (1972) equated 'clay minerals' with 'phyllosilicates' (see additional comments below) and was given as "Clay minerals belong to the family of phyllosilicates and contain continuous two-dimensional tetrahedral sheets of composition  $T_2O_5$  ( $T = Si, Al, Be...$ ) with tetrahedra linked by sharing three corners of each, and with a fourth corner pointing in any direction. The tetrahedral sheets are linked in the unit structure to octahedral sheets, or to groups of coordinated cations, or individual cations." Although continuous tetrahedral sheets often form six-fold rings, other ring configurations are considered part of the phyllosilicate family.

Guggenheim and Martin (1995) defined the term 'clay' and separated the terms 'clay minerals' from 'phyllosilicates', and Guggenheim and Martin (1996) further explained the rationale behind the definitions of these terms. The term 'clay' refers to "a naturally occurring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents and will harden when dried or fired. Although clay usually contains phyllosilicates, it may contain other materials that impart plasticity and harden when dried or fired. Associated phases in clay may include

materials that do not impart plasticity and organic matter." Although the 'naturally occurring' requirement of clay excludes synthetics, it is permissible to refer to a man-made material of similar character as 'synthetic clay' following the reasoning of Guggenheim *et al.* (1997) for commercial names and synthetic material (see below). Different disciplines have uniquely defined the size of clay particles, and it is for this reason that 'fine grained' is used in the definition rather than a precise value. However, because of these size variations from discipline to discipline, it is important that the particle size be specified in the context of the application. 'Plasticity' is defined by Grim (1968, p. 1) as a property where material deforms under applied pressure, with the deformed shape remaining when the deforming force is removed. The term 'clay mineral' refers to "phyllosilicate minerals and to minerals which impart plasticity to clay and which harden upon drying or firing". This definition expands the previous definition of Brindley and Pedro (1972) by relating clay minerals to the properties of clays. However, clay minerals are not defined *a priori* as fine-grained because clays are fine-grained, but rather they may be of any crystallite size so that the term 'clay mineral' is consistent with the definition of 'mineral', which is unrelated to crystallite size. Clearly, although the small particle size and high surface area of clays contribute to their unique properties and are very important (Guggenheim and Martin, 1996), the particle-size issue has been separated from the clay-mineral definition. 'Anionic clays', where there is a positive layer charge and linkage of the layers via anionic (negative) interlayers, have not been considered by the AIPEA Nomenclature Committee, and are not considered further here.

Other structural terms previously discussed include the use and misuse of 'lattice' and 'structure' (Brindley and Pedro, 1976). For three dimensions, the term 'lattice' is simply a collection of equivalent points which are distributed periodically in space, and this term commonly refers to Bravais lattices. In contrast, a 'structure' refers to the accepted atomic, ionic, and molecular arrangement of atoms of a material. The term 'layer lattice' is incorrect and should not be used. Layer structure and layer silicate are acceptable terms. The term 'layered structure' should not be used in place of 'layer structure'.

### *Polymorphism and polytypism*

The IMA-IUCr Joint Committee on Nomenclature (Bailey, 1977) recommended the definitions of some terms that are of special interest to clay scientists, and these terms were approved also by the AIPEA Nomenclature Committee (Bailey, 1980). 'Polytypism' is defined as "the existence of an element or compound in two or more layer-like crystal structures that differ in layer-stacking sequences. Polytypism differs from polymorphism (in the present and strict definition of the latter term) in permitting small differences in chemical composition between structures, not to exceed 0.25 atoms per formula unit (p.f.u.) of any constituent element. Layer structures that differ from one another by more than this amount are to be called *polytypoids* rather than *polytypes*". 'Polymorphism' is the ability of a given element or compound to crystallize in more than one form, with each form having a distinct crystal structure. "In general, polytypes should not receive individual mineral names. Instead, a set of related polytypes should be designated by a single name followed by a structural symbol suffix that defines the layer stacking differences." Ramsdell-style notation (Guinier *et al.*, 1984) is commonly in use for phyllosilicates, with the number of layers given as a first part of the suffix, followed by a capital letter, in italics, to indicate the crystal system of the phase: *C* (= cubic), *H* (= hexagonal), *T* (= trigonal with hexagonal Bravais lattice), *R* (= trigonal with rhombohedral Bravais lattice), *Q* (= quadratic or tetragonal), *O* (= orthorhombic), *M* (= monoclinic), and *A* (= anorthic or triclinic). "Polytype mineral names already in existence that have international acceptance and serve a useful function need not be discarded. Decision on the retention of individual names should be the responsibility of the IMA Commission on New Minerals and Mineral Names." Furthermore, it was recommended that "*X*, *Y*, *Z*, or [100], [010], [001] be used for directions of crystallographic axes and *a*, *b*, *c* for the repeat distances along these axes".

### *Classification*

The first general classification scheme for the phyllosilicates was proposed after existing schemes were considered, symposia were held, and polls of international clay scientists were taken in the 1960s (*e.g.* Brindley, 1967). This scheme was subsequently updated, most importantly with the following adaptations: 2:1 layer (+ octahedral interlayer) for the chlorite layer type (previously 2:1:1 layer or 2:2 layer; Brindley and Pedro, 1972), smectite (previously montmorillonite-saponite; Brindley and Pedro, 1976), non-planar hydrous phyllosilicates (Martin *et al.*, 1991), kaolin-serpentine group and kaolin subgroup (previously kaolinite-serpentine group and kaolinite subgroup; Guggenheim *et al.*, 1997), and regular interstratifications of different layer types (this report).

Table 2, modified from Martin *et al.* (1991), gives the revised classification scheme for planar hydrous phyllo-

silicate structures. These phyllosilicates are divided by layer type, and within layer type, by groups based on charge p.f.u., further subdivisions by subgroups based on dioctahedral or trioctahedral character, and finally by species based on chemical composition. The classification scheme is based on details of structure, and it also corresponds to a succession of stages of refinement in identification. The charge p.f.u., *x*, is the net negative charge per layer, expressed as a positive number; thus, a brittle mica will have a layer charge of between  $\sim -1.8$  and  $-2.0$ , which is given in Table 2 as  $\sim 1.8-2.0$ . The net negative layer charge is balanced by the positively charged interlayer material. The classification scheme depicted in Table 2 should be independent of the method of characterization, but net layer charge is difficult to determine directly and clay scientists use a phenomenological approach (Martin *et al.*, 1991, p. 334) to discriminate between smectite (defined with a layer charge between  $-0.2$  and  $-0.6$  p.f.u., Brindley and Pedro, 1976) and vermiculite (defined with a layer charge of  $-0.6$  to  $-0.9$  p.f.u.). The term 'smectite' (Brindley and Pedro, 1976) is now in common usage rather than the old term 'montmorillonite-saponite' for the group name. Modifications to Table 2 include changes to the mica layer charge based on Rieder *et al.* (1998). Previously suggested names for kaolin and serpentine minerals, 'kandite' and 'septechlorite' respectively, have not been approved by the AIPEA Nomenclature Committee and should not be used (Bailey, 1980).

Early nomenclature committee (CIPEA Nomenclature Committee, 1963; Brindley, 1967; Bailey *et al.*, 1971a) recommendations noted that kaolinite, nacrite and dickite have 1:1 layers with close similarities in structure. Differences are primarily related to the location of the vacant site from layer to layer and layer stacking, and thus they are polytypes; they should be designated by a single name (*e.g.* kaolinite) followed by a structural symbol suffix that defines the layer-stacking sequence. These earlier reports, however, left open the question of the exact nature of the stacking-sequence symbols pending further study. One issue in these earlier reports involved the correct stacking sequence for each of the three forms. An additional issue was that for complete structure characterization, both the vacant-site position in the 1:1 layer and the interlayer shifts between the layer must be determined, and a stacking symbol alone is not sufficient to describe both aspects. Without a resolution in how best to describe both aspects simply (within the context that a polytype is composed of layers of near identical composition and only a single name should be designated), the names kaolinite, nacrite and dickite have become well established in the literature. This issue was resolved when the AIPEA Nomenclature Committee (Guggenheim *et al.*, 1997) recommended that 'kaolinite', 'nacrite', and 'dickite' be retained as mineral

Table 2. Classification of planar hydrous phyllosilicates.

Layer type	Interlayer material <sup>1</sup>	Group	Octahedral character	Species <sup>2</sup>
1:1	None or H <sub>2</sub> O only ( $x \approx 0$ )	Serpentine-kaolin	Trioctahedral Diocahedral Di,triocahedral	Lizardite, berthierine, amesite, cronstedtite, nepouite, kellyite, fraipontite, brindleyite Kaolinite, dickite, nacrite, halloysite (planar) Odinite
2:1	None ( $x \approx 0$ )	Talc-pyrophyllite	Triocahedral Diocahedral	Talc, willemseite, kerolite, pimelite Pyrophyllite, ferripyrophyllite
	Hydrated exchangeable cations ( $x \approx 0.2-0.6$ )	Smectite	Triocahedral Diocahedral	Saponite, hectorite, saucnite, stevensite, swinefordite Montmorillonite, beidellite, nontronite, volkonskoite
	Hydrated exchangeable cations ( $x \approx 0.6-0.9$ )	Vermiculite	Triocahedral Diocahedral	Triocahedral vermiculite Diocahedral vermiculite
	Non-hydrated monovalent cations, ( $\geq 50\%$ monovalent, $x \approx 0.85-1.0$ for dioctahedral)	True (flexible) mica	Triocahedral Diocahedral	Annite, phlogopite, lepidolite, aspidolite Muscovite, celadonite, paragonite
	Non-hydrated mono- or divalent cations ( $x \approx 0.6-0.85$ )	Interlayer-deficient mica	Triocahedral Diocahedral	Illite, glauconite, brammallite Wonesite <sup>3</sup>
	Non-hydrated divalent cations, ( $\geq 50\%$ divalent, $x \approx 1.8-2.0$ )	Brittle mica	Triocahedral Diocahedral	Clintonite, kinoshitalite, bityite, anandite Margarite, chernykhite
	Hydroxide sheet ( $x = \text{variable}$ )	Chlorite	Triocahedral Diocahedral Di,triocahedral Tri,diocahedral	Clinochlore, chamosite, pennantite, nimate, baileychlore Donbassite Cookeite, sudoite none
2:1	Regularly interstratified ( $x = \text{variable}$ )	Variable	Triocahedral Diocahedral	Corrensite, alietite, hydrobiotite, kulkeite Rectorite, tosudite, brinrobertsite
1:1, 2:1			Triocahedral	Dozyite

<sup>1</sup>  $x$  is net layer charge p.f.u., given as a positive number

<sup>2</sup> not an exhaustive list of species

<sup>3</sup> net layer charge may be  $<0.6$ , but this is an exception

names. Interestingly, transmission electron microscopy (TEM) studies (*e.g.* by Kogure and Inoue, 2005a, 2005b) have better described stacking defects in the kaolin minerals, and this work implies that stacking symbols associated with each of the kaolin minerals (*i.e.* kaolinite, nacrite and dickite) would be useful to define layer-to-layer stacking and vacancy ordering in the layer.

Brindley and Pedro (1976) reported that the AIPEA Nomenclature Committee recommended the use of halloysite(7 Å) and halloysite(10 Å) to describe the (planar) forms of halloysite with differing amounts of H<sub>2</sub>O between the 1:1 layers, and that the term 'endellite' was to be discarded.

Because the chlorite group has two octahedral sheets, one in the 2:1 layer and one as the interlayer sheet, the group can be subdivided structurally based on the type of

sheets (dioctahedral vs. trioctahedral) that occur. Four possible subgroups (Table 2) may be defined: 'dioctahedral chlorite' has dioctahedral sheets only (*e.g.* donbassite) and 'trioctahedral chlorite' has trioctahedral sheets only, and this is the common form of chlorite. The terminology for the remaining two forms is to give the character of the octahedral sheet of the 2:1 layer first, followed by the interlayer. Thus, 'di,triocahedral chlorite' has a dioctahedral 2:1 layer and a trioctahedral interlayer (*e.g.* cookeite). There are no known 'tri,diocahedral chlorite' structures, although Bailey (1988) has suggested that franklinfurnaceite, which has Ca between the 2:1 layer and the interlayer and thus is not a true chlorite, would fall into this subgroup if the Ca is not considered. Following this argument, glagolevite (Krivovichev *et al.*, 2004), which has Na between the

2:1 layer and the interlayer and thus is also not a true chlorite, would be considered a trioctahedral chlorite if the Na is not considered. Previous nomenclature schemes (*e.g.* Foster, 1962) for the trioctahedral chlorite subgroup were very complex and consisted of a mineral name for each variant in chemical constituent, but this chemical classification scheme was dropped (unpublished report, 1978 Oxford meeting, AIPEA Nomenclature Committee; Bailey *et al.*, 1979) in favor of the suggestion by Bayliss (1975) that names should be based on the dominant divalent octahedral cation: Mg, clinocllore; Fe<sup>2+</sup>, chamosite; Ni, nimite; Mn<sup>2+</sup>, pennantite; Zn, baileychllore with end-member formulae of (R<sub>5</sub><sup>2+</sup>Al)(Si<sub>3</sub>Al)O<sub>10</sub>(OH)<sub>8</sub>, where R<sup>2+</sup> is the dominant divalent octahedral cation. No other species names should be used for the trioctahedral chlorite subgroup. Note that tetrahedral compositions and trivalent octahedral cations are not relevant to these schemes, and that partitioning of cations between the interlayer and 2:1 is not considered. Adjectival modifiers, such as Fe<sup>2+</sup>-rich clinocllore, may be used to clarify variations in chemical composition (see above for other examples).

Except for di, trioctahedral chlorite (sудоite: Li-poor, Al- and Mg-rich; cookeite: Li-rich, Al-rich) and dioctahedral chlorite (donbassite: primarily Al), Al content is not an important part of the chlorite classification scheme. Examination of chemical-composition trends of the trioctahedral chlorites from metamorphic environments (Guidotti and Guggenheim, unpublished internal AIPEA Nomenclature Committee report, 2002) showed that the use of Al as a distinguishing element is not particularly advantageous, and there is no apparent reason to designate species based on Al

content. Where appropriate, however, the use of 'Al-rich' as an adjectival modifier is encouraged.

Dioctahedral smectite species are named according to the dominant trivalent octahedral cation present (AIPEA Nomenclature Committee, 1985, as reported by Bailey, 1989). If a monovalent or divalent octahedral cation is dominant over the trivalent cation, as is possible in a dioctahedral structure, a new species name should be avoided unless the dominant cation is unusual, *e.g.* Cu. Otherwise, an adjectival modifier should be used. Differences in the number of H<sub>2</sub>O planes in the interlayer and in stacking sequences upon dehydration are not justification for new species.

Table 2 also shows the general separation between the true micas and the brittle micas. The detailed classification of the mica group has been considered by Rieder *et al.* (1998) and is not summarized here.

Table 3 shows the classification scheme for modulated/non-planar species presented by Martin *et al.* (1991), which is based on a scheme for modulated phyllosilicates given by Guggenheim and Eggleton (1988). These minerals generally have close similarities to traditional phyllosilicates (Table 2), but have inverted tetrahedra that link adjacent layers. Thus, these minerals have an approximate 1:1 or 2:1 layer, although the inverted tetrahedra generally produce chains (*i.e.* strips or ribbons) or island-like regions thereby producing a more three-dimensional character. In addition to inversions of tetrahedral units, the octahedral sheet may remain infinite in two dimensions or discontinuous, as in the case of sepiolite-palygorskite. Thus, variations to the structure may affect the periodicity along the direction perpendicular to the basal plane, in addition to within the

Table 3. Classification of non-planar hydrous phyllosilicates.

Layer type	Modulated component	Linkage configuration	Unit layer, <i>c</i> sinβ value	Traditional affiliation	Species
Modulated structures					
1:1 layer	Tetrahedral sheet	Strips	7 Å	Serpentine	Antigorite, bementite
		Islands	7 Å	Serpentine	Greenalite, caryopilite, pyrosmalite, manganpyrosmalite, ferropyrosmalite, friedelite, megillite, schallerite, nelenite
	Other		None	None	
2:1 layer	Tetrahedral sheet	Strips	9.5 Å 12.5 Å	Talc Mica	Minnesotaite Ganophyllite, eggletonite
		Islands	9.6–12.5 Å	Mica/complex	Zussmanite, parsettensite, stilpnomelane, ferrostilpnomelane, ferristilpnomelane, lennilenapeite
		Other	12.3 Å 14 Å	None Chlorite	Bannisterite Gonyerite
	Octahedral sheet	Strips	12.7–13.4 Å	Pyribole	Sepiolite, loughlinite, falcondoite, palygorskite, yofortierite
Rolled and spheroidal structures					
1:1 layer	None	Trioctahedral	–	Serpentine	Chrysotile, pecoraite
		Dioctahedral	–	Kaolin	Halloysite (non-planar)

(001) plane. Some structures lack long-range periodicity because the structures are rolled, coiled or approximately spherical, and it is for this reason that Table 3 is divided into two parts. The modulated phyllosilicate classification supercedes an earlier concept (Pedro, 1970; Bailey *et al.*, 1971a) referred to as 'quasi-layer silicates'. Similarly, a category of 'pseudo-layer structures' was abandoned (Brindley and Pedro, 1972).

Table 4 is a summary of the known species of regular interstratifications of clay minerals. Criteria for defining the degree of regularity of alternation of different layer types (*e.g.* 1:1 or 2:1 layers) are given below. Although the CNMMN is the authoritative body in determining mineral names, they have generally followed the AIPEA recommendations for the criteria in naming these minerals. There are many examples in the literature of interstratifications that do not warrant mineral species classification because of the lack of regularity in alternation of layer types, and these are not discussed further. The term 'mixed layer' is often used interchangeably with 'interstratification', although 'mixed layer' is less precise because it may be inferred that individual layers are composed of more than one type of tetrahedral (or octahedral) linkage. Although the term 'hydro-' is not a suitable prefix for a clay mineral name (Bailey, 1989), hydrobiotite is 'grand-fathered', having been named earlier.

#### Criteria for interstratification nomenclature

Brindley and Pedro (1972) reported that the AIPEA Nomenclature Committee (Madrid, 1972) recommended that mineral names not be given to poorly definable materials, which includes non-regular interstratifications, 'imperfect' structures (*e.g.* 'deweylite', 'aquacreptite'), and non-crystalline materials. Approximately

a decade later, a nomenclature for regular interstratifications (Bailey, 1981) was proposed, and it was reported in 1984 (Bailey *et al.*, 1984) that the nomenclature had been approved without changes by the CNMMN. The criteria for naming interstratifications are:

"(1) Names should be restricted to regular interstratifications where the kinds of layers, their relative proportions, chemical compositions and regularity of interstratification have been well documented. In determining the kinds of layers present, it is important that the swelling-shrinking behavior of each type of layer be demonstrated relative to water, organic solvates and heat.

(2) In order to merit a name, an interstratification of two layer types *A* and *B* should have sufficient regularity of alternation to give a well defined series of at least ten 001 summation spacings  $d_{AB} = d_A + d_B$ , for which the suborders are integral and the even and odd suborders have closely similar diffraction breadths (*sic*). If any odd 001 suborders are absent, calculations must be given to show that their intensities are too small to be observed. The coefficient of variation CV of the  $d(001)$  values should be less than 0.75 to demonstrate adequate regularity of alternation. The coefficient of variation is defined as  $CV = 100s/\bar{x}$ , where the standard deviation for a small sample is  $s = \{\Sigma(x_i - \bar{x})^2/(n - 1)\}^{1/2}$ ,  $x_i$  is an individual, observed  $1/d(001)$  value,  $\bar{x}$  is the mean of the  $x_i$  values and  $n$  is the number of observed  $x_i$  values.

(3) Names should not be used for less regular interstratifications, for specimens that deviate from the ideal ratio of mixing or chemistry or for less well documented specimens. Instead, such specimens should be characterized according to the information available, *e.g.* mica-smectite irregular interstratification or [1:1 dioctahedral mica-dioctahedral smectite]<sub>pP(A,B)=0.7, etc.</sub>

Table 4. Regularly interstratified phyllosilicates.

Layer types	Group affiliation of layers	Octahedral character	Species
Interstratifications of alternating layers in 50-50 proportions			
1:1	none		
2:1	pyrophyllite-smectite <sup>1</sup>	dioctahedral-dioctahedral	Brinrobertsite
	talc-smectite	trioctahedral-trioctahedral	Aliettite
	talc-chlorite	trioctahedral-trioctahedral	Kulkeite
	mica-smectite	dioctahedral-dioctahedral	Rectorite
	biotite-vermiculite	trioctahedral-trioctahedral	Hydrobiotite
	chlorite-smectite chlorite-vermiculite chlorite-smectite	trioctahedral-trioctahedral trioctahedral-trioctahedral dioctahedral on average <sup>2</sup>	Low-charge corrensite High-charge corrensite Tosudite
1:1 and 2:1	serpentine-chlorite	trioctahedral-trioctahedral	Dozyite

<sup>1</sup> group affiliations are given from smallest  $d(001)$  component in the natural state to the larger

<sup>2</sup> rigorously defined as having a total octahedral population between 6.0 and 7.0 on the basis of  $O_{20}(OH)_{10}$ . Thus, possible combinations are: di,dioctahedral chlorite-dioctahedral smectite, di,dioctahedral chlorite-trioctahedral smectite, di,triocahedral chlorite-dioctahedral smectite, and tri,dioctahedral chlorite-dioctahedral smectite. There are no known occurrences of tri,dioctahedral chlorite.

(4) Interstratifications incorporating imperfect types of layers, which could not qualify for names by themselves in the non-stratified state (*e.g.* 'swelling chlorite' and 'labile chlorite') do not merit names. Interstratifications with considerable inhomogeneity of layer charge do not merit names. Interstratifications with only a single summation peak  $d(001) = d_A + d_B$  and no other odd suborders do not merit names, because a single peak could result from a short-range association of layers.

(5) It is not certain that single layers of smectite or of vermiculite sandwiched between layers of a different type in an interstratification react in the same way as the non-interstratified minerals would react to solvation, hydration and dehydration tests. MacEwan and Wilson (1980) stated that glycerol solvation of a Mg-saturated clay gives the best differentiation between non-swelling vermiculite and swelling smectite, as defined according to the present boundary between these types of clay mineral of 0.6 charge per formula unit. For interstratifications where the distinction between vermiculite and smectite may be critical, we suggest that both glycerol and ethylene glycol solvation be used in connection with several saturation cations.

(6) Because of the difficulty in determination, the species of smectite involved in the definition of the species of a regular interstratification should not be specified beyond its dioctahedral or trioctahedral nature. Names so defined are apt to be of more widespread and practical usage than would be the case for a more restrictive definition. Where feasible, however, the smectite species may be noted by the investigator and used to characterize a particular occurrence in more detail."

The remainder of the report gave a literature review of reported interstratifications and how the criteria may be applied to these names; these interstratifications are summarized in Table 4, which has been updated. Several comments, clarifications, and suggestions may be made concerning these criteria. Because the behavior of a swelling clay (either smectite or vermiculite) is commonly affected by relative humidity, exchangeable cations, *etc.*, the rule relating to the ten orders of basal reflections may be applied to either an untreated sample and/or a sample treated by glycerol solvation, heat, air drying, exchangeable cations, *etc.* Differences in diffraction breadths between even and odd 00 $l$  suborders, are usually an indication of two co-existing (*e.g.* separate) phases, each with different layers rather than a regular interstratification of two layers, and this is the reason why diffraction breadths for both even and odd orders should be the same after correcting for Scherrer broadening.

The coefficient of variation of  $<0.75$  is a value to ensure that there is an adequate regularity of alternation. This criterion requires a sufficient sample size for a powder diffractometer, the technique of choice in common usage in 1981. Because of the need for a

relatively large sample size (*e.g.* grain aggregates) and because clays may be inhomogeneous, the coefficient of variation may fail to indicate regular interstratification over the entire sample used in the experiment on the powder diffractometer. In 1981, however, the use of TEM was not yet widespread. With TEM, the regularity of alternation can now be inspected directly with smaller sample sizes (*e.g.* individual grains), although it must be proven that the image shows a truly regular interstratification of layers. The ultimate question of how small a sample showing regularity of interstratification is considered necessary to name a new mineral is undetermined, and each case must be considered separately (Nickel and Grice, 1998).

A clay may be referred to, for example, as "rectorite-like" or "of the rectorite-type" (Bailey *et al.*, 1984) if interstratifications are shown to be of the types given in Table 4 but not sufficiently regular (*e.g.* CV of  $d(00l) \geq 0.75$ ). However, at least three orders of basal reflections (including two odd orders) must be observed. Such references are useful for both pure material that does not show sufficient regularity or for impure material where CV cannot be determined because of peak overlap. For highly irregular interstratifications, a more general term may be useful. For example, mica-smectite irregular interstratifications instead of rectorite-like interstratifications. Likewise, specimens, for example, with an Fe-rich mica as a major component and with some swelling characteristics may be referred to as randomly interstratified glauconite-smectite (Bailey *et al.*, 1979).

#### *Crystallinity and crystallinity indices*

Guggenheim *et al.* (2002) discussed the terms 'crystalline' and 'amorphous' in some detail when developing concepts of nomenclature for different degrees of crystallinity. Earlier, however, the CIPEA Nomenclature Committee (Brindley, 1967) recommended that the term 'non-crystalline' was preferable to the term 'amorphous'. In contrast, the present AIPEA Nomenclature Committee has agreed that either 'non-crystalline' or the commonly used 'amorphous' are acceptable terms. A 'crystalline' solid is defined as a solid consisting of atoms, ions, or molecules packed together in a periodic arrangement (*e.g.* long-range order). A 'non-crystalline' solid is where the constituent components are randomly packed. Many variations can occur between the two extremes of crystalline *vs.* non-crystalline. For example, a non-crystalline material, such as many glasses, consists of atoms arranged as groups of tetrahedra or octahedra. However, although such groups have almost the same mutual arrangements, they are displaced without periodicity with respect to each other (*i.e.* limited order or short-range order). Thus, this latter material differs from a simple random arrangement of atoms. Disturbance of order and periodicity may occur in crystalline materials. The degree of such disturbances can be described only qualitatively by the terms 'order'



and 'disorder'. The terms 'crystalline' and 'non-crystalline' do not have simple definitions, if they are to be explained fully.

The nature of order and disorder in phyllosilicates may involve stacking sequences, isomorphous substitutions where various ions or vacancies occur in certain coordination sites, and in the arrangement of material in the interlayer. Stacking disorder generally shows two-dimensional periodicity within the planes of the layer, but a lack of periodicity in the direction of stacking. In some cases, stacking may follow certain rules so that, for example, layer-to-layer hydrogen bonds are maintained (*e.g.* serpentine or chlorite groups) or interlayer cations can link to adjacent layers (*e.g.* mica group), but there are still multiple ways in which adjacent layers may link and the lack of periodicity is common. Turbostratic stacking, where disorder is high and there is a lack of registry between layers, is encountered in the smectite group. As noted above, interstratifications in phyllosilicates can occur; order-disorder in the alternation of the layers is often non-periodic. In addition, defects involving mosaic character (coherent scattering domain), interstitial impurities, thermal or positional displacement, dislocations, *etc.* may also occur (Guggenheim *et al.*, 2002).

Besides the variety of order/disorder phenomena, the way the sample is analyzed also presents problems in defining the crystalline nature of a material. Powder X-ray diffraction methods provide data on bulk material, which may suggest a lack of periodicity, whereas electron diffraction data are generally from finely divided material where an individual grain in the bulk may show considerable periodicity. Sample preparation or experimental conditions can also affect apparent crystallinity. For example, a powder X-ray diffraction pattern with an improper counting time per step may lead to an incorrect conclusion based on unresolved peaks, although these peaks may become resolved with a longer counting time (Guggenheim *et al.*, 2002).

A 'crystallinity index' is a misnomer because the term suggests that the complex idea of crystallinity may be represented by a single value. Guggenheim *et al.* (2002) recommended that the use of a 'crystallinity index' should be avoided, although it may be placed within quotation marks when referring in a limited way to previously referenced work. Some indices are a useful indicator, *e.g.* for crystallite size, grade of diagenesis, *etc.* Indices were derived by Hinckley (1963) to distinguish between different samples of kaolinite and by Kübler (1964) to describe certain origins of samples of illite. Árkai (1991) initially and in later papers referenced an index involving chlorite. It was recommended to refer to an index by relating it to the author describing the procedures necessary to define the value, regardless of what the index may actually be describing. Thus, it is appropriate to refer to a 'Hinckley index', 'Kübler index', 'Árkai index', *etc.*, but none of these

indices are truly 'crystallinity indices'. In addition, because of the continuum between 'crystalline' and 'non-crystalline' (or 'amorphous'), it was further recommended to clarify these last two terms when used, such as an accompanying description of the diffraction effects, sample-preparation techniques, experimental conditions, *etc.*

#### *Commercial names and synthetic material*

The AIPEA Nomenclature Committee (Guggenheim *et al.*, 1997) endorsed the use of commercial names and synthetic-name nomenclature established by the CNMMN (Nickel, 1996). Synthetic material that is commercially available is referenced by enclosing the name in quotation marks, unless the synthetic material has been recorded as a trademark, in which case the name starts with a capital letter. For example, a synthetic mica-like material where the name has been recorded as a trademark, perhaps called 'Londonshireite', would be properly referenced initially as: 'Londonshireite' (a synthetic mica-like material, Londonshire Manufacturing Co., Chicago, Illinois, USA.) and thereafter as 'Londonshireite'. Synthetic material may be referred to as 'hectorite-like', but never as 'hectorite'; the mineral name implies a naturally occurring phase. It is permissible to use the description modifier 'synthetic' with a mineral name, as in 'synthetic quartz', because 'synthetic' is unambiguous and specifically negates the naturally occurring aspect of the mineral.

#### MISCELLANEOUS

dehydroxylate. Any phase obtained by elimination of the hydroxyl from phyllosilicates prior to recrystallization (Brindley, unpublished AIPEA report, 1971).

*Non-mica species names specifically discussed in various nomenclature reports. (If more than one citation is provided in a sequence, the first citation refers to the committee report.)*

aliettite. Regular interstratification of talc and trioctahedral smectite in a 1:1 ratio (Bailey, 1981).

corrensite. Regular interstratification of either trioctahedral smectite in a 1:1 ratio or trioctahedral vermiculite in a 1:1 ratio with trioctahedral chlorite. Where trioctahedral smectite is involved, the term "low-charge corrensite" applies, and where trioctahedral vermiculite occurs, the term "high-charge corrensite" should be used (Bailey, 1981).

beidellite. See nontronite.

berthierine. Serpentine mineral with Fe<sup>2+</sup> dominant as the octahedral cation, sometimes previously referred to as chamosite (chamosite is now classified as a chlorite mineral). Berthierine may contain Fe<sup>3+</sup>, Mg and Al (Brindley, unpublished AIPEA Committee report, 1967).

chamosite. Chlorite, a 2:1 phyllosilicate, mineral with Fe<sup>2+</sup> dominant as the octahedral cation (Bailey *et al.*,

- 1971a); sometimes previously referred to as a 1:1 (serpentine) mineral.
- high-charge corrensite. See corrensite.
- imogolite. A hydrous aluminosilicate (Pedro, 1970) having a fine thread-like morphology and diffraction characteristics described by Wada and Yoshinaga (1969). Bayliss (1987) described imogolite as having a chemical composition of  $\text{Al}_2\text{SiO}_3(\text{OH})_4$ , and he provided X-ray data.
- kulkeite. Regular interstratification of talc and trioctahedral chlorite in a 1:1 ratio (Bailey, 1981).
- low-charge corrensite. See corrensite.
- nontronite. Compares to beidellite with all octahedral Al replaced by  $\text{Fe}^{3+}$  and with Al substitutions for Si. A series exists from end-member beidellite to end-member nontronite. In the corresponding montmorillonite series, the term  $\text{Fe}^{3+}$ -rich montmorillonite is appropriate until  $\text{Fe}^{3+}$  exceeds Al. Additional consideration of the terminology for nontronite may be needed if  $\text{Fe}^{3+}$  exceeds Al in octahedral sites (Brindley and Bailey, unpublished AIPEA Committee report, 1978).
- pecoraite. Ni-rich clinochrysotile (Bailey *et al.*, 1971b; Faust *et al.*, 1969).
- rectorite. A regular interstratification of dioctahedral mica and dioctahedral smectite in a 1:1 ratio. The type of dioctahedral smectite is not required in the description. The dominant interlayer cation associated with the mica can be specified in the description by using adjectival modifiers, such as Na-rich, K-rich, *etc.* (Bailey, 1981).
- tosudite. A regular interstratification of chlorite and smectite in a 1:1 ratio. The smectite is, on average, dioctahedral in nature. Dioctahedral is defined as between 6.0 and 7.0 on the basis of  $\text{O}_{20}(\text{OH})_{10}$  for the assemblage and a  $d(060)$  value of 1.49 to 1.506 Å. Combinations of dioctahedral or trioctahedral smectite and di,dioctahedral chlorite (donbassite) and of di, trioctahedral (sудоite, cookeite) or tri,dioctahedral chlorite (not currently known to exist) and dioctahedral smectite are possible (Bailey, 1981).
- volkonskoite. Dioctahedral Cr-rich smectite where Cr is the dominant trivalent octahedral cation (Bailey *et al.*, 1986). Smectite with  $\text{Fe}^{3+}$  as the dominant trivalent octahedral cation, but with substantial Cr is referred to as "Cr-rich nontronite".
- willemseite. Ni-rich talc (Bailey *et al.*, 1971b; Hiemstra and de Waal, 1968).
- Discredited names specifically discussed by various nomenclature committees; names on the left should be abandoned in favor of those on the right*
- anaxite. Mixture containing kaolinite (CMS Nomenclature Committee unpublished report, 1967–8).
- attapulgite (synonym). Palygorskite (CMS Nomenclature Committee unpublished report, 1967–8).
- cerolite. Kerolite (Brindley and Pedro, 1976).
- hormite (synonym). Palygorskite-sepiolite group (Brindley and Pedro, 1970; Bailey *et al.*, 1971a).
- hydroferripyrophyllite (synonym). Nontronite.
- kandite (synonym). Kaolin-serpentine group (Bailey, 1980).
- medmontite. Mixture of chrysocolla and mica (Bailey *et al.*, 1971b; Chukhrov *et al.*, 1968; 1969).
- palysepiole (synonym). Palygorskite-sepiolite group (this report).
- septechlorite (synonym). Kaolin-serpentine group (Bailey, 1980).
- schuchardite. Nimate, a Ni-rich chlorite (Bailey *et al.*, 1971b; Fleischer, 1969).
- tarasovite. Formerly referred to as a regular interstratification of mica layers and rectorite, and thus described as MMMS, *i.e.* three mica layers and one dioctahedral smectite layer. However, because the degree of regularity is insufficient to warrant a species name, "tarasovite" is not a valid species (Bailey, 1981).

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*Unpublished AIPEA Nomenclature Committee reports from the 1960s and 1970s:*

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