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Chemical and mineralogical heterogeneities of weathered igneous profiles: implications for landslide investigations

N. S. Duzgoren-Aydin and A. Aydin

Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong SAR, China

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Abstract. Landslides in tropical and sub-tropical regions are generally associated with weathered rock profiles which often possess chemical and mineralogical heterogeneities at material- and mineral-scales. Such heterogeneities reach a climax by the occurrences of oxyhydroxide- and clay-rich zones. Weakness and low permeability of these zones makes them ideal for the development of slip zones along which landslides take place. This paper describes the nature and distribution of chemical and mineralogical heterogeneities within weathered profiles developed from felsic igneous rocks in Hong Kong. It sets out the use of integrated geochemical and mineralogical studies to improve understanding of the development of critical heterogeneities and hence to predict their types and presence in a given weathered profile.

1 Introduction

The term “heterogeneity” within a weathered profile implies sudden and substantial changes in weathering signatures and thus in mechanical and hydraulic characteristics across the profile. Therefore, understanding the nature and distribution of heterogeneities within weathered profiles is of a paramount importance. Weathering processes in tropical and subtropical settings modify mineralogical, petrographical (microfabric) and geochemical characteristics of rocks through their thermodynamic readjustments in various forms and scales. These readjustment processes take place in a unique way depending on the overall geological setting of the profile largely determined by lithological, structural, geomorphological and hydrological conditions. Readjustment processes (such as leaching, decomposition of primary minerals and formation of secondary phases) induce new heterogeneities and enhance existing ones at various scales (field, material and mineral). The resulting weathered profiles in tropical and subtropical settings are often associated with landslides. Basal slip zones and detachment surfaces of these landslides are partly or completely delineated by persistent heterogeneities which produce localized pore water pressure anomalies. Field scale heterogeneities and their role in slope instability have been discussed by Aydin (2006).

This paper focuses on the nature and development of chemical and mineralogical heterogeneities in weathered profiles and their significance in forensic landslide investigations, as well as their use as indicators of potential presence of heterogeneities critical to stability of weathered slopes. Hong Kong is infamous for frequent occurrences of large landslides (with displaced volume equal or greater than 800 m^3) (Large Landslides in Hong Kong, 2005) developed within weathered Middle Jurassic to Early Cretaceous felsic igneous (mostly granitic and pyroclastic) rocks (Fig. 1). Landslides in Hong Kong are usually triggered by heavy rainfalls (Table 1) and developed along heterogeneous zones (e.g., Kirk et al., 1997; Wen et al., 2004). As summarized in Table 1, both granitic and pyroclastic weathered profiles are equally vulnerable for landslide incidents.

2 Chemical weathering indices

Chemical weathering indices (CWI) as other weathering indices (physical, microstructural, mechanical) were introduced as a result of dissatisfaction with and the subjectivity of the six-fold weathering classification (Moye, 1955) and its improved versions (GSL, 1995). There are more than 30 different CWI, mostly proposed for felsic igneous weathered materials developed under tropical and subtropical environments. These indices basically belong to few major categories and are mostly expressed as molecular ratios of major elements. The principal assumption in formulating these

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Correspondence to: N. S. Duzgoren-Aydin
(nsaydin@hku.hk)

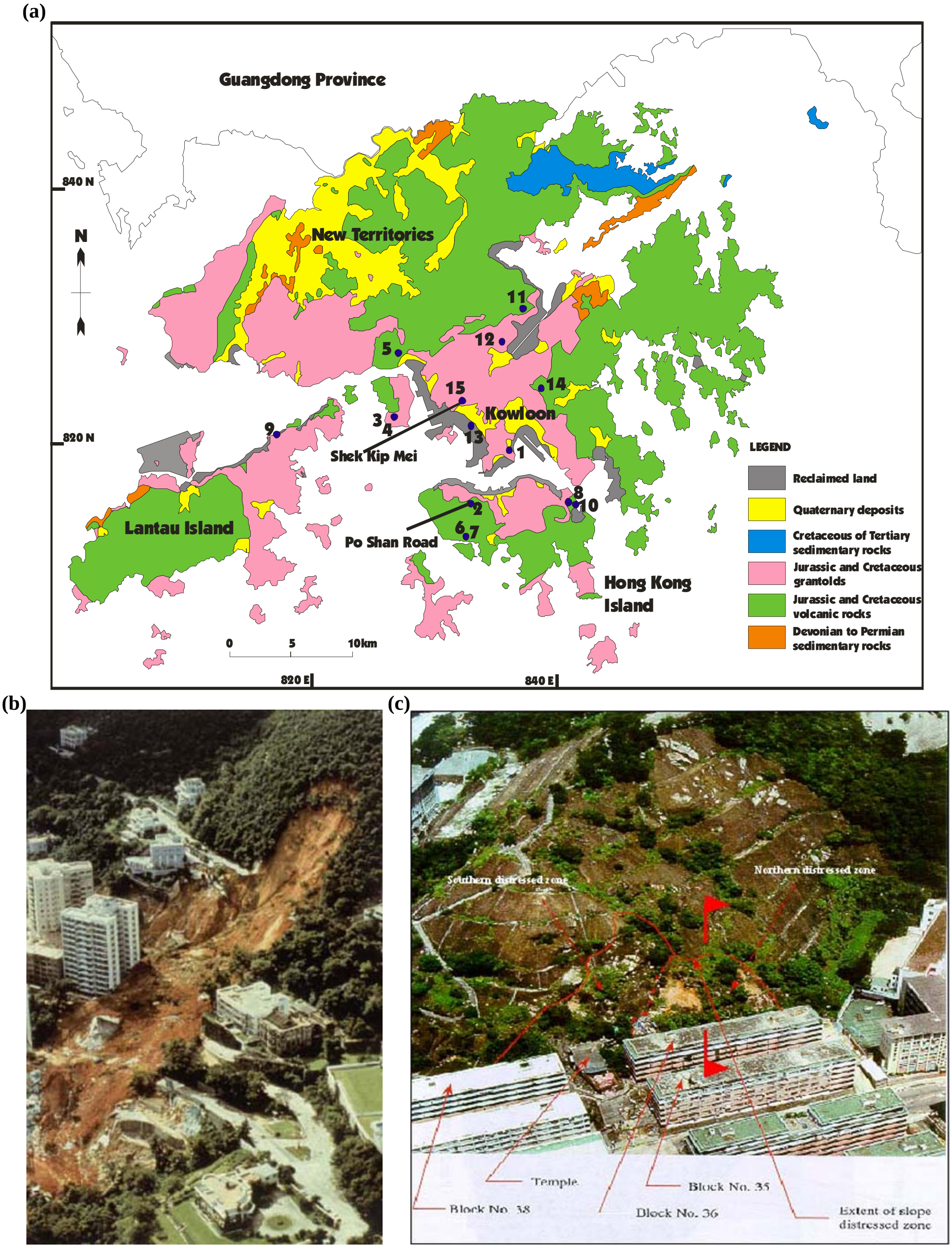

Fig. 1. **(a)** Simplified geological map of Hong Kong (after Campbell and Sewell, 1998) and distribution of large landslides in Hong Kong (after Large Landslides in Hong Kong, 2005). Incidents of Po Shan (GEO, 1983) **(b)** and Shek Kip Mei landslides (GEO, 2000) **(c)** developed within pyroclastic and granitic weathered profiles, respectively.

indices is that behavior of chemical elements is principally controlled by the degree of weathering. However, as summarized in Table 2, depending on the behavior and distributions of the selected elements within weathered profiles, the performances of CWI vary significantly.

Table 1. Large landslides in Hong Kong (from Large Landslides in Hong Kong, 2005).

Landslide ID number*	Landslide case	Date of incident	Associated major lithology	Rainfall (period)
1	Fat Kwong Street	Sep 1970	Granite	>200 mm (8–10 September 1970)
2	Po Shan Road **	June 1972	Volcanic	>650 mm (16–18 June 1972)
3	Tsing Yi (1)	May 1982	Granite	>300 mm (May to June 1982)
4	Tsing Yi (2)	Aug 1982	Granite	>300 mm (21 August 1982)
5	Tuen Mun Highway	Sep 1983	Volcanic	After Typhoon Ellen, 1983
6	Tin Wan Hill Road	Sep 1985	Volcanic	Moderate rain fall
7	Island Road	Aug 1988	Volcanic	Moderate rain fall
8	Siu Sai Wan	May 1992	Volcanic	Slope Cutting
9	Sham Shui Kok	July 1995	Volcanic	>400 mm
10	Fei Tsui Road	Aug 1985	Volcanic	Heavy Rain fall (26–27 August 1985)
11	Lai Ping Road	July 1997	Volcanic	370 mm (12 August 1997)
12	Ville de Cascade	July 1997	Granite	500 mm (2 July 1997)
13	Ching Cheung Road	Aug 1997	Granite	420 mm (2 July 1997)
14	Tate's Ridge	June 1998	Volcanic	130 mm (within two hours)
15	Shek Kip Mei ***	Aug 1999	Granite	>350 mm (23–25 August 1999)

(*For the location of landslide, see Fig. 1a; ** Fig. 1b; *** Fig. 1c)

Comprehensive re-assessment of chemical weathering indices for felsic igneous rocks (in Hong Kong) revealed that:

1. behavior of chemical elements during weathering is not only a function of intensity of weathering;
2. the distribution, type and abundance of secondary phases play significant role in distribution and behavior of chemical elements; and
3. the search for universally accepted "best chemical index" is likely to be unsuccessful, mainly because CWI deviate from the general pattern where there are heterogeneities (Duzgoren-Aydin et al., 2002a).

In sum, chemical weathering indices may not be as useful to determine the weathering grades as it was thought originally, but they can be used as practical tools to detect chemical heterogeneities. Nevertheless, as most CWI are limited to a few major and minor elements, their application and implications are also limited in assessing type and extent of chemical heterogeneities. In this context, parent-normalized variation diagrams were found most reliable (Duzgoren-Aydin and Aydin, 2003).

3 Parent-normalized variation diagrams

In parent-normalized variations diagrams, each element is investigated individually, and is normalized with corresponding parent-rock's value. If the ratio (element-i_{sample}/element-$i_{\mathrm{parent-rock}}$) is less or greater than 1, the element is considered leached out or fixated within the system, respectively. Parent-normalized variation diagrams are not limited to any specific type of elements.

Analyses of parent-normalized variation diagrams (Fig. 2) of the felsic igneous rocks of Hong Kong revealed that:

1. distributions of chemical elements within weathered profiles reflect combination of complex, usually competing (leaching and fixation) processes;
2. behaviors of chemical elements vary during the course of weathering;
3. each profile has its own characteristic variation pattern; and
4. deviations from the general trend correspond to sudden and usually substantial changes in behavior of chemical elements (i.e., chemical heterogeneity).

Accordingly, these observations directly or indirectly invalidate the basic assumptions made to use CWI determine weathering grades, but on the other hand, they justify utilization of parent-normalized diagrams as an effective tool to assess level or extent of chemical heterogeneity within weathered profiles. As illustrated in Fig. 2, particularly at the advanced stages of weathering, deviations from the general patterns become obvious. This is especially evident for Ca and Na for granitic (Lai Chi Kok – LCK) and Fe and Mn for pyroclastic profiles (Shum Wan – SW and Siu Sai Wan – SSW), and can be attributed to high abundance of clay and oxyhydroxide phases, respectively.

4 Mineralogical signatures of weathering

Advancements in high resolution microscopic techniques such as scanning electron microscope (SEM) and

Table 2. Behavior of chemical elements along the felsic weathered profiles developed under subtropical conditions, and implications for the formulation and selection of the chemical indices involving each considered element as the major component (from Duzgoren-Aydin, 2003).

	Course of weathering				Potential implications to performance of chemical weathering indices
	Early stages Trend	Remarks	Late stages Trend	Remarks	
Si	Remains relatively stable or decreases slightly	Quartz (SiO_2) is the most resistant mineral to weathering	Decreases slightly to significantly	Dissolution of quartz occurs at the advanced stages of weathering.	At the early stages, the index is insensitive to weathering
Al	Remains relatively stable or increases slightly	Decomposition of Al-bearing primary minerals and initiation of formation of Al-bearing secondary minerals (clay minerals) The relative abundance ratio of clay to non-clay minerals is low	Increases moderately to significantly	Al-bearing secondary minerals (clay minerals) dominates the overall mineralogy The relative abundance ratio of clay to non-clay minerals is high	At the early stages, the index is insensitive to weathering
Loss on Ignition	Increases rather gradually	Formation of hydrous minerals Can be modified by the type and abundance of clay minerals	Same as at early stages		Good index: however, caution must be taken due to the type and abundance of clay minerals, particularly those of the kaolin group
K	Decreases slightly But fluctuates strongly	Slight decomposition of K-feldspar Presence of K-bearing clay minerals (illite) due to pre-weathering alteration history (hydrothermal or late-stage magmatic)	Decreases moderately to significantly But fluctuates strongly	Moderate to significant decomposition of K-feldspar Type and abundance of clay minerals can affect the pattern	The index exhibits abnormal patterns over the course of weathering
Ca & Na	Decrease rather gradually and significantly	Decomposition of feldspars, particularly plagioclases	Remain constant at low level	Most plagioclases are already decomposed	At the late stages, the index becomes insensitive to weathering
Fe & Mn	Remain stable or increase slightly	Initiation of formation of oxyhydroxides and dissolution of mafic minerals including biotite	Increases moderately to significantly Can fluctuate strongly	Directly influenced by presence of oxyhydroxides and/or oxyhydroxide-rich zones Closely related to overall leaching conditions of the profile and of the microenvironments	If the profile is relatively well-drained, the index works well If the profile has oxyhydroxide-rich zones, the index perform poorly (and a great caution must be taken)

transmission electron microscope (TEM) and application of X-ray diffraction (XRD) method have improved our understanding about common products of weathering, especially their type, morphology (Fig. 3), in-situ chemical composition and distribution within weathered profiles.

In essence, two major competing processes, namely leaching and fixation, determine the chemical and mineralogical characteristics of weathered profiles. From mineralogical point of view, “leaching” refers to decomposition of primary minerals, while “fixation” to formation of secondary phases and to relative enrichment of certain primary minerals due to their higher resistance to decomposition. Among common rock-forming minerals, quartz is the most resistant mineral to weathering, while plagioclase and biotite are easily replaced by secondary phases. Thus, while absolute abundance of quartz remains almost constant, its relative abundance continuously increases as other primary minerals (feldspar and biotite) are gradually decomposed during the course of weathering. On the contrary, absolute abundances of clay minerals and oxyhydroxides increase with the degree of weathering (Duzgoren-Aydin, 2003).

Individual response of each mineral to weathering is similar in igneous rocks despite a wide range of mode of occurrences of these rocks. However, formation of new (secondary) phases and their distribution within weathered profiles depends not only on the nature of weathering, but also on parent-rocks’ inherited features including previous alteration history and micro-fabric characteristics (Duzgoren-Aydin et al., 2002b).

Petrographic examinations of weathered rocks under polarized light microscope provide most reliable information about the nature and of their parent-rock. However, application of petrographic microscope is sufficient for mineralogical characterization of only slightly to moderately decomposed samples (representing early to intermediate stages of weathering). Clay minerals and oxyhydroxide phases dominate the mineralogy in highly to completely decomposed samples (i.e. late stages of weathering). Therefore, SEM and XRD techniques are necessary to support petrographic observations for complete mineralogical description of these samples.

4.1 Clay mineralogy

Recent studies on clay minerals within weathered igneous profiles (e.g., Merriman and Kempt, 1995; Merriman et al., 1996; Kirk et al., 1997; Duzgoren-Aydin et al., 2002b; Duzgoren-Aydin, 2003; Wen et al., 2004) in Hong Kong revealed that understanding the type and abundance of clay minerals and their distribution within weathered profiles are necessary to:

1. characterize weathering profiles and assess degree of weathering;
2. explain nature and extent of mineral-scales heterogeneities; and
3. assess potential presence of heterogeneous zones along which landslides may occur.

Kaolinite, halloysite, illite and trace amount of inter-layered illite-smectite are ubiquitous clay minerals within weathered igneous profiles. However, their distributions and relative abundances within and between weathered profiles vary considerably (Table 3 and Fig. 3).

At the early stages of weathering, the type of parent rock, its inherited mineralogical heterogeneities and pre-weathering alteration history may play an important role in defining the type and abundance of clay minerals during the course of weathering. Type and nature (such as crystallinity) of clay minerals are closely associated with source of clay minerals. For example, chlorite is relatively stable in high temperature conditions, but not stable at atmospheric (surface or near surface) conditions (e.g., Velde, 1995). Therefore, high abundances of chlorite and well-crystallized illite in fresh to moderately decomposed pyroclastic samples were attributed to pre-weathering high temperature alteration processes such as hydrothermal or late stage magmatic (deuteric) alterations (Duzgoren-Aydin et al., 2002b).

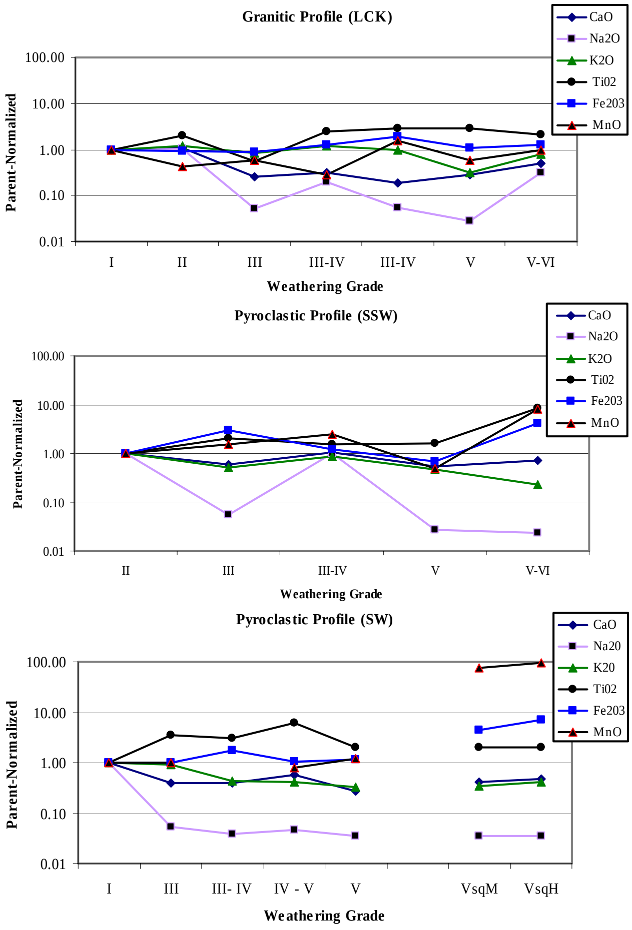

Fig. 2. Parent normalized variation diagrams.

Relative abundances of clay minerals within weathered profiles are of a great significance for evaluating micro-environmental conditions (such as extent of leaching). Kaolinite to halloysite and kaolin to illite ratios were found to be particularly useful. This is mainly because of the fact that although halloysite and kaolinite belong to kaolin group (polymorphic) clay minerals, halloysite has an additional water layer in its crystal-structure compared to kaolinite. Therefore hydrous micro-environmental conditions, for instance, favor occurrence of halloysite over kaolinite (Keller and Hanson, 1975; Keller, 1976). Similarly, relatively impeded hydrological conditions favor occurrence of illite over kaolinite (e.g., Velde, 1995). In Hong Kong, halloysite to kaolinite ratios of samples from granitic profiles are larger than those of the samples from pyroclastic ones at the same degree of weathering. This has been attributed to better leaching conditions in granitic profiles than those of the pyroclastic profiles (Duzgoren-Aydin, 2003). Thus probability and mode of occurrence of critical heterogeneities in granitic and pyroclastic profiles are likely to be different as confirmed by the landslide investigations.

Intense leaching in granitic profiles may be responsible for occurrences of clay rich zones in which transported colloidal particles deposited along especially sheeting joints. Weakness and low permeability of these zones makes them ideal

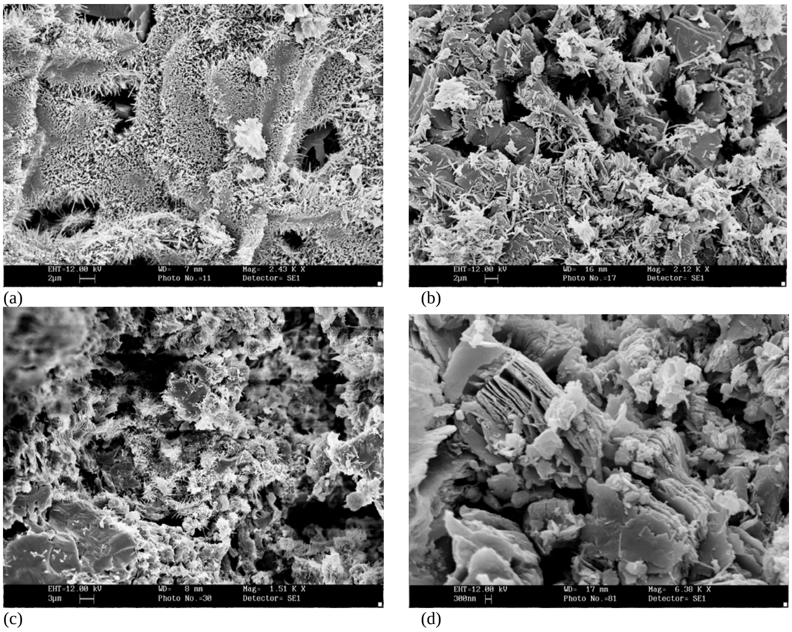

Fig. 3. SEM images from weathered granitic **(a–b)** and pyroclastic profiles **(c–d)**. Samples are from Grade I (a and c) and Grade IV (b and d).

for the development of slip zones. The type and abundance of clay minerals within slip zones is different from those within their surrounding host-materials (e.g., Wen et al., 2004). For example, slip zones of Shek Kip Mei (SKM) landslide (see Fig. 1c) developed within weathered granitic rocks have considerably higher abundance of kaolinite and clay-size particles compared to their host materials, suggesting that the slip zone had relatively impeded leaching conditions compared to its host-materials. Because, in granitic weathered profiles, halloysite is the dominant clay mineral even at the advanced stages of weathering, occurrence of kaolinite-rich zones within halloysite dominated host-materials is a crucial indicator of high risk potential for the development of slip zones in such profiles.

In pyroclastic profiles the relative abundance of kaolinite to halloysite increases with the degree of weathering, and at the advance stages of weathering, kaolinite become the dominant clay mineral (Table 3 and Fig. 3). Consequently, impeded leaching conditions in pyroclastic profiles are often encountered at the advance stages of weathering and often accompanied by oxyhydroxide-rich zones. Persistent occurrence of such zones may induce localized pore water pressure anomalies and thus lead to development of slip zones as confirmed by post-landslide investigations (e.g., Kirk et al., 1997).

4.2 Oxyhydroxides

As clay minerals, oxyhydroxides are common products of dominantly chemical weathering and are ubiquitous along the weathered igneous profiles developed under tropical and subtropical conditions. It is easy to locate them in hand specimen or on thin sections due to their dark colored opaque nature. In general, high abundances of oxyhydroxides are marked by substantial increase in relative abundance of Fe and Mn. Their occurrences and relative abundance ratios (i.e., Fe/Mn) within a weathered profile have been extensively studied (Hem, 1972; Weaver, 1977; McKenzie, 1989; Schwertmann and Taylor, 1989). On the other hand, little attention was given to the type and abundance of oxyhydroxides in landslide investigations (e.g., Zheng et al., 2002; Wen et al., 2004). It has been documented that oxyhydroxide-rich zones are more frequent in pyroclastic profiles compared to granitic profiles. This becomes particularly evident at the advance stages of the weathering (Duzgoren-Aydin, 2003).

Post-landslide investigations in the granitic and pyroclastic profiles (Merriman and Kempt, 1995; Wen et al., 2004) also revealed that the slip zones not only have distinct type and abundance of clay minerals compared to their host-materials, but also higher abundance of oxyhydroxide phases which are typically enriched in Mn, Ba and Ce contents. This can be attributed to cyclic occurrence of poorly drained conditions (e.g., Koppi et al., 1996). It has been well-established that the type and abundance of oxyhydroxides and associated trace elements are primarily controlled by micro-environmental leaching and redox (oxidation and reduction) conditions (McKenzie, 1989; Koppi et al., 1996). For example, at the early stages of weathering, the pyroclastic SW profile contains Mn-free, Fe-rich oxyhydroxides, suggesting relatively well-drained conditions allowing disassociation of Mn from Fe. On the other hand, at the advance stages of

Table 3. Type and relative abundance of clay minerals within weathered profiles (after Duzgoren-Aydin et al., 2002b; Duzgoren-Aydin, 2003).

Weathering Grade	Halloysite	Kaolinite	Illite	I/S*	Chlorite
Granitic Profile (Lai Chi Kok)					
I–II	92	3	5	Trace	NP
II	84	5	11	Trace	NP
III	80	15	5	Trace	NP
III–IV	92	4	4	Trace	NP
V	82	12	6	Trace	NP
V–VI	62	32	6	Trace	NP
Volcanic Profile (Shum Wan)					
I	NP	NP	35	Trace	65
III	48	4	48	Trace	NP
III–IV	74	20	6	Trace	NP
IV-V	41	48	11	Trace	NP
V	38	56	6	Trace	NP
VsqM**	18	74	8	Trace	NP
VsqH***	12	71	17	Trace	NP
Volcanic Profile (Siu Sai Wan)					
II	31	9	50	NP	10
III	34	8	47	NP	11
III–IV	76	4	20	Trace	NP
V	61	11	28	Trace	NP
V–VI	41	49	10	Trace	NP

(I/S*: Interstratified illite-smectite; VsqM**: Moderately enriched in oxyhydroxides; VsqH***: Highly enriched in oxyhydroxides)

weathering, the profile contain Mn-rich oxyhydroxides with variable amount of Fe content, suggesting relatively impeded leaching conditions compared to early stages of weathering. Therefore, similar to clay minerals, the type and abundance of oxyhydroxide phases, and their distribution within weathered profiles are valuable information to help assess prevalent leaching conditions. Consequently, persistent occurrence of kaolinite- and Mn-oxyhydroxide-rich zones makes an ideal environment to develop potential slip zones along which landslides may occur.

5 Summary and conclusions

Weathering processes progressively modify the chemical and mineralogical composition of rocks and are governed by a large array of factors such as geological setting of the profile, inherited fabric features, pre-weathering alteration history, etc. The relative role of each factor can vary noticeably within the same profile. Therefore, behavior of chemical elements within weathering profiles cannot be solely explained by means of weathering degree, as there is no unique pathway during the course of weathering. Therefore, it is important to realize that chemical weathering indices should be used to assess level of chemical heterogeneity, rather than determining the weathering stage.

Chemical and mineralogical heterogeneities in saprolitic profiles are most evident by the occurrence of clay- and oxyhydroxides-rich zones. Post-landslide investigations confirm that such heterogeneous zones are potential features along which slip zones usually develop.

This paper presented the fundamental micro-environmental conditions and accompanied chemical and mineralogical changes during weathering of igneous profiles by which inherited or newly induced discontinuities become transformed into slip planes and how the potential presence of these features can be recognized through integrated chemical and mineralogical studies. It has been concluded that chemical and mineralogical heterogeneities are closely associated with localized impeded leaching conditions. In general, impeded leaching conditions within weathered igneous profiles developed under humid, subtropical/tropical conditions, likely favor occurrence of kaolinite and Mn-rich oxyhydroxides over halloysite and Fe-rich oxyhydroxides, respectively, compared to their host materials. Therefore, integrated chemical and mineralogical studies, particularly focusing on the type, distribution and abundance of clay minerals and oxyhydroxides within weathered profiles are crucial to advance our understanding of the nature and distribution of slip zones and their micro-environmental conditions, which is of great importance for assessing landslide potential of weathered profiles.

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References

Aydin, A.: Stability of saprolitic slopes: nature and role of field scale heterogeneities, Nat. Hazards Earth Syst. Sci., 6, 89–96, 2006.

Campbell, S. D. G. and Sewell, R. J.: A proposed revision of the volcanic stratigraphy and related plutonic classification of Hong Kong, Hong Kong Geol. Soc., 4, 1–11, 1998.

Duzgoren-Aydin, N. S.: Comparative study of weathering signatures in felsic igneous rocks of Hong Kong, Chem. Spec. Bioavailab., 14, 1–18, 2003.

Duzgoren-Aydin, N. S. and Aydin, A.: Chemical heterogeneities of weathered igneous profiles: implications for chemical indices, Environ., Eng., Geosci., IX, 363–377, 2003.

Duzgoren-Aydin, N. S., Aydin, A., and Malpas, J.: Re-assessment of chemical weathering indices: case study from pyroclastic rocks of Hong Kong, Eng. Geol., 63, 99–119, 2002a.

Duzgoren-Aydin, N. S., Aydin, A., and Malpas, J.: Distribution of clay minerals along a weathered pyroclastic rock profile, Hong Kong, Catena, 50, 17–41, 2002b.

Geological Society of London (GSL): The description and classification of weathered rocks for engineering purposes, Geological Society Engineering Group Working Party Report, Q. J. Eng. Geol., 28, 207–242, 1995.

Geotechnical Engineering Office: Reassessment of the Po Shan Landslide of 18 June 1972, SPR 16/92, 75 p., 1983.

Geotechnical Engineering Office: Report on Shek Kip Mei Landslide of 25 August 1999, 1, 156 p., 2000.

Hem, J. D.: Chemical factors that influence the availability of iron and manganese in aqueous systems, Geol. Soc. Am. Bull., 83, 443–450, 1972.

Keller, W. D.: Scan electron micrographs of kaolin collected from diverse environments of origin: I, Clays and Clay Miner, 24, 107–113, 1976.

Keller, W. D. and Hanson, R. F.: Dissimilar fabrics by scan electron microscopy of sedimentary versus hydrothermal kaolins in Mexico, Clays and Clay Miner, 23, 201–204, 1975.

Kirk, P. A., Campbell, S. D. G., Flecther, C. J. N., and Merriman, R. J.: The significance of primary volcanic fabrics and clay distribution in landslides in Hong Kong, J. Geol. Soc. London, 154, 1009–1019, 1997.

Koppi, A. J., Edis, R., Filed, D., Geering, H. R., Klessa, D. A., and Cockayne, D. J. H.: Rare earth element trends and Ce-uranium-manganeseassociations in weathered rocks from Koongarra, Norther Territory, Australia, Geoch. Cosmoch. Acta, 60, 1695–1707, 1996.

Large landslides in Hong Kong: University of Hong Kong, Department of Earth Sciences, http://www.hku.hk/earthsci/tools/landslide/index.html, 2005.

McKenzie, R. M.: Manganese oxides and hydroxides, in: Minerals in Soil Environments (2nd Edition), Soil Science Society of America, edited by: Dixon, J. N. and Weed, S. B., SSSA Book Series, Madsion, Wisconsin, 439–465, 1989.

Merriman, R. J. and Kemp, S. J.: Mineralogical and microtextural analysis of altered tuffs associated with landslips in Hong Kong, British Geological Survey, Technical Report, WG/95/30C, 1995.

Merriman, R. J., Kemp, S. J., and Hards, V. L.: Halloysite and kaolinite in altered tuff hosting landslips, Hong Kong, Bristish Geological Survey Technical Report, WG/96/47C, 1996.

Moye, D. G.: Engineering geology of Snowy Mountains scheme, J. Institution Engineers Australia, 27, 287–298, 1955.

Schwertmann, U. and Taylor, R. M.: Iron oxides, in: Minerals in Soil Environments (2nd Edition), Soil Science Society of America, edited by: Dixon, J. N. and Weed, S. B., SSSA Book Series. Madsion, Wisconsin, 379–438. 1989.

Velde, B.: Origin and Mineralogy of Clays: Clays and the Environments, Springer, NewYork, 334 p., 1995.

Weaver, C. E.: Mn-Fe coatings on saprolite fracture surfaces, J. Sed. Petrol., 48, 2, 595–610, 1977.

Wen, B. P., Duzgoren-Aydin, N. S., and Aydin, A.: Geochemical characteristics of the slip zones of a landslide in granitic saprolite, Hong Kong: implications for their development and microenvironment, Environ. Geol., 47, 140–154, 2004.

Zheng, G., Lang, Y., Takamo. B., Kuno, A., Tsushima H.: Iron speciation of sliding mud in Toyama Prefecture, Japan. J. Asian Earth Sciences, 20, 955–963, 2002.