Moderate Chemical Weathering of Subtropical Taiwan: Constraints from Solid-Phase Geochemistry of Sediments and Sedimentary Rocks

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ABSTRACT

The well-known earthquake-and-storm-triggered extremely high physical weathering rate in Taiwan is consistent with present geochemical studies of sediments from different subenvironments (offshore, coastal, river, and lake) and sedimentary rocks of different geological ages, indicating a moderate chemical weathering condition. Major and trace element concentrations normalized to the average upper crust of Yangtze Craton show that the sediments and the average composition of sedimentary rocks of Taiwan are depleted in Ca, Mg, Na, and Sr, enriched in Rb and Zr, and unchanged with respect to K, indicating their moderately altered nature. The mean chemical index of alteration (CIA; 71–75) and plagioclase index of alteration (PIA; 81–86) values of coastal and offshore sediments reveal the sediments’ derivation from sedimentary rocks by moderate silicate chemical weathering processes. The mean CIA value (62) of sedimentary rocks of Taiwan is similar to that for Chinese sediment (61), further confirming the above inference. A-CN-K, (A-K)-C-N, and A-CNK-FM plots also confirm that the sediments and sedimentary rocks in Taiwan have undergone moderate silicate weathering, an interpretation consistent with CIA and PIA values. The plots also indicate the presence of illite, chlorite, and a subordinate amount of unaltered feldspars in sediments and sedimentary rocks, which are indicative of the physically weathered and/or moderately chemically altered nature of sediments. The dominance of illite, chlorite, and unaltered feldspars as inferred from geochemical data suggests that the immature nature of sediments and sedimentary rocks is probably a result of low residence times in the source region or river basin and quick removal of materials from the soil profile by steep, mountainous rivers [physical weathering dominates]. Elemental ratios such as Rb/Sr, K/Rb, molar K/Na, and Al/Na are close to crustal values. Average shale and river particulates such as those from the Yellow River also indicate moderate chemical weathering conditions for sediments and sedimentary rocks, except for high alpine lake sediments, where the prevailing extreme chemical weathering condition over erosion is clearly differentiated by higher CIA (80–84) and PIA (92–96) values and by their positions on triangular plots. These inferences have also been illustratively corroborated by scatter plots of data such as Rb/Sr versus molar K/Na, and Al/Na versus CIA. Additional evidence from published sources noted here also favors moderate chemical weathering conditions for Taiwan. Geochemical variation of offshore, coastal, and river sediments is mainly controlled by non–steady state weathering dominated by erosion. Steady state weathering, however, seems to produce highly weathered sediments in the alpine region of Taiwan.

Online enhancement: appendix table.

Introduction

Disproportionately high physical and chemical denudation rates occur in the oceanic island of Taiwan under the influence of copious orographic rainfall associated with the Asian monsoon, frequent typhoon activities, and related storm-triggered landslides. The average erosion rate estimated for the entire island is 5 mm/yr [WRPC 1973]. The average physical denudation rate for Taiwan [1365 mg/cm²/yr] is probably the highest in the world, as is the chemical denudation rate [50 mg/cm²/yr], which is ~27% of the physical denudation rate [Li 1976]. Recent estimates of maximum erosion rates (3–6 mm/yr) and the 30-yr average maximum sediment erosion rate (3.9 mm/yr; Dadson et al. 2003)
have demonstrated that across Taiwan, cumulative seismic moment release [earthquakes of magnitude greater than \( M_w = 5.0 \)] correlated linearly with decadal erosion rates over a sixfold range during a period between 1900 and 1998. Dadson et al. (2003) concluded that storm runoff is a first-order control on erosion rates in Taiwan, and the modern erosion rates are not controlled by relief and precipitation. Other recent erosion rates estimated from river water and sediment discharges of the Eastern Central Range of Taiwan show a wide range of values (2.2–8.3 mm/yr) resulting from the influence of variable intensity of storms rather than from lithology, tectonic environment, or climate [Fuller et al. 2003; Li 1976], however, inferred that the great change in the physical denudation rate is related to relief and/or bedrock geology. Indeed, Milliman and Syvitski (1992) projected that mountainous rivers draining in South Asia and Oceania have much greater sediment yields [two- to threefold] than other mountainous rivers of the world, owing to the influence of human activity, climate, and geology. Chen et al. (2004) listed 13 rivers in Taiwan among the top 20 worldwide in terms of sediment yield. Previous studies have documented highly variable physical and chemical denudation rates for this island, but no clear consistency between them has been established because relationships among climate, physical erosion, and chemical weathering remain poorly quantified since long-term weathering rates are difficult to measure [Riebe et al. 2001]. The purpose of this article is to determine if the very high, widely variable physical and chemical denudation rates reported from this oceanic island show any covariance with the intensity of chemical weathering, especially silicate weathering.

Geochemical studies have contributed appreciably to the understanding of the growth of the continents through time [Taylor and McLennan 1985]. Numerous factors including source area composition, source area weathering conditions, hydraulic sorting, adsorption, diagenesis, and metamorphism affect the composition of siliclastic sediments and sedimentary rocks over a wide scale [Fedo et al. 1996]. Silicate weathering strongly affects the major-element geochemistry and mineralogy of siliciclastic sediments [e.g., Nesbitt and Young 1982; Johnsson et al. 1988; McLennan 1993], where larger cations [\( Al_{2}O_{3}, Ba, Rb \)] remain fixed in the weathering profile preferentially over smaller cations [\( Ca, Na, Sr \)], which are selectively leached [Nesbitt et al. 1980]. These chemical signatures are ultimately transferred to the sedimentary record [e.g., Nesbitt and Young 1982; Wronkiewicz and Condie 1987], thus providing a useful tool for monitoring source area weathering conditions. Silicate weathering indexes such as chemical index of alteration (CIA), plagioclase index of alteration (PIA), and chemical index of weathering (CIW) are therefore widely used to interpret the weathering history of modern and ancient sediments [Harnois 1988; Fedo et al. 1996; Colin et al. 1999; Tripathi and Rajamani 1999]. For example, high CIA values reflect removal of labile cations [\( Ca^{2+}, Na^+, K^+ \)] relative to stable residual constituents [\( Al^{3+}, Ti^{4+} \)] during weathering [Nesbitt and Young 1982]. Conversely, low CIA values indicate the near absence of chemical alteration and might reflect cool and arid conditions [Fedo et al. 1995].

Chemical weathering rate [based on dissolved loads] includes dissolution of elements from both carbonate and aluminosilicate source rocks as well as atmospheric and modern anthropogenic inputs [Gaillardet et al. 1999; Sarin 2001; Han and Liu 2004]. Though silicate weathering is Earth’s long-term sink for atmospheric CO\(_2\) [Berner et al. 1983], in most natural environments, ionic contribution from carbonate rocks generally dominates the dissolved phase [Han and Liu 2004], with silicate contributing smaller amounts of dissolved solids (<15%; Sarin 2001). This is especially true where Cenozoic rocks dominate, such as in Taiwan. Hence, the chemical weathering rate, especially silicate weathering, of this island may be lower than previously projected [e.g., 97.09% ± 2.41% of total chemical weathering; Lai 2003]. Sediments produced by landslides and typhoon activities from rough, mountainous terrain and rapidly transported to the continental margin by fluvial systems of Taiwan would be expected to display minimal chemical weathering. That is, silt and mud would be expected to contain a comparatively low proportion of aluminous clay minerals and a commensurately higher proportion of primary minerals [feldspars].

In order to evaluate the chemical weathering intensity and provide accurate conditions of silicate weathering of Taiwan rocks, a wide representative range of geochemical data of offshore, coastal, river, and lake sediments of Taiwan [see table A1, available in the online edition or from the *Journal of Geology* office], along with published geochemical results of sediments from Taiwan Strait [Chao and Chen 2003] and sedimentary rocks [Lan et al. 2002] of different geological ages of Taiwan, has been subjected to calculation of weathering indexes [CIA, PIA, and CIW]. A variety of triangular and scatter plots have also been constructed from the geochemical data to accomplish our aim. To facilitate the interpretation of sediments and sedimentary
rocks, elemental values of representative river particulates such as Kaoping [Lai 2003], Yellow and Yangtze [both from Li et al. 1984], and Amazon [Martin and Meybeck 1979], as well as loess [Li et al. 1984] and other important reference compositions such as upper continental crust (UCC), post-Archean Australian shale [both from Taylor and McLennan 1985], average shale [Turekian and Wedepohl 1961], and North American shale composite [Gromet et al. 1984], have also been included for comparison.

**Methodology**

A total of 106 sediment samples were collected from different subenvironments [12 offshore surface sediments, eight coastal surface sediments, and core sediment consisting of 16 subsamples, all from off southwestern Taiwan; one bed sediment sample from Kaoping River; and core sediment consisting of 69 subsamples from high alpine, anoxic Great Ghost Lake] in southern Taiwan [fig. 1], with the help of appropriate sampling devices and techniques. Before chemical analysis, the samples were freeze-dried and homogenized, and the bulk sediment of each sample was finely ground (<200 mesh) in an agate mortar. Major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P) and trace (Ba, Rb, Sr, and Zr) elements were determined using an x-ray fluorescence (XRF) spectrometer (Rigaku RIX 2000) equipped with an Rh tube at the Institute of Marine Geology and Chemistry, National Sun Yat-Sen University, Taiwan. Details of the XRF method are described by Chen et al. [2001]. The accuracy of the analytical method was established using six internationally recognized standard reference materials: MAG-1, BCSS-1, PACS-1, MESS-1, NIES-2, and GBW 07314. Based on these standards, the accuracy and precision of the analysis were within ±1% for major elements such as Al, Ca, Fe, Mn, Mg, Na, Si, and Ti and within ±5% for Mn, P, Rb, Sr, and Zr. The precision and accuracy for Ba were within ±10%.

A LECO CHN-932 elemental analyzer was employed to determine carbon content at 950°C. After the samples were repeatedly rinsed with 1 N HCl to remove inorganic carbon [IC], total organic carbon was determined. The amount of IC was estimated by the difference between measured total carbon and organic carbon. The detection limit of IC is 0.01%. In the samples that were not measured for inorganic carbon, the mean value of each sample’s particular subenvironment was used for the calculation of CaO in only the silicate fraction [CaO*]. The CIA and PIA values of sedimentary and metasedimentary rocks as well as reference compositions such as UCC, average shale, post-Archean Australian shale, and North American shale composite were calculated without correcting CaO for carbonates and phosphates. In most of the sedimentary rocks of Taiwan, the CaO value is less than 2% [see table A1], with the exception of argillite (2.53%); the calculated values are, therefore, slightly lower than actual CIA and PIA values. Loss on ignition [LOI] was calculated as a percentage of dry weight after the samples were ignited at 550°C for 1 h [Dean 1974].

![Map of Taiwan showing the study area](image)

**Figure 1.** Map of Taiwan showing the study area (dashed line). Representative surface and core sediment samples collected from different subenvironments in southern Taiwan—offshore (open circle), coastal (filled circle), river (star), and lake (open triangle)—have been used for this study. The open square represents Kaohsiung City.
Table 1. Summary Statistics of Geochemical Compositions of Sediments and Sedimentary Rocks of Taiwan

<table>
<thead>
<tr>
<th></th>
<th>Major oxides (wt%)</th>
<th>Trace elements (ppm)</th>
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<tbody>
<tr>
<td></td>
<td>SiO₂</td>
<td>TiO₂</td>
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<tr>
<td>Offshore sediments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[n = 12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>54.33</td>
<td>14.60</td>
</tr>
<tr>
<td>Maximum</td>
<td>64.38</td>
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</tr>
<tr>
<td>Mean</td>
<td>60.43</td>
<td>15.65</td>
</tr>
<tr>
<td>SD</td>
<td>2.84</td>
<td>.06</td>
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<td>Coastal sediments</td>
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</tr>
<tr>
<td>[n = 8]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>51.55</td>
<td>13.70</td>
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<tr>
<td>Maximum</td>
<td>72.73</td>
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<tr>
<td>Mean</td>
<td>63.69</td>
<td>14.48</td>
</tr>
<tr>
<td>SD</td>
<td>7.32</td>
<td>.09</td>
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<tr>
<td>Offshore core sediment</td>
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<tr>
<td>[n = 16]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>66.32</td>
<td>14.56</td>
</tr>
<tr>
<td>Maximum</td>
<td>68.63</td>
<td>15.34</td>
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<tr>
<td>Mean</td>
<td>67.30</td>
<td>15.01</td>
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<tr>
<td>SD</td>
<td>.65</td>
<td>.01</td>
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<td>Core sediment, Great Ghost Lake</td>
<td>[n = 69]</td>
<td></td>
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<tr>
<td>Minimum</td>
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<tr>
<td>Maximum</td>
<td>58.74</td>
<td>23.08</td>
</tr>
<tr>
<td>Mean</td>
<td>53.78</td>
<td>17.04</td>
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<td>SD</td>
<td>1.71</td>
<td>.03</td>
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<td>Bed sediment, Kaoping River [n = 1]:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>72.36</td>
<td>12.39</td>
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<td>Core tops, Taiwan Strait [n = 3]:&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>73.12</td>
<td>5.55</td>
</tr>
<tr>
<td>Maximum</td>
<td>86.60</td>
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<tr>
<td>Mean</td>
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<td>8.72</td>
</tr>
<tr>
<td>SD</td>
<td>6.91</td>
<td>1.39</td>
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<tr>
<td>Sedimentary rocks of Taiwan [n = 14]:&lt;sup&gt;d&lt;/sup&gt;</td>
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<td></td>
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<tr>
<td>Minimum</td>
<td>58.75</td>
<td>6.65</td>
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<tr>
<td>Maximum</td>
<td>86.50</td>
<td>17.97</td>
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<td>Mean</td>
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<td>13.37</td>
</tr>
<tr>
<td>SD</td>
<td>9.81</td>
<td>4.12</td>
</tr>
</tbody>
</table>

<sup>a</sup> Total Fe expressed as Fe₂O₃.

<sup>b</sup> LOI = loss on ignition.

<sup>c</sup> Analysis from Chao and Chen 2003.

<sup>d</sup> Analysis from Lan et al. 2002.
Sediment Composition

The average composition of sedimentary rocks of Taiwan [table 1] has been calculated based on the data of Lan et al. (2002). The calculation involves 14 samples consisting of four widely varying sedimentary and metasedimentary rocks, such as phyllite [one sample], sandstones [three], argillites [two], and metapelites [eight], with the assumption that these four rock types will represent approximately average values for sedimentary rocks in this small area [0.024%] of the earth's surface. Based on Sr-Nd-O isotopic geochemistry of Taiwan granitoids and metapelites, Lan et al. (1995) suggested that cover sediments of Taiwan received recycled continental crustal material from South China and the basement rocks of Taiwan. It has recently been shown, based on the Nd isotopic composition of sedimentary and metasedimentary rocks of Taiwan, that these rocks are recycled materials of the UCC of the South China region [Lan et al. 2002]. South China consists of the Yangtze Craton in the west and the Cathaysian fold in the east [Jahn et al. 1990; Lan et al. 1995]. Because we are not aware of published results for the UCC of South China, in this study, sediment and sedimentary rock compositions of Taiwan were compared with the upper crust of Yangtze Craton (Gao et al. 1998). The average major [Si, Al, Ti, Fe, Ca, Mg, Na, and K] and trace [Ba, Rb, Sr, and Zr] element compositions of sediments from different subenvironments [offshore, coastal, river, and lake] and the average composition of sedimentary rocks [table 1] normalized with upper crustal values of Yangtze Craton [Gao et al. 1998] are shown in figure 2. The sediments and sedimentary rocks have remarkably similar patterns. The similarity suggests that most of the sediments are dominantly physically eroded and/or moderately chemically modified. All the sediments and average composition of sedimentary rocks are invariably depleted in Ca, Mg, Na, Ba, and Sr, enriched in Rb and Zr, and unchanged with respect to K. The degree of elemental variation is more prominent in lake sediments because of their highly altered nature. The slight depletion of Ti, Fe, and Mg shown by the average composition of sedimentary rocks of Taiwan is similar to UCC normalized values for these elements in the Huanghe sediments (Yang et al. 2004). Like sedimentary rocks, coastal and river sediments are depleted in Al, Ti, and Fe, whereas slight richness of these elements is evident in offshore and lake sediments.

Silicate Weathering: Geochemical Indicators and Triangular Plots

Geochemical processes such as weathering and soil formation are dominated by alteration of feldspars (and volcanic glass), which accounts for 70% of the upper crust if the relatively inert quartz is discounted (Nesbitt and Young 1982, 1984). Feldspars are by far the most abundant labile minerals, and consequently, the key process during silicate weathering of the earth’s upper crust is the degradation of feldspars by aggressive soil solutions so that the proportion of alumina to alkalis typically increases in the weathered product. A good measure of the degree of weathering can be obtained by calculation of the CIA using molecular proportions: 

\[ \text{CIA} = 100 \left( \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}} \right) \]

where \( \text{CaO} \) is the amount of \( \text{CaO} \) incorporated in the silicate fraction of the rock. The re-
resultant CIA gives a measure of the proportion of secondary aluminous clay minerals to primary silicate minerals such as feldspars (Nesbitt and Young 1982; Young et al. 1998).

The calculated CIA values for sediments and sedimentary rocks including river particulates, loess, and important reference compositions presented in table 2 demonstrate that the surface sediments off southwestern Taiwan (water depth 105–537 m) have moderate CIA values of 66–77, with an average of 74. Values for the near coastal sediments (water depth <100 m) from the same region are slightly lower but comparable, with CIA ranging from 59 to 78 and a mean of 73. Sixteen subsamples of core sediment off southwestern Taiwan (water depth 294 m) exhibit a narrow range of CIA values (73–76) with a mean of 75. Three surface sediments (top 0–15 cm) of three cores from Taiwan Strait, off central Taiwan (data from Chao and Chen 2003), also show comparable CIA values (69–72). The CIA values of surface and core sediments have means ranging from 71 to 75 and fall within the range of values for average shale (70–75), indicating that the sediments are possibly the product of sedimentary and metasedimentary rocks that have undergone intermediate chemical weathering. To deduce the silicate weathering trends, Nesbitt and Young (1982) and Nesbitt et al. (1996) used A-CN-K [Al2O3–CaO–Na2O–K2O] and A-CNK-FM [Al2O3–CaO–Na2O–K2O–FeO2–MgO] ternary plots. The data of sediments and sedimentary rocks of Taiwan plotted in Al2O3–CaO–Na2O–K2O compositional space (fig. 3) fall on a trend parallel to the A–CN join, and the trend approaches the Al2O3–K2O join at about CIA 80. The CIA values of many weathering profiles and sediments are linear, subparallel to the A-CN join in the A-CN-K plot (e.g., Nesbitt and Young 1984; Fedo et al. 1995; Selvaraj et al. 2004). All the samples that display moderate silicate weathering are thus plotted between CIA 60 and 80 (scale shown on the right side of the diagram for comparison), except for the sediments from high alpine Great Ghost Lake of southern Taiwan. The lake sediments that show a narrow range of higher CIA values between 80 and 84 (mean = 82; table 2), therefore, fall very near to apex A [fig. 3] as advanced weathering leads to an aluminum-rich composition (e.g., Nesbitt and Young 1984; Nath et al. 2000). This indicates extreme chemical weathering in the high altitude region of this island. The lake is one of the wettest places in Taiwan (annual rainfall = 4200 mm; Lou et al. 1997); the presence of thick vegetation on the gently sloping shore [24°–27° inclination] surrounding the lake acts as an ideal site for soil development, and the large amount of humus material (mean total organic carbon = 11.92%; n = 69) available in this region is probably responsible for the relatively low pH in soil solutions of lake catchments caused by production of organic acids. It has been shown by Colin et al. (1999) that increasing vegetation cover in the flood plains of the Irrawaddy River during the summer monsoon reinforcement favors soil development. This inference indicates that acidic byproducts of vegetation promote silicate weathering. The lowest CIA value of loess (46; table 2) indicates low-input acids to soils as a result of a cool, dry climate.

Most of our sedimentary rocks plot between CIA 60 and 70 in figure 3, close to values for the reference compositions such as the upper crusts of Yangtze Craton (56) and Central East China (54). The weathering trend [arrow 2 in fig. 3] connecting recent sediments and sedimentary rocks falls in a single line, suggesting that the sediments are the products of moderately weathered sedimentary rocks. The weathering trend of sediments and sedimentary rocks shows slight enrichment of K2O compared with particulate matters of the major rivers Yellow, Yangtze, Brahmaputra, and Amazon and with upper crustal compositions, indicating the presence of considerable unaltered K-feldspar in the samples. In figure 3, arrow 2 intersects the feldspar join [Pl-Ks] at point x and may represent the original parent rock composition, which is also slightly rich in K-feldspar when compared with upper crustal compositions. Indeed, values for the bed sediment of the Kaoping River and its suspended particulate matter fall very close to those for river particulates of the Yellow River and average world values, which is evidence for the moderate silicate weathering in the river basin.

The CIA values of sediments from different subenvironments are higher than the calculated CIA values of sedimentary rocks [argillite, metapelite, phyllite, and sandstone] in Taiwan (Lan et al. 2002), which all have mean CIA in the narrow range between 61 and 64 (table 2). These values are strikingly similar to the mean CIA (61) of Chinese sediment (Yang et al. 2004), suggesting that sedimentary rocks of Taiwan have experienced silicate weathering of moderate intensity similar to that of Chinese sediments. This further substantiates that the sediments and sedimentary rocks are the product of rocks that experienced moderate chemical weathering in the source regions. The calculated CIA values of sediments and sedimentary rocks have been classified according to the scheme suggested by Fedo et al. (1995) and shown in table 2. Nearly all the sediments and sedimentary rocks, including metapelites, invariably show intermediate intensity of chemical weather-

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<table>
<thead>
<tr>
<th>Location</th>
<th>CIA Range</th>
<th>CIA Mean</th>
<th>PIA Range</th>
<th>PIA Mean</th>
<th>Mean Rb/Sr</th>
<th>Mean K/Rb</th>
<th>Weathering intensity</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore sediments, southwestern Taiwan</td>
<td>66–77</td>
<td>74</td>
<td>71–90</td>
<td>84</td>
<td>.89</td>
<td>197</td>
<td>Intermediate</td>
<td>This study</td>
</tr>
<tr>
<td>Coastal sediments, southwestern Taiwan</td>
<td>59–78</td>
<td>73</td>
<td>64–90</td>
<td>83</td>
<td>.78</td>
<td>235</td>
<td>Intermediate</td>
<td>This study</td>
</tr>
<tr>
<td>Core sediments, southwestern Taiwan</td>
<td>73–76</td>
<td>75</td>
<td>83–88</td>
<td>86</td>
<td>.36</td>
<td>508</td>
<td>Intermediate</td>
<td>This study</td>
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<tr>
<td>Lake core sediments, Taiwan</td>
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<td>82</td>
<td>92–96</td>
<td>94</td>
<td>2.67</td>
<td>134</td>
<td>Extreme</td>
<td>This study</td>
</tr>
<tr>
<td>Bed sediment, Kaoping River</td>
<td>...</td>
<td>63</td>
<td>...</td>
<td>66</td>
<td>.72</td>
<td>185</td>
<td>Intermediate</td>
<td>This study</td>
</tr>
<tr>
<td>Core tops, Taiwan Strait</td>
<td>69–72</td>
<td>71</td>
<td>79–82</td>
<td>81</td>
<td>.55</td>
<td>220</td>
<td>Intermediate</td>
<td>Chao and Chen 2003</td>
</tr>
</tbody>
</table>

Earlier Cenozoic to Oligocene metasedimentary to sedimentary rocks of Taiwan:
- Phyllite, Early Cenozoic [Chulai]<sup>b</sup>
- Sandstone, Eocene [Meichi]<sup>b</sup>
- Sandstone, Oligocene [Tsuku]<sup>b</sup>
- Argillite, Oligocene [Kankou]<sup>b</sup>
- Argillite, Oligocene [Tatungshan]<sup>b</sup>
- Metapelites, Jurassic [Tienhsiang]<sup>b</sup>

River particulates:
- Kaoping, Taiwan<sup>b</sup>
- Yangtze, China<sup>a</sup>
- Yellow, China<sup>a</sup>
- Amazon<sup>a</sup>
- Brahmaputra<sup>a</sup>
- Ganges<sup>a</sup>
- River particulate matter<sup>b</sup>

Shale compositions:
- Average shale<sup>a</sup>
- Post-Archean Australian shale<sup>b</sup>
- North American shale composite<sup>b</sup>

Loess and crustal compositions:
- Loess<sup>a</sup>
  - CIA: 46, PIA: 46, Rb/Sr: .43, K/Rb: 196, Equal to UCC: Li et al. 1984
- Upper continental crust [UCC]<sup>b</sup>
- Mean crust<sup>a</sup>
  - CIA: 46, PIA: 45, Rb/Sr: ..., K/Rb: ..., Bowen 1979
- Yangtze Craton, China [upper crust]<sup>a</sup>
- Central East China [upper crust]<sup>a</sup>
- East China (total crust)<sup>a</sup>

Note. Weathering intensity has been given based on the threefold classification of Fedo et al. [1995]; weathering intensity for reference compositions such as UCC and mean crust are not given.

<sup>a</sup> Indicates the CaO values of only the silicate fraction.

<sup>b</sup> Represents the total CaO used for CIA and PIA calculations.
Figure 3. Major element composition of sediments and sedimentary rocks, river particulates, loess, and other reference compositions plotted as molar proportions on an Al$_2$O$_3$-( )-K$_2$O(A-CN-K) diagram. Arrow 1 represents the weathering trend of river particulates, arrow 2 indicates the weathering trend of sediments and sedimentary rocks of Taiwan, and arrow 3 marks the limit of weathering. The diagram also represents the fields of idealized minerals: ; Pl; K-feldspars; Bi; Biotite; Sm; Smectite; Mu; Muscovite; Il; Illite; Ka; Kaolinite; Gi; Gibbsite; Ch; Chlorite; Gt; Garnet. Arrow 2 through the sediments and sedimentary rocks intersects the feldspar join (Pl-Ks) at point x, which may give an indication of the original composition of the source material. The relation between chemical index of alteration (CIA) scale (Nesbitt and Young 1982) and the triangle is shown at right. Most of the sediments and sedimentary rocks fall between CIA 60 and 80, indicating intermediate intensity of silicate weathering. Note that the lake sediments fall above CIA 80, suggesting their extremely altered nature. The reason for the parallelism between the weathering trends of major river particulates (arrow 1) and sediments and sedimentary rocks of Taiwan (arrow 2) could be explained as follows: most of the world’s major rivers are perhaps draining in the terrains consisting of significant amounts of granite, granodiorite, gneiss, and related geologically older rocks. In Taiwan island, however, the percentage of these rocks is very low, and most of the rocks are geologically younger sedimentary and metasedimentary clasts. This probably causes the chemical variability observed between the two weathering trends, which in turn suggests the slight but significant differences between the composition of the original source rocks of sediments and sedimentary rocks of Taiwan and the composition of the UCC. The values of A coordinates are given in parentheses for comparison as well as to avoid confusion from overlapping points.
Figure 4. Triangular plot (after Fedo et al. 1995) showing molar proportions of Al$_2$O$_3$ (minus that associated with K), CaO, and Na$_2$O. The diagram shows that the plagioclase index of alteration (PIA) for most of the sediments falls between 80 and 90 (scale shown at right) because of the presence of small amounts of plagioclase feldspar resulting from moderate silicate weathering. Lake sediments fall very close to the Al$_2$O$_3$-K$_2$O apex, which substantiates that they are the products of highly weathered sedimentary rocks. An = anorthite; Al = albite. Symbols and other abbreviations are as in figure 3.

The consistency of CIA and PIA values among the sediments, sedimentary rocks, and metasedimentary rocks clearly suggests that, in general, the degree of silicate weathering in this island is a process operating on a moderate scale over a long period (from Jurassic to recent, even though our study has some gaps in sampling representation for a few periods such as Miocene, Pliocene, and Pleistocene). The Pleistocene sediments (ODP site 1144) of the northern South China Sea have CIA values of 73–79 (Boulay et al. 2003). Among the sedimentary rocks, metapelites have a wide range of CIA values (45–78), the lowest value being equal to those of UCC and loess. The mean value (62; $n = 8$), however, is consistent with those of the other sedimentary rocks (61–64) but lower than those of the sediments discussed above. The CIA and PIA values of average composition of sedimentary rocks are about 20% higher than upper crust values of Yangtze Craton (fig. 2).

To illustrate the approximate mineralogical composition of sediments and sedimentary rocks, major element data of all the samples have been plotted in the mafics triangle (fig. 5; Nesbitt and Young 1984; Nesbitt and Wilson 1992). It portrays molecular proportions of Al$_2$O$_3$, CaO$^+$, Na$_2$O, K$_2$O, and FeO$^+$+MgO [A-CNK-FM]. Most of the sediments, sedimentary rocks, and river particulates (Kaoping, Yellow, and Yangtze) plot within the compositional triangle of feldspars, garnet, and chlorite. This implies the approximate mafic minerals composition of samples; however, x-ray diffractogram (XRD) patterns of recent sediments...
have not shown any presence of garnet. Therefore, the coastal and offshore sediments plot away from the feldspar-garnet join but close to the feldspar-chlorite join, suggesting that sediments are essentially composed of feldspars and chlorite, dominated by the latter. This inference is compatible with the XRD patterns of our coastal and offshore sediments, all showing prominent feldspar ($d = 3.18$) and chlorite ($d = 7.16$ and $3.51$) peaks [Chen 1997]. The presence of illite and chlorite inferred from geochemical data is consistent with the earlier clay mineral investigation by Chen [1973], who found the illite-chlorite dominant suite over the continental shelf from the East China Sea to the southern part of Taiwan Strait. The close association of sediments with sedimentary rocks [fig. 5] indicates that the former is mostly the product of the latter. The lake sediments again plot toward higher Al than do other sediments and sedimentary rocks and well above the line of the feldspar-chlorite join, further confirming their higher silicate weathering. Bed sediment of the Kaoping River plots close to river particulates of the Yellow River and average world values, as in the A-CN-K plot; this denotes moderate silicate weathering in the river basin of the Kaoping and the similarity in the mineralogical composition of source rocks of the Kaoping and Yellow rivers. This finding, however, contradicts some previous reports [e.g., Yang 2001; Lai 2003] that suggested high chemical/silicate weathering rates based on dissolved river flux, probably because the dissolved flux also includes the carbonate dissolved elements. The river particulates of the Amazon and Yangtze rivers, however, plot close to the sediments, with lower values resulting from the incorporation of total CaO instead of CaO in only the silicate fraction.

**Large-Ion Lithophile Elements: Rb, Sr, K, and Na**

The increase in chemical weathering intensity rapidly leaches Sr compared to Rb [Nesbitt and Young 1982]; therefore, the Rb/Sr ratio increases with increasing CIA [Ma et al. 2000]. Likewise, with the increase in chemical weathering intensity, K will normally show depletion against Rb [Wronkiewicz and Condie 1989], thus leading to a lower K/Rb ratio. Rb has been considered to be primarily fixed in weathering residues and less reactive than Ca, Na, and Sr [Nesbitt et al. 1980]. The Rb/Sr ratios of sediments and sedimentary rocks can thus be used to monitor the degree of source rock weathering [McLennan et al. 1993]. The mean Rb/Sr ratios [0.89 and 0.78] of offshore and coastal surface sediments of southwestern Taiwan are consistent with the Rb/Sr ratios of different shale compositions [0.80–0.88; table 2], corroborating that the degree of source rock weathering was moderate. The lower mean Rb/Sr ratios of core sediments off southwestern Taiwan [0.36; $n = 16$] and Taiwan Strait [0.55; $n = 3$] are closer to the Rb/Sr ratios of different upper crustal and loess compositions [0.31–0.43]. The mean Rb/Sr ratios of sandstones and metapelites are 0.88 and 0.80, respectively, indicating that the recent sediments from coastal and offshore regions are mainly derived from these sedimentary rocks. This inference is supported by the similar Rb/Sr ratio [0.71] for bed sediment of the Kaoping River. High Rb/Sr ratios [1.74–3.77] of lake sediments and their higher mean value of 2.67 ($n = 69$) further support their derivation from intensively weathered rocks such as phyllite and argillite [mean Rb/Sr ratios 1.48 and 1.71], which are dominant in the entire drainage basin ($90.3 \text{ km}^2$) of the lake. Rb/Sr ratios in the illite minerals are usually >1, with a maximum value of 6.46 [Chaudhuri and Brookings 1979], suggesting that the higher illite content in lake sediments might be responsible for higher Rb/Sr ratios. The moderate chemical weathering of sediments is also indicated by K/Rb ratios (table 2) of the investigated sediments that are not depleted in K [fig. 2], and mean K/Rb ratios of coastal [235], offshore [197], and river [185] sediments are consistent with K/Rb ratios of Taiwan’s sedimentary rocks [220], upper crusts of Yangtze Craton [248], and loess [196].

Molar ratios of K/Na of sediments and sedimentary rocks are correlated well with Rb/Sr ratios as well as CIA and PIA values [fig. 6]. Both ratios are moderate and consistent with different shale compositions and bed sediment of the Kaoping River, demonstrating moderate silicate weathering. The diagram shows the presence of minor plagioclase (Na and Sr) and K-feldspar (K and Rb) in recent sediments. The close association of sediments with loess and Yellow River particulates suggests compositional similarity and also that the Taiwan Strait might have been sourced considerably from the loess plateau either by the Yellow River or from dust storm input. High K/Na and Rb/Sr ratios of lake sediments indicate stronger chemical weathering at higher altitudes as well as preferential dissolution of plagioclase (Na and Sr) relative to K-feldspar during the silicate weathering process [Yang et al. 2004]. The scatter plot of Al/Na ratio versus CIA [fig. 7] illustrates the interrelation between both indexes, which reflects the silicate weathering intensity. The diagram shows that the degree of chemical weathering of sediments and sedimentary rocks of Taiwan is moderate, as in-
Figure 6. Diagram showing variations in Rb/Sr versus molar K/Na in sediments and sedimentary rocks of Taiwan and other reference compositions. Note the two separate fields, low and intermediate values of chemical and plagioclase indexes of alteration (CIA and PIA) for sediments and sedimentary rocks in field 1, having low Rb/Sr and K/Na ratios compared to field 2, encircle the high CIA and PIA samples of Great Ghost Lake [GGL], which have higher Rb/Sr and K/Na ratios. See figure 3 for explanation of symbols and abbreviations.

dicated by their low Al/Na ratios (0–13.09), which reveal the presence of small amounts of Na₂O [plagioclase] in the samples. The degree of chemical weathering of lake sediments is high, as shown by their very high Al/Na ratios (20.75–41.42) resulting from extreme dissolution of plagioclase. These inferences are consistent with their positions on the other triangular and scatter plots.

Several lines of evidence have been drawn as additional support for the conclusions arrived at in this study. The XRD patterns of our offshore and coastal surface sediments show quartz-feldspar-chlorite-illite-calcite-kaolinite association [Chen 1997]. Consequently, illite and chlorite are the most abundant and ubiquitous clay minerals in the rock formations on the Hengchun Peninsula in southern Taiwan [Lin and Wang 2001]. Both illite and chlorite may be derived either from the degradation of muscovite and biotite from metamorphic formations or from the erosion of sedimentary rocks [Chamley 1989]. Micas are essential minerals of rocks such as schist and phyllite. Chlorite is considered a primary mineral of low-grade metamorphic rocks. The basement complex of Taiwan, Tananao schist and the associated choritoid rocks, is considered the probable source of chlorite in these sediments. Accordingly, illite, chlorite, and quartz are treated as products of physical erosion or moderate chemical weathering [Chamley 1989]. Colin et al. [1999] identified from the core sediments of the Bay of Bengal and Andaman Sea that the sediments deposited during the last glacial maximum are characterized by a decrease in the smectite/(illite + chlorite) ratio resulting from increased physical weathering. If the source rocks experienced intense chemical weathering, feldspars present in the source rock would be altered totally as aluminous clay [Fedo et al. 1996]. Repeated cycles of weathering and abrasion during transport eventually result in destruction of feldspars and formation of clay minerals [Nesbitt and Young 1996]. As long as feldspars persist, the sediments will remain compositionally immature [Nesbitt and Young 1996]. It has also been mentioned that the absence of feldspar in sediments and sedimentary rocks is a characteristic feature of supermature sedimentary rocks [Medaris et al. 2003]. Maturity would have been further enhanced by additional weathering during fluvial transport in a warm, humid climate [Johnsson et al. 1988] and by preferential destruction of labile minerals and lithic fragments in the high-energy fluvial and shallow marine environments [Odom et al. 1976]. The presence of feldspars in sediments of this study, inferred from figures 4 and 6 and the illite-chlorite association shown in figure 5, suggests their derivation by physical weathering [a key process in Taiwan] and/or moderate chemical weathering.

Direct evidence of chemical weathering was
found in the record of clay minerals in sedimentary basins by France-Lanord and Derry (1997). To estimate CO₂ consumption from silicate weathering, they selected the Himalayan-derived sediments of the late Pleistocene–mid-Miocene age recovered from the distal Bengal Fan on ODP Leg 116. Before 7 Ma and after 1 Ma, the clay mineral assemblage in the Bengal Fan was dominantly illite and chlorite (I-C assemblage), reflecting moderate weathering in the Ganges-Brahmaputra system. Between 7 and 1 Ma, clays in the Fan were dominantly pedogenic smectite and kaolinite (S-K assemblage), reflecting more intense weathering. The I-C sediments have lost little or no K₂O or MgO relative to the source rocks but have lost about half of their Na₂O and CaO, while the S-K sediments have lost some MgO, about half of their K₂O and CaO, and much of their Na₂O. Therefore, the secondary mineral assemblage of I-C in the sediments of southwestern Taiwan inferred from figures 5 and 6 and their unchanged K and slightly depleted Mg contents (fig. 2) corroborate that these sediments are the products of physically weathered rocks and/or intermediate chemical weathering. The clay mineral composition of present-day Ganges River sediment is essentially illite and chlorite, however, indicating rapid mechanical weathering in the source area (Singh et al. 2003).

Mean grain sizes (determined with a Coulter LS particle size analyzer) of offshore surface (6.47–15.08 μm; n = 12) and core (5.13–8.55 μm; n = 13) sediments fall within fine and very fine silt classes of siliclastic sediments. Coarser coastal sediments have a wide range of mean sizes, from 65 to 452 μm, and fall in very fine to medium sand classes. Fine and medium silt sizes (7.30–27.4 μm; n = 37) are the characteristics of highly weathered lake sediments. Silt and sand dominance suggests the presence of a relatively higher amount of feldspars than secondary clay minerals. The insignificant correlation (r = 0.465; P = 0.0001; n = 69) between mean grain size and CIA of studied sediments (fig. 8) supports the above inference and indicates that the chemical variability seems to be less likely to be grain-size controlled because of non–steady state weathering.

Consequences of Erosion and Chemical Weathering

Tectonism and climate generally determine the relative rates of erosion and chemical weathering (McLennan and Taylor 1991). Likewise, the relative rates of chemical weathering and erosion chiefly control the composition of siliclastic sediments (Nesbitt et al. 1997). Balanced rates of chemical weathering and erosion result in steady state weathering, which produces compositionally similar sediments over a long period. Non–steady state weathering, however, occurs where climate and tectonism vary greatly, altering the rates of chemical weathering and erosion and resulting in production of chemically diverse sediments. The extreme height of Taiwan’s mountains (4 km) and the monsoon climate (average precipitation is 2500 mm/yr with an average of four typhoons per year) result in very rapid physical denudation and fast transport of sediments to the ocean. In such a weathering-limited regime, soils are thin because of a high rate of mechanical denudation (physical weathering > soil formation). The residence time of secondary products of weathering is much lower because storage within the high-standing island’s riverine systems is thought to be minimal (Lyons et al. 2002); rates of chemical weathering are low, similar to those of the Himalayas (France-Lanord and Derry 1997), but high physical weathering rates continuously create new mineral surfaces that are responsible for enhanced river chemical fluxes (Gaillardet et al. 1999). Rivers of Taiwan, therefore, show high elemental fluxes that are highly related to huge storm-induced, physically eroded sediments transported in short mountainous rivers (erosion effect) rather than true alteration of feldspars to clay minerals, i.e., silicate weathering.

Rivers draining in low-altitude areas may have a better chance of segregation of elements in weathering relative to high-altitude systems, as concluded by Zhang and Liu (2002). They observed that
the segregation factor \( [\text{Ca + K + Na + Mg}] / [\text{Fe + Al}] \) in suspended matter of Chinese rivers increases with sediment yields in regions dominated by physical weathering. In contrast, the segregation factor decreases with sediment yield in regions dominated by chemical and biological weathering because the reduced water column turbidity allows chemical and biological reactions to process into depth over the drainage basin. In addition, an increase in the height/length (H/L) ratio of the river course corresponds to a reduced segregation of elements in weathering. Therefore, the very high H/L ratios of Taiwan rivers and their huge suspended load (~400 t/yr; Dadson et al. 2003) are also probably not conducive to chemical weathering. Further, extensive erosion results in reduction of soil particle retention in the weathering crust, coupled with incomplete chemical reaction caused by reduction of water-particle contact and segregation of elements [e.g., Al and Si; Zhang et al. 2003].

The ratio between the rates of physical and chemical denudation in Taiwan ranges from 10 to 40 mg/cm²/yr, approximately. In general, the areas of lower physical denudation rate show higher chemical denudation rates and vice versa [see fig. 1 of Li 1976]. Similarly, the ratios of physical and chemical denudation rates of Chinese rivers lie mostly between 2 and 10 mg/cm²/yr, excluding loess areas, where the ratio is high, at 90 mg/cm²/yr. The average physical erosion rate in the Yellow Basin was about \( 1.4 \times 10^4 \) kg/km²/yr, while the average chemical erosion rate was \( 25 \times 10^3 \) kg/km²/yr. In comparison, the average physical and chemical erosion rates in the Yangtze Basin were \( 0.29 \times 10^4 \) and \( 104 \times 10^3 \) kg/km²/yr, respectively [Li et al. 1984]. This implies that intense physical weathering cannot naturally result in a high silicate weathering rate, mainly because the strong erosion prevents the newly formed sediment from accumulating in the catchments area or in the soil profile. As a consequence, the source rocks and sediments have less time to react with the weathering agents, leading to moderately weathered material. Hence, because of the combination of active tectonic and climatic regimes [high relief, high rainfall, and storm-induced landslides], the continental rocks of Taiwan are eroding rapidly at 3–7 mm/yr [Dadson et al. 2004] through processes of fluvial bedrock incision [Hartshorn et al. 2002], landsliding [Hovius et al. 2000], and debris flows [Lin et al. 2004]. Large volumes of such physically eroded detritus are responsible for high dissolved elemental fluxes [mass/volume ratio] in the fluvial system. Chemical weathering has a smaller effect, and physical denudation and subsequent erosion are more important in controlling sediment compositions of the coastal and offshore sediments studied. These sediments are produced through non–steady state weathering dominated by hill-slope mechanical erosion. The possibilities of highly weathered zones of soil profile are expected to be slight on the slopes of steep mountains, since the profile materials are eroded before chemical weathering can produce the appropriate mineralogy or soil zonation [Nesbitt et al. 1997]. This non–steady state weathering is likely to be a characteristic feature of tectonically active high-standing islands of Asia and Oceania, such as Taiwan, the Philippines, Indonesia, New Zealand, and Papua New Guinea, where the entire spectrum of weathering zones developed on bedrock is susceptible to rapid erosion. Tectonism, moderate relief of lake catchments, and very high rainfall in the alpine region of Taiwan result in more vegetation, which stabilizes soils and aids in the production of organic acids that decompose most of the feldspars. Deep weathering profiles are therefore possible in high-altitude areas of Taiwan where the dominance of chemical weathering rates resulting from high annual acid input to mineral zones of soils over erosion produces highly weathered sediments.

In spite of huge orographic rainfall in this mountainous island, chemical weathering is not an intense process, except in the sediments of alpine Great Ghost Lake, where the CIA and PIA values show extreme weathering conditions. The CIA and PIA values between the upper crust of Yangtze Craton and the sedimentary rocks of Taiwan and sedimentary rocks and recent sediments increase by just 20% in each stage. Moreover, sedimentary rocks are recycled continental crustal materials, their derivatives are recent sediments, and the chemical weathering intensity of sediments is more or less equal to the weathering conditions of rivers such as Changjiang and Brahmaputra. Our conclusions in this study emphasize the need for additional data in this area and the need to recheck the chemical weathering rates of this orogen with more precise and appropriate techniques. The dissolved flux data of almost all the rivers in Taiwan show a very high concentration of nitrate, clearly indicating the influence of anthropogenic input in the dissolved loads rather than true weathering fluxes from dissolution of rock-forming minerals. Anthropogenic input appears to be the major source of riverine nutrients in the Kaoping River (Yang 2001). For example, anthrop-
pogenic inputs of total dissolved nitrogen and phosphate are about $5 \times 10^4$ and $4 \times 10^3$ kg/day, respectively. This condition may hold for most of the west-flowing rivers of Taiwan, where the total population of the country is residing. Moderate silicate weathering is further supported by the fact that the concentrations of dissolved silica in all but six rivers of Taiwan (C.-T. A. Chen, unpublished data) are lower than the reported values of this parameter in 60 large rivers in the world (Galjardet et al. 1999). Clearly there is still a need for additional information and long-term geochemical evidence about chemical weathering of this orogen. Therefore, our future investigation will focus on long core sediments of the northwest Pacific eastern side of the island, where huge amounts of weathered materials are directly transported by 11 fast-flowing rivers from the steep slopes of the Eastern Range of Taiwan (Fuller et al. 2003), with an aim to reconstruct the long-term weathering history of Taiwan.

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