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ORIGINAL ARTICLE

Evolution of Soil on Young Volcanic Bedrocks: Revisiting Geochemical and Cosmochemical Informations from Tatun Volcanic Area, Northern Taiwan

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Abstract

Residence times and production rate of soil samples from a profile developed over andesitic bedrock in the Tatun volcanic area of northern Taiwan are estimated. Existing data sets of major element chemistry and meteoric ^{10}Be deposition are re-analyzed using newly introduced approaches for soil erosion and production rate calculations. Soil residence times estimated using Si-based weathering indices (WIS) vary from 10 to 100 kyr from bottom to top of the profile. Distinctive weathering characteristics exist in two identified layers of soil profile. The soil production rate in the upper layer is 325 mm/kyr whereas that in the lower layer is only 19 mm/kyr. Weighted average of these production rates for the whole profile is 509 mm/kyr. Calculations using meteoric ^{10}Be concentrations in soil gave a soil production rate of 593 mm/kyr, which is comparable to the average soil production rate, estimated using WIS. The approach using variation in WIS with soil depth to estimate soil production rate seems to be applicable to profiles developed over young bedrocks (<1 Ma), where the applicability of commonly used uranium–series disequilibrium evolution model has limitations.

Keywords: Soil Production Rate, WIS, Meteoric ^{10}Be, Erosion.

1. Introduction

Sustainability of soil resources depends on the balance between soil denudation and soil production. Soil denudation refers to the removal soil by chemical and physical erosion. If the rate of soil production by bedrock weathering is equal to or greater than the rate of denudation, the soil resource is expected to be sustainable. Soil profiles also play a major role in fixing CO_2, by storing soil organic carbon (Suresh, 2014a). In a recent review, Montgomery (2007) pointed the imbalance between to higher agricultural erosion rates than global soil production rates. The author relates the decline of ancient Arabian, Greek and Mesoamerican civilizations with the loss of soil due to denudation without sufficient replenishment by soil production. Until last two decades, the lack of proper tools resisted the scientific community to accurately assess the rate of soil production. Recently, in situ produced cosmogenic radionuclides of ^{26}Al and ^{10}Be in the soil are used for determining soil production rates (Heimsath *et al.*, 2010; 2001; 2000; McKean *et al.*, 1993). The method utilizes the concentration of these isotopes in soils, exposed bedrocks, tors and river sediments, produced by the interaction of cosmic rays. The rate of exposure of cosmic rays can then be modeled, which in turn gives the rate of denudation. Assuming a steady state thickness of soil, this denudation rate is interpreted as the soil production rate. This method has limited applicability to soil profiles which are not at steady state.

More recently, a model using the evolution of uranium series (U – series) isotope disequilibria (^{238}U – ^{234}U – ^{230}Th) in the soil induced due to chemical weathering of the bedrock to form soil has been applied to estimate age of weathering and hence the rate of soil production (Suresh *et al.*, 2013; Dosseto *et al.*, 2012; Ma *et al.*, 2010; Dosseto *et al.*, 2008a; Dequincey *et al.*, 2002). Similar technique can be applied to estimate residence timescales of river sediments also (Suresh *et al.*, 2014b). The activity ratios of ^{238}U – ^{234}U – ^{230}Th isotopes in undisturbed bedrocks older than 1 Myr are expected to be equal to 1, which represent secular equilibrium of these isotopes. During the onset of chemical weathering, due to the differences in the mobilization of the isotopes of U and Th the equilibrium will be disturbed. U is more mobile than

Th, hence the (^{230}Th/^{238}U) ratio will be greater than 1 in the residue of weathering and will be less than 1 in the fluid medium which causes weathering. The alpha decay of ^{238}U causes high recoil and damages the lattice points in the minerals of soil, which increases the leach ability of the product nucleus, ^{234}U. Also, if the alpha decay of ^{238}U is occurring near the surface region of soil grains, there is a possibility of the product nuclide being ejected out. Both these processes push the (^{234}U/^{238}U) ratio to less than 1. These ratios then tend to move back to secular equilibrium due to natural radioactive decay. Hence, the time since the onset of chemical weathering of the bedrock can be estimated by modeling the time-dependant evolution of these activity ratios (U-Th isotope loss gain model). Individual residence times of soil samples at different depths of undisturbed soil profiles may be determined, and by fitting a straight line on the residence time verses soil depth data, the rate of soil production may be estimated (Suresh *et al.*, 2013). The U – series method does not require the assumption of steady state soil thickness, but the bedrock on which the soil profile has been developed must be old enough to have its U-series activity ratio at secular equilibrium. This limitation restricts the application of the method to soil profiles developed over younger bedrocks.

In a study of evolution of soil from slightly acidic profiles from south-eastern Australia, Suresh *et al.* (2013) reported $Al_2O_3$to be more mobile than SiO_2. They introduced a new Si-based Weathering Index (WIS: the ratio of SiO_2 content to the sum of SiO_2, Al_2O_3, CaO and Na_2O expressed in percentage) which increased with the increase of the extent of chemical weathering of the soil. Also, they reported a linear relationship between the residence times of soil estimated using the U-Th isotope loss-gain model and WIS. Residence time here refers to the time since the onset of chemical weathering of bedrock. The authors used this relationship to estimate soil production rates in profiles from that area. It is expected that, in an undisturbed soil profile, the soil residence times increases with decreasing depth. Similarly, for these profiles the extent of chemical weathering (indicated by WIS) will also increase with decreasing soil depth (Suresh *et al.*, 2013).

The method of estimating soil residence times using WIS values are yet to be demonstrated on bedrocks other than granitic and climate settings different from that in south-eastern Australia. However, since the evolution of WIS does not depend on the formation age of bedrock or steady state of soil thickness, it is expected to be applicable to develop a first estimate of soil production rates in acidic soil profiles from the Tatun volcanic area in northern Taiwan. Here, we revisit the major element chemistry of soil samples in a profile from Tatun volcanic area reported by Chen *et al.* (1988) in their study of bauxitization processes. Reported data of meteoric ^{10}Be deposited in the soil by rainfall by You *et al.* (1988) is expected to be useful to compare the sustainability of soil mantle in this area.

2. Studied site

The soil profile studied was collected from a bauxite mine opening in the NE side of Huangtsuishan area of the Tatun Volcanic Group, marked in Fig 1 (N 25° 14’ 34”, E 121° 26’ 38”). The cross sectional soil profile is shown in Fig 2. The mine site is currently abandoned and covered with dense vegetation. Annual precipitation in this region is 4000 mm and the mean temperature is 20° C (Chen *et al.*, 2006; Chen *et al.*, 1988). The soil in this area is acidic with pH ~5 (Chen *et al.*, 1988). The regolith profile is ~16 m thick above the bedrock (You *et al.*, 1988). Two soil zones were identified by Chen *et al.* (1988) with a boundary at 3.6 m from top. The bottom zone, which has distinctive soil properties such as color, may be the saprolite. The underlying bedrock is andesitic. The K-Ar age of the oldest bedrock in this region is reported to be 0.7 Ma (You *et al.*, 1988, Juang and Bellon, 1984).

3. Erosion and soil production

By studying modern river sediment load, Holocene river incision and thermo-chronometry, a long term erosion rate of 3 – 6 mm/yr for the mountainous regions in Taiwan is reported by Dadson *et al.* (2003). Earlier, You *et al.* (1988) studied the concentration of meteoric^{10}Be (produced in the atmosphere by interaction of cosmic rays with nitrogen and oxygen nuclei, which then gets attached to aerosol and subsequently deposited on earth through rainfall) in the soil profile from Tatun area to estimate the erosion rates (Table 1). They reported a ^{10}Be inventory of 1.8×10^{11} atoms/cm^2 in the profile. The concentration does not show significant variation with soil depth in the profile, indicating removal of the deposited ^{10}Be by ground water is negligible.

The authors used a formula:

$$N(t) = QT(1-\xi n/Q)[1-e^{(-t/T)}] \qquad (1)$$

(where $N(t)$ is the inventory of ^{10}Be at time t, Q is the deposition rate of ^{10}Be, ξ is the sediment yield, n is the ^{10}Be concentration in the yielded sediment and T is the mean life of ^{10}Be) to estimate the erosion rate using their data. Taking an upper age limit of soil formation of 0.8 Ma and assuming a soil bulk density of 1.5 g/cm^3, the authors estimated an extremely low erosion rate of~1 cm/kyr. They used the measured ^{10}Be concentration of 10^8 atoms/g in the eroded materials. The used Q value was 1.7 x 10^6 atoms/cm^2/yr, which had been commonly used by researchers then (You *et al.*, 1988 and references therein).

Table 1: Concentration of ^{10}Be in the soil profile of Huangtsuishan area. *Data reproduced from You et al. (1988).*

Soil Depth (cm)	Concentration of ^{10} (10^6atoms/g)
0	168
80	38
200	57
400	50
500	55
600	88
800	90
900	40
1000	33
1100	100
1200	305
1300	115

If the loss of ^{10}Be through ground water is negligible from the profile, the only mechanism by which ^{10}Be is lost is by radioactive decay and erosion. According to Fifield *et al.* (2010), the inventory (N_0) of ^{10}Be can then be expressed as:

$$N_0 = (Q - \xi\eta)/\lambda (2)$$

Where Q is the fallout rate of ^{10}Be, ξ is the erosion rate, η is the concentration of ^{10}Be in the eroded materials and λ is the decay constant of ^{10}Be (4.59 x 10^{-7}/yr). This equation can be used to calculate ξ in the soil profile. Assuming a steady state soil thickness, i.e. a balance between the rate of erosion and soil production, Fifield *et al.* (2010) interpreted ξ as the rate of soil production. They used a globally averaged proportionality constant (1.5 x 10^4 atoms/cm^3) between the amount of rainfall and the number of atoms of ^{10}Be deposited to estimate Q value. Using this technique, they estimated a soil production rate of 1-7 mm/kyr for a location near Canberra in the south-eastern Australia. Their study site is on the western escarpment of the Great Dividing Range of south-eastern Australia. For Frogs Hollow, a nearby location in the high lands of the Great Dividing Range, the soil production rates estimated using in-situ produced cosmogenic radio nuclides ranges between 1- 50 mm/kyr (Heimsath *et al.*, 2001). At Bega Valley, a location further south of that of Fifield *et al.* (2010), the estimated soil production rate also fall in the same range (Heimsath *et al.*, 2000; Dosseto *et al.*, 2008a). The production rate estimated using U-series isotopes, cosmogenic radionuclides and fallout ^{10}Be nuclide concentrations are in the comparable range. Hence, the fallout ^{10}Be concentration reported by You *et al.* (1988) may be used to re-estimate the soil production rate in the Tatun Volcanic area. Taking that value with an updated record of annual rainfall (400 cm) a soil production rate of 593 mm/kyr can be estimated for the profile from Huangtsuishan area.

Fig 1: The map shows the location of the Tatun Volcanic Group, north of Taipei in northern Taiwan.

Fig 2: The soil profile collected from the Bauxite mine in the Tatun Volcanic Area. This picture is taken in 1988.

Using the major element chemistry of the soil samples from the profile the soil production rate can be estimated independent of steady state assumption. The WIS values calculated using the data reported by Chen *et al.* (1988) for the soil samples in the two zones from the profile show a linear increase with decreasing soil depth (Table 2), which could indicate the increase of extent of weathering with time (Fig. 3). According to Suresh *et al.* (2013), the linear relationship of residence time (T_{res}) of soil with WIS can be expressed as:

$$T_{res} = 1.3 \text{ x WIS} \quad (3)$$

Table 2: Major element data (wt %) (reproduced from Chen et al., 1988) and WIS (%) of the soil samples. T_{res} is calculated using eqn. (3).

Sample No.	1	2	3	4	5	6	7	8	9	10
Depth	0	60	120	180	240	300	360	420	480	540
SiO_2	57.36	55.18	52.8	51.78	48.86	48.04	46.06	32.33	16.1	4.16
Al_2O_3	18.16	19.14	19.83	20.21	22.47	21.89	20.92	26.21	39.12	50.54
Fe_2O_3	8.12	8.56	9.13	9.26	9.13	13.28	14.73	16.93	17.06	13.16
CaO	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
MgO	1.33	1.3	1.01	1.14	1.14	0.8	0.73	0.61	0.52	0.27
Na_2O	0.28	0.18	0.16	0.2	0.14	0.1	0.14	0.06	0.02	0.02
K_2O	2.14	2.22	2.4	2.38	2.22	2.43	2.2	1.47	0.73	0.06
MnO	0.07	0.07	0.07	0.07	0.08	0.05	0.04	0.07	0.09	0.06
TiO_2	1	1.01	1.08	1.06	0.98	1.39	1.82	1.57	1.35	0.97
WIS	75.65	74.05	72.52	71.71	68.35	68.58	68.60	55.15	29.13	7.60
Tres (Kyr)	98.35	96.26	94.27	93.22	88.85	89.15	89.18	71.70	37.88	9.88

This equation can be applied to the soil samples from the two zones of the profile from the profile of Huangtsuishan to estimate residence times (Table 2). The soil production rates can be estimated by fitting a straight line between the soil depth data and the T_{res} for both the zones (Fig 3). For zone 'A' the soil residence time varies between 88 to 98 kyr, which means a rapid soil production in 10 kyr timescale, with a rate of 325 mm/kyr. In zone B, the values of WIS is much lower than those in zone 'A', indicating a lower extent of chemical weathering and hence a lower rate of soil production (19 mm/kyr). A change in weathering intensity due to geothermal conditions might have occurred to affect the soil evolution process during that time (Chen *et al.*, 1988). The weighted average of soil production rates of both the zones can be calculated using a soil bulk density of 1.5 g/cm^3, which is 509 mm/kyr. This is comparable to that determined using eq. (2) (593 mm/kyr), which supports the estimated values of soil production rates using WIS. Also, these values are comparable to the production rates (~450 mm/kyr) reported for soil profiles developed over andesitic bedrocks in Puerto Rico (Dosseto *et al.*, 201; 2012).

4. Discussion and conclusion

Determination of soil production rate by modeling the evolution of U – series disequilibria may be limited to the profiles developed over bedrocks older than 1 Ma, as one of the requirements for the model is the secular equilibrium of the isotopes as initial condition (Dosseto *et al.*, 2008b). For profiles developed over young volcanic bedrocks (<1 Ma) in Tatun volcanic area, the new approach using Si – based weathering index of the soil to estimate soil production rates reported by Suresh *et al.* (2013) shows better applicability. The match between soil production rates determined using meteoric ^{10}Be (which assumes steady state soil thickness) and that estimated using WIS – T_{res} relationship could possibly indicate that the soil mantled landscape attained steady state in about 100 Kyr. However, the fast erosion rate in the island of Taiwan could create short term instability in the soil mantle. Tectonic activities may have positive as well as negative effects on sustainability of the soil resources in Taiwan, which needs to be investigated. A combined approach using short lived radio-nuclides and elemental chemistry of soil, sediments and river water covering wider sampling areas is expected to give better insight into the landscape processes in tectonically active areas like Taiwan.

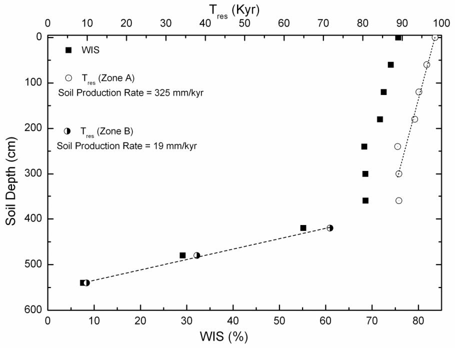

Fig 3: Variation of residence times of soil with depth estimated using Si-based Weathering Indices. WIS shows distinct characteristics in the two studied zones (A and B).

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