Figures

Fig. 1 Map of Nasuno-ga-hara, the study area.

Fig. 2 Geomorphic map of Nasuno-ga-hara. Stars (★) shows sampling sites, from Loc.1 to Loc. 10.

Recent River Floodplain (0-ka surface), Loc. 1 in Fig. 2

Fig. 3 Outcrop at Loc. 1, *Recent River Floodplain* (0-ka surface)

Fig. 4 Longitudinal profiles of riverbed and terraces.

Lower Terrace I (20-ka surface), Loc. 3 in Fig. 2

Fig. 5 Outcrop at Loc. 3, *Lower Terrace I* (20-ka surface).

Fig. 6 Profiles of four terraces (a: 20-ka surface, b: 320-ka surface, c: 450-ka surface and d: 830-ka surface).

Fig. 7 Outcrop at Loc. 6, *Upper Terrace* (320-ka surface).

Fig. 8 Outcrop at Loc. 8, *Lower Hill* (450-ka surface).

Fig. 9 Outcrop at Loc. 10, *Upper Hill* (830-ka surface).

0-ka Rocks

Fig. 10 Andesite rocks taken from 0-ka surface.

20-ka Rocks

Fig. 11 Andesite rocks taken from 20-ka surface.

Fig. 12 Andesite rocks taken from 320-ka surface.

Fig. 13 Andesite rocks taken from 450-ka surface.

830-ka Rock

Fig. 14 Andesite rocks taken from 830-ka surface.

Fig. 15 Polarization micrographs of 0-ka rocks.

Fig. 16 Polarization micrographs of 20-ka rocks.

Fig. 17 Polarization micrographs of 320-ka rocks.

Fig. 18 Polarization micrographs of 450-ka rocks.

(c)
Rock surface
Brown layer
Inner part
1mm
Open nicol
Pl
P
Cross nicol
450-B39
(d)
Rock surface
Brown layer
White layer
?
Inner part
1mm
Open nicol
Cross nicol
450-B64
Pl
Cross nicol

Fig. 19 Polarization micrographs of 830-ka rocks.

(a) 0-ka rocks, inner part

(b) 20-ka rocks, inner part

Voltage: 40kV, Current: 25mA, Scan speed: 1°/ min,
Sampling 0.02deg, Slit: 1° - 0.3 mm - 1° - 0.6 mm

Fig. 20 X-ray diffractograms.

Q: Quartz, T: Trydimite, F: Feldspar, Px: Pyroxene, Mgn: Magnetite, Py: Pyrite
Z: Zeolite, K: Kaolin minerals, Z: Smectite, Mgh: Maghemite, H: Hematite

(c) 320-ka rocks, inner part

(d) 450-ka rocks, inner part

(e) 830-ka rock, inner part

Voltage: 40kV, Current: 25mA, Scan speed: 1°/ min,
Sampling 0.02deg, Slit: 1° - 0.3 mm - 1° - 0.6 mm

(f) 20-ka rocks, brown layer

(g) 320-ka rocks, brown layer

(h) 450-ka rocks, brown layer

(i) 830-ka rock, brown layer

Voltage: 40kV, Current: 25mA, Scan speed: 1°/ min,
Sampling 0.02deg, Slit: 1° - 0.3 mm - 1° - 0.6 mm

Fig. 21 Colour changes with depth in terms of L* a* b* colour-system values.

(d)
450-B1
Brown layer
Inner part
L*
a*
b*
Depth from Rock Surface, mm

(e)
450-B38
Brown layer
Inner part
L*
a*
b*
Depth from Rock Surface, mm

(f)
Brown layer
Inner part
450-B39
L*
a*
b*
Depth from Rock Surface, mm
(g)
Brown layer
White layer
Inner part
450-B64
L*
a*
b*
Depth from Rock Surface, mm

Fig. 22 Visible spectra determined from colour measurement.

Fig. 23 PSD histograms of 0-ka rocks.

Fig. 24 PSD histograms of 20-ka rocks.

0.002
0.001
0.000
Pore Volume, cm3/g
← α →
← β →
← γ →
← δ →
20-A3
10 2
10 1
10 0
10 -1
10 -2
Pore Diameter, µm

0.002
0.001
0.000
Pore Volume, cm3/g
← α →
← β →
← γ →
← δ →
20-A16
10 2
10 1
10 0
10 -1
10 -2
Pore Diameter, µm

Fig. 25 PSD histograms of 320-ka rocks.

320-B20
Brown layer
Inner part
320-B20
Inner part
320-B22
Brown layer
Inner part
320-B22
Inner part
Pore Volume, cm³/g
Pore Diameter, µm
α
β
γ
δ

Fig. 26 PSD histograms of 450-ka rocks.

450-B39
450-B64
Pore Volume, cm³/g
Pore Diameter, µm
Inner part
Brown layer
White layer
← α →
← β →
← γ →
← δ →
0.00
0.01
0.02
0.000
0.001
0.002
10²
10¹
10⁰
10⁻¹
10⁻²

0.002
0.001
0.000
Pore Volume, cm³/g
α
β
γ
δ
450-B10
Inner part
10²
10¹
10⁰
10⁻¹
10⁻²
Pore Diameter, µm

0.002
0.001
0.000
Pore Volume, cm³/g
α
β
γ
δ
450-B37
Inner part
10²
10¹
10⁰
10⁻¹
10⁻²
Pore Diameter, µm

0.002
0.001
0.000
Pore Volume, cm³/g
α
β
γ
δ
450-C1
Inner part
10²
10¹
10⁰
10⁻¹
10⁻²
Pore Diameter, µm

Pore Volume, cm³/g
0.020
0.010
0.000
450-B12
α
β
γ
δ
Brown layer
Inner part
10²
10¹
10⁰
10⁻¹
10⁻²
Pore Diameter, μm
0.002
0.001
0.000
Pore Volume, cm³/g
450-B12
Inner part
Pore Diameter, μm

Fig. 27 PSD histograms of 830-ka rock.

Fig. 28 Relationship between chemical compositions for the brown layers and those of the inner parts.

Fig. 29 Relationship between the absolute weight in unit volume of chemical elements for the brown layers and those of the inner parts .

Fig. 30 Element-concentration maps for sample 450-B1 constructed by EPMA.

Fig. 31 Element-concentration maps for sample 830-A1 constructed by EPMA.

Fig. 32 Results of EPMA line analyses of Si, Fe and Ca (a: sample 450-B1, b: sample 450-B64).

Fig. 33 Chemical changes with depth from the rock surface (a: sample 20-B2, b: sample 20-B6, c: sample 450-B1, d: sample 450-B10, e: sample 450-B12, f: sample 450-B64).

(b)

Brown layer
Inner part
20-B6, Major elements
30 (wt.%)
20
10
0
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
1.5 (wt.%)
1.0
0.5
0.0
K2O
TiO2
MnO
P2O5
0
10
20
30
40
Depth from Rock Surfase, mm

Brown layer
Inner part
20-B6, Trace elements
1000 (ppm)
800
600
400
200
0
Ba
Cr
Ni
400 (ppm)
300
200
100
0
Sr
V
Co
Cu
Zr
Zn
30 (ppm)
20
10
0
As
Li
Pb
0
10
20
30
40
Depth from Rock Surface, mm

(c)
Brown layer
Inner part
450-B1, Major elements
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
20 (wt. %)
15
10
5
0
K2O
TiO2
MnO
P2O5
2.5 (wt. %)
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
Depth from Rock Surface, mm
Brown layer
Inner part
450-B1, Trace elements
Ba
Cr
Ni
2500 (ppm)
2000
1500
1000
500
0
Sr
V
Co
Cu
Zr
Zn
500 (ppm)
400
300
200
100
0
As
Li
Pb
20 (ppm)
10
0
0
5
10
15
20
25
30
Depth from Rock Surface, mm

(a)
Brown layer
Inner part
450-B10, Major elements
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
25 (wt. %)
20
15
10
5
0
K2O
TiO2
MnO
P2O5
2.0 (wt.%)
1.5
1.0
0.5
0.0
0
5
10
15
20
25
Depth from Rock Surface, mm
Brown layer
Inner part
450-B10, Trace elements
Ba
Cr
Ni
2000 (ppm)
1000
0
Sr
V
Co
Cu
Zr
Zn
500 (ppm)
400
300
200
100
0
As
Li
Pb
(ppm)
20
10
0
0
5
10
15
20
25
Depth from Rock Surface, mm

(e)

Brown layer
Inner part
450-B12, Major elements
25 (wt. %)
20
15
10
5
0
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
2.0 (wt. %)
1.5
1.0
0.5
0.0
K2O
TiO2
MnO
P2O5
0
5
10
15
20
25
30
Depth from Rock Surface, mm
Brown layer
Inner part
450-B12, Trace elements
1500 (ppm)
1000
500
0
Ba
Cr
Ni
500 (ppm)
400
300
200
100
0
Sr
V
Co
Cu
Zr
Zn
30 (ppm)
20
10
0
As
Li
Pb
0
5
10
15
20
25
30
Depth from Rock Surface, mm

(f)
Brown layer
White layer
Inner part
450-B64, Major elements
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
20 (wt.%)
15
10
5
0
K2O
TiO2
MnO
P2O5
1.5 (wt.%)
1.0
0.5
0.0
0
5
10
15
20
25
Depth from Rock Surface, mm
450-B64, Trace elements
Ba
Cr
Ni
1200 (ppm)
800
400
0
Sr
V
Co
Cu
Zr
Zn
300 (ppm)
200
100
0
As
Li
Pb
20 (ppm)
10
0

Fig. 34 VHN-values versus depth from the rock surfaces for 0-ka rocks.

Fig. 35 VHN-values versus depth from the rock surfaces for 20-ka rocks.

(d)
Zone II
Zone III
VHN, gf/μm²
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Depth from Rock Surface, mm
20-B2

(e)
Zone II
Zone III
VHN, gf/μm²
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Depth from Rock Surface, mm
20-B6

Fig. 36 VHN-values versus depth from the rock surfaces for 320-ka rocks.

Fig. 37 VHN-values versus depth from the rock surfaces for 450-ka rocks.

(e)
Zone I
Zone II
VHN, gf/μm²
450-B39
Depth from Rock Surface, mm
(g)
Zone I
Zone II
Zone III
VHN, gf/μm²
450-C1
Depth from Rock Surface, mm

(f)
Zone I
Zone II
VHN, gf/μm²
450-B64
Depth from Rock Surface, mm

Fig. 38 VHN-values versus depth from the rock surfaces for 830-ka rocks.

Fig. 39 Changes in apparent thickness of weathering rinds with time.

Fig. 40 Changes in chemical composition with time.

MnO
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
0.25
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
Time, ka

MgO
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
200
400
600
800
1000
Time, ka

CaO
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
200
400
600
800
1000
Time, ka

Na2O
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
200
400
600
800
1000
Time, ka

K2O
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
Time, ka

P2O5
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
Time, ka

Ig. loss
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
Weight %
15
10
5
0
-5
0
200
400
600
800
1000
Time, ka

Ba
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
1200
800
400
0
0
200
400
600
800
1000
Time, ka

Cu
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
250
200
150
100
50
0
0
200
400
600
800
1000
Time, ka

Ga
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
35
30
25
20
15
0
200
400
600
800
1000
Time, ka

Mo
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
Time, ka

Nb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
8
6
4
2
0
200
400
600
800
1000
Time, ka

Ni
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
200
150
100
50
0
0
200
400
600
800
1000
Time, ka

Pb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
25
20
15
10
5
0
0
200
400
600
800
1000
Time, ka

Rb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
80
60
40
20
0
0
200
400
600
800
1000
Time, ka

Sr
ppm
Time, ka
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer

Th
ppm
Time, ka
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer

U
ppm
Time, ka
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer

V
ppm
Time, ka
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer

Y
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
50
40
30
20
10
0
0
200
400
600
800
1000
Time, ka

Zr
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
ppm
300
250
200
150
100
50
0
0
200
400
600
800
1000
Time, ka

Fig. 41 Changes in absolute weights in unit volume of chemical elements with time.

MnO
MgO
CaO
Na_2O
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm^3
Time, ka
0
200
400
600
800
1000

K2O
P2O5
lg. loss
Total
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
Time, ka
0.20
0.15
0.10
0.05
0.00
0.05
0.04
0.03
0.02
0.01
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
200
400
600
800
1000

Ba
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
Time, ka

Cu
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.03
0.02
0.01
0.00
0
200
400
600
800
1000
Time, ka

Ga
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.010
0.008
0.006
0.004
0.002
0.000
0
200
400
600
800
1000
Time, ka

Mo
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.0008
0.0006
0.0004
0.0002
0.0000
0
200
400
600
800
1000
Time, la

Nb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.0020
0.0015
0.0010
0.0005
0.0000
0
200
400
600
800
1000
Time, ka

Ni
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
Time, ka

Pb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
1000
Time, ka

Rb
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
0.020
0.015
0.010
0.005
0.000
0
200
400
600
800
1000
Time, ka

Sr
Th
U
V
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
g/cm3
Time, ka
0.10
0.08
0.06
0.04
0.02
0.00
0.0015
0.0010
0.0005
0.0000
0.0006
0.0004
0.0002
0.0000
0
200
400
600
800
1000

Y
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
0.015
0.010
0.005
0.000
g/cm3
0
200
400
600
800
1000
Time, ka

Zr
Inner part
Brown layer
Inner part (average)
Brown layer (average)
White layer
0.06
0.04
0.02
0.00
g/cm3
0
200
400
600
800
1000
Time, ka

Fig. 42 Changes in chemical weathering indices with time.

(d)

Inner part
Inner part (average)
Brown layer
Brown layer (average)
White layer
WPI
20
15
10
5
0
-5
-10
-15
0
200
400
600
800
1000
Time, ka

(e)

Inner part
Inner part (average)
Brown layer
Brown layer (average)
White layer
PI
80
70
60
50
0
200
400
600
800
1000
Time, ka

Fig. 43 Relationships between time and pore volumes (V_α, V_β, V_γ, V_δ and V_t), $(V_\alpha+V_\beta)/V_t$ and $(V_\gamma+V_\delta)/V_t$.

(e)

Inner part
Inner part (Average)
White layer
Brown layer
Brown layer (Average)
V_t, mm^3/g
800
600
400
200
0
0
200
400
600
800
1000
Time, ka

(f)

Inner part
Inner part (Average)
White layer
Brown layer
Brown layer (Average)
$(V_\alpha+V_\beta)/V_t$
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
Time, ka

(g)

Inner part
Inner part (Average)
White layer
Brown layer
Brown layer (Average)
$(V_\gamma+V_\delta)/V_t$
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
Time, ka

Fig. 44 Changes in bulk density and porosity with time.

Fig. 45 Changes in VHN values with time.

Fig. 46 Changes in chemical, physical and mechanical properties with time.

Fig. 47 Differences in pore development between porous rhyolite and andesite.

Fig. 48 Variations of rock properties with depth (a: sample 20-B2, b: sample 20-B6, c: sample 450-B1, d: sample 450-B64).

Brown layer
Inner part
(b)
20-B6
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
Major Elements
(wt. %)
K2O
TiO2
MnO
P2O5
Trace Elements
(ppm)
Sr
V
Co
Cu
Zr
Zn
L*
a*
b*
VHN, gf/μm²
Depth from Rock Surface, mm

(c)
450-B1
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
(wt. %)
20
10
0
Major Elements
3.0
(wt. %)
2.0
1.0
0.0
K2O
TiO2
MnO
P2O5
500
(ppm)
400
300
200
100
0
Trace Elements
Sr
V
Co
Cu
Zr
Zn
60
50
40
30
L*
6
2
-2
a*
20
10
0
-10
b*
600
300
0
VHN, gf/μm2
0
5
10
15
Depth from Rock Surface, mm

(d)
Brown layer
White layer
Inner part
450-B64
Al2O3
FeO+Fe2O3
MgO
CaO
Na2O
Major Elements
20 (wt. %)
10
0
K2O
TiO2
MnO
P2O5
2.0 (wt.%)
1.0
0.0
Sr
V
Co
Cu
Zr
Zn
Trace Elements
300 (ppm)
200
100
0
L*
70
50
30
a*
6
3
0
-3
b*
30
10
-10
VHN, gf/μm²
600
300
0
0
5
10
15
20
Depth from Rock Surface, mm

○ : exist × : null - : almost null

apparent thickness of weathered zone

actual thickness of weathered zone

(1) In the case of enough large or slightly weatherd gravel

Fig. 49 Summary of rock properties and weathered zones.

1. Alkali/alkali earth metals are dissolved due to inward water flux.

2. Dissolved metals move out of the rock due to outward water flux, which makes dissolution zone whose thickness corresponds to that of Zone A+B.

3. Fe^{3+} precipitation, formed by Fe^{3+} oxidization, accumulates within outermost zone with brownish colour. The oxidation zone corresponds to Zone A.

Fig. 50 Mechanism of the development of oxidation zone (Zone A) and dissolution zone (Zone A+B)

Fig. 51 Definitions of the thickness of Zones A and B (a: dense rock, b: porous rock).

Fig. 52 Relationships between weathering time and thickness of Zones A and A+B.

Fig. 53 Relationships between L and $t^{1/2}$ (a: L_A, b: L_{A+B}).

Fig. 54 Relationships between L and $(n \cdot t)^{1/2}$ (a: L_A, b: L_{A+B}).

Fig. 55 A model for the development of oxidation zone (Zone A) and dissolution zones (Zone A+B) with the different porosity.