## 溶岩流シミュレーションコードに見られる粘性率等のパラメータの設定について

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ねらい:

- 徳永卒論で単純モデルで異常な高速　⇒　シミュレーションでどのように処理されているか？
- 粘性率測定実験は溶岩流シミュレーションに役立つか？全体の中で位置づける。

## 溶岩流シミュレーション研究

| Author | year | Name | basic equation | energy equation | Cell Dimension | viscosity | yield strength |
|---|---|---|---|---|---|---|---|
| Ishihara et al | 1990 | – | NS equation, no inertia moment | radiation | 2D (3D) | Linear T dependence | Linear T dependence |
| Young & Wadge | 1990 | FLOWFRONT | | | | | |
| Miyamoto & Sasaki | 1997 | – | NS equation, no inertia moment | radiation | 2D (3D) | f(T) | F(T) |
| Harris & Rowland | 2001 | FLOWGO | NS equation for channel flow | radiation, conduction, convection, rain crystallization, visc.heating, | 1D | f(T, ϕ) | F(T, ϕ) |
| Crisci et al. | 2004 | SCIARA-hex1 | | | hexagonal | | |
| Hidaka et al. | 2005 | LavaSIM | NS equation | radiation, conduction, convection | 3D | WLF f(T,(c)) | constant? |
| Costa & Macedonio | 2005 | (SWE) | NS equation | radiation, conduction, convection, vis heating | 2D (3D) | f(T) | ? |

## Ishihara, Iguchi, Kamo(1990)

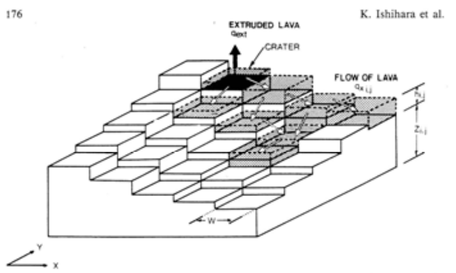



*Fig. 1.* Schematic illustration of numerical simulation of lava flows on a digital topography

$Q=S_y h_c^2(a^3-1.5*a^2+0.5)$　$(h>h_c)$　但し、$a=h/h_c$

$Q=0$　$(h<h_c)$　$h_c=S_y/(\rho g\sin(A))$

## Miyamoto & Sasaki 1997

$$\eta\frac{\partial^2 u}{\partial z^2} = -\frac{\partial h}{\partial x}\rho g\cos\alpha + \rho g\sin\alpha.$$

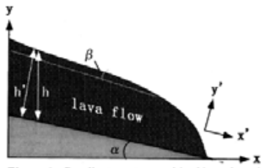


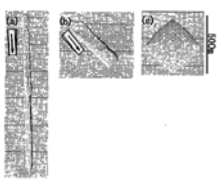

**Figure 3.** Coordinate system used in this study; α is the inclination of the slope and β is the angle due to the difference of thickness of lava.

Navier-Stokesの式

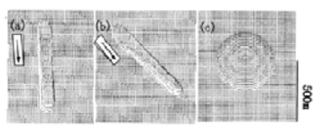
$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{f}$$

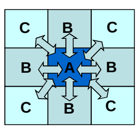
## 直交座標セル･オートマトンの座標依存性
Miyamoto & Sasaki (1997)

Ishihara et al.(1990)



Miyamoto& Sasaki(1997)

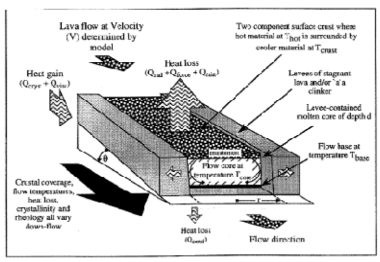





A⇒B　10

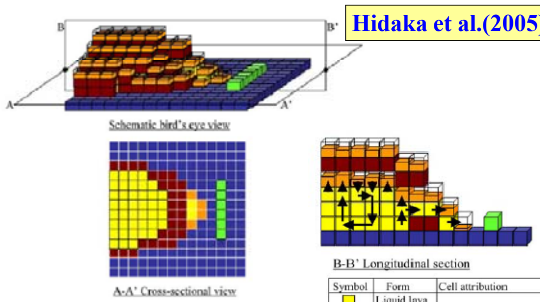
A⇒C　3

## Harris and Rowland(2001)




$$V = (r^2\rho_{lava}g\sin\theta/8\eta)[1-(4/3)(YS_{core}/YS_{base}) + (1/3)(YS_{core}/YS_{base})^4]$$

## Hidaka et al.(2005)




| Symbol | Form | Cell attribution |
|---|---|---|
| (yellow) | Liquid lava | Convection cell |
| (dark red) | Crust | |
| (orange) | Liquid lava or crust | Free surface cell |
| (blue) | Ground | |
| (green) | Structure (Protection bank, etc.) | |

## Hidaka, Goto, Umino, Fujita (2005)

**質量保存式**

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \qquad (5)$$

**運動方程式**

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z} =\frac{1}{\rho}\left[-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)\right] - g\sin^2\theta\cos^2\phi\frac{\partial H}{\partial x}, \qquad (6)$$

**エネルギー保存式**

$$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}+w\frac{\partial h}{\partial z} =\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)\right]+Q, \qquad (9)$$

## エネルギー保存則の処理

Harris and Rowland

Lava flow at Velocity (V) determined by

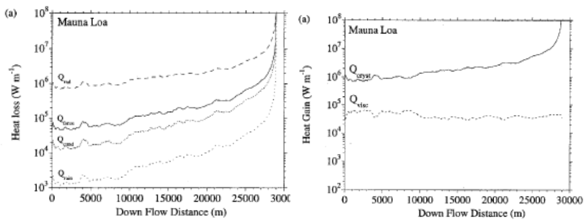
Two component surface crust where hot material at $T_h$ ... is surrounded by

| Term | Definition | Derivation of flux in W m$^{-1}$ |
|---|---|---|
| $Q_{rad}$ | Radiative heat loss | $Q_{rad}=\sigma\varepsilon[f_{crust}T_{crust}^4+(1-f_{crust})T_{hot}^4]w$ |
| $Q_{force}$ | Forced convection | $Q_{force}=UC_H\Delta T_{surf}\rho_{air}cp_{air}w$ |
| $Q_{free}$ | Free convection | $Q_{free}=0.14\alpha_{air}(g\kappa_{air}\rho_{air}\eta_{air}\beta_{air})^{1/3}(T_e-T_{air})^{4/3}w$ |
| $Q_{rain}$ | Heat loss by rain vaporization | $Q_{rain}=\delta R/\delta t\rho_{H2O}L_{H2O}w$ |
| $Q_{cond}$ | Conductive heat loss | $Q_{cond}=\alpha_{lava}(\Delta T_{base}/H_b)w$ |
| $Q_{cryst}$ | Heat from crystallization | $Q_{cryst}=\delta T/\delta x E_r\rho_{lava}L_{cryst}\delta\phi_{micro}/\delta T$ |
| $Q_{visc}$ | Heat from viscous dissipation | For semi-circular channel<br>$Q_{visc}=\eta(V/w)^2d$<br>Where w>d<br>$Q_{visc}=\eta(V/d)^2w$ |

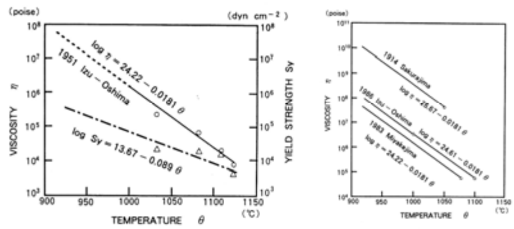
$(Q_{cond})$ Flow direction

$$\Delta H = -Q_{cond}-Q_{rad}-Q_{force}-Q_{rain}+Q_{cryst}+Q_{visc} \qquad (7a)$$

## 熱の収支(Harris & Rowland)




## 粘性率： Ishihara et al. (1990)




## 粘性率
Hidaka et al.(2005)

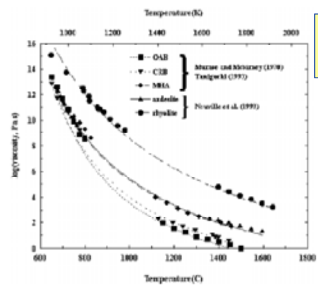



Figure 12. Evaluated viscosity of magmatic silicate melts. Viscosity is the most variable among the four physical properties. It changes by several orders of magnitude against composition at the same temperature, and ten or more orders of magnitude against temperature for the same composition.

$$\log\mu = \log\mu_{Tg} - \frac{A(T-T_g)}{B+T-T_g},$$

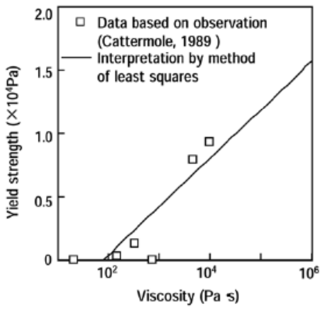
$\log\mu_{Tg} = 13.0,$

$A = 17.5,$

$B = 64S^2 - 202S + 446,$

$T_g = 57S^2 - 306S + 1341,$

## Hidaka et al.(2005)




必ずしもこの関係
をそのまま使用せず
両者の関係はバラつく
のでYsは一定とする、
と記述されている。

## Harris & Rowland(2001)

$$\eta = \{[1-R\phi_{total}]^{-2.5}\}\{\eta_{erupt}\exp[a(T_{erupt}-T_{core})]\}$$

$$YS_{core} = \{6500\phi_{total}^{2.85}\} + b\{\exp[c(T_{erupt}-T_{core})-1]\}$$

and

$$YS_{base} = \{6500\phi_{base}^{2.85}\} + b\{\exp[c(T_{erupt}-T_{base})-1]\},$$

$$\delta\phi_{micro}/\delta x = (\delta T/\delta x)(\delta\phi_{micro}/\delta T)$$

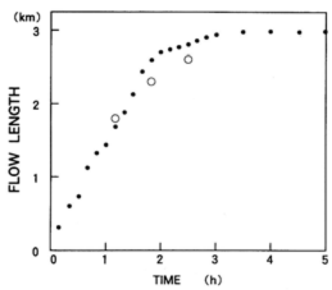
## 比較表(その2)

| Author | year | Example | Initial temperature | starting $\eta$ (Pa s) | crysta-llinity | Yield strength (Pa) | character |
|---|---|---|---|---|---|---|---|
| Ishihara et al | 1990 | Miyakejima Oshima | 1000 1100 | $3*10^5$ $5*10^3$ | – | $10^3$–$10^4$ f(T) | orthodox |
| Young & Wadge | 1990 | | | | | | |
| Miyamoto & Sasaki | 1997 | Miyakejima | 1047 | 850 | – | 225 | diagonal cell flux, thickness variation |
| Harris & Rowland | 2001 | Mauna Loa Puu Oo Etna | 1140 | 1000 | 0–0.4 | $10^2$–$10^4$ f($\phi$,T) | full for channeled lava flow |
| Crisci et al. | 2004 | Etna | 1100 | | | | |
| Hidaka et al. | 2005 | Oshima | 1051 | 5000, $1.5*10^5$ | – | | full 3D, lava tunnel, crust etc |
| Costa & Macedonio | 2005 | Etna | 1080 | 1000 | – | ? | |

## Ishihara et al.(1990)の例

| | 1983 Miyakejima | 1986 IzuOshima LC1 | 1986 IzuOshima LBI | 1986 IzuOshima LBIII | 1914 Sakurajima W |
|---|---|---|---|---|---|
| Cell size | 25×25m | 10×10m | 25×25m | 25×25m | 50×50m |
| $Q_0$ | 537m³ | 44m³ | 212—478 $m^3s^{-1}$ | 231-521 $m^3s^{-1}$ | 2380-84 $m^3s^{-1}$ |
| Duration | 1.5 hr | 1 hr | 5 hr | 5 hr | 100 hr |
| Temp. | 1078℃ | 1100℃ | 1000℃ | 1000℃ | 970-1050℃ |
| Viscosity | $5\times10^3$ Pas | $5\times10^3$ | $3\times10^5$ | $3\times10^5$ | $10^8$—$10^{10}$ $3\times10^6$ |

## Ishihara et al.(1990)




Hidaka et al. (2005)

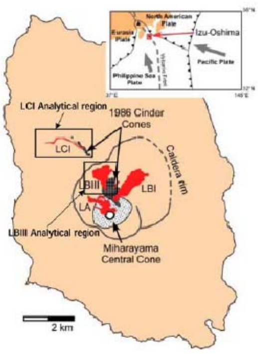
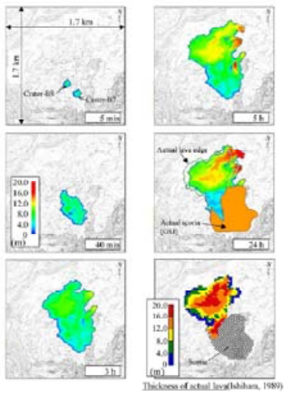



**Figure 13.** Location and tectonic setting of Izu-Oshima. Izu-Oshima is a Quaternary volcano situated on the northern end of the volcanic front of the Izu-Bonin arc, 100 km southwest of Tokyo, Japan. Fountain-fed lava (LB-I and LB-III) flowed onto the caldera floor 1.1 km to the north and 1.7 km to the northeast, while lava (LCI) flowed down 1.7 km along a valley and reached within 600 m of downtown Motomachi.




Hidaka et al. (2005)

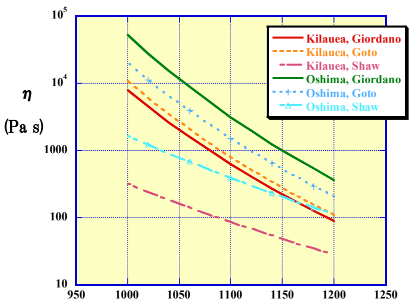
**Figure 17.** Calculated distribution of lava thickness with actual data [*Ishihara et al.*, 1989]. The underestimation in the NW area and the overestimation in the NE area were visible from the thickness distribution; however, the calculated distribution of lava thickness agreed with actual data qualitatively.

Hidaka et al. (2005)

**Table 6.** Conditions for Test Calculation

| Parameters | Conditions |
|---|---|
| Analysis region ($X$, $Y$, $Z$) | 2.6 km × 1.6 km × 16 m |
| Mesh partitioning ($X$, $Y$, $Z$) | 260 × 160 × 16 |
| Cell size ($X$, $Y$, $Z$) | 10 m × 10 m × 1 m |
| Extrusion rate at each crater (Period) | $1.1 \times 10^5$ kg/s (0–3600 s)<br>0 kg/s (3600 s-) |
| Lava specific enthalpy (C6) | $1.9647 \times 10^6$ J/kg |
| Extrusion temperature | 1050.3°C (1323.3 K) |
| Solidification fraction of liquidity loss | 0.5 |
| Latent heat of fusion $h_{sl}$ | $1.256 \times 10^6$ J/kg |
| Solidus temperature | 1000°C (1273 K) |
| Liquidus temperature | 1100°C (1373 K) |
| Lava emissivity ε | 0.66 |
| Lava composition | |
| ($SiO_2$) | 54.48% |
| ($Al_2O_3$) | 14.57% |
| ($FeO$) | 14.10% |
| ($CaO$) | 9.02% |
| ($MgO$) | 4.07% |
| ($Na_2O$) | 2.05% |
| ($TiO_2$) | 1.24% |
| ($K_2O$) | 0.47% |
| Atmospheric temperature | 17°C (290 K) |
| Ground temperature | 27°C (300 K) |

## 粘性係数計算の比較



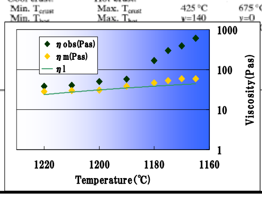

## Harris & Rowland(2001)

| Term | Definition | Value or source |
|---|---|---|
| a | Constant given by Dragoni (1989) | 0.04 $K^{-1}$ |
| $\alpha_{air}$ | Thermal conductivity of air | Kays and Crawford (1980) |
| $\alpha_{lava}$ | Thermal conductivity of basalt[c] | Calculated following Peck (1978, p 41; W $m^{-1}$ $K^{-1}$) |
| b | Constant given by Dragoni (1989) | $10^{-2}$ Pa |
| $\beta_{air}$ | Thermal diffusivity of air | Kays and Crawford (1980) |
| c | Constant given by Dragoni (1989) | 0.08 $K^{-1}$ |
| $C_H$ | $=(U^*/U)^2$ where $U^*$ is friction wind speed[a] | 0.0036[b] |
| $cp_{air}$ | Specific heat capacity of air | 1099 J $kg^{-1}$ $K^{-1}$ |
| $cp_{lava}$ | Specific heat capacity of basalt[c] | 1225 J $kg^{-1}$ $K^{-1}$ |
| $\varepsilon$ | Emissivity of basalt | 0.95 |
| g | Acceleration due to gravity | 9.8 m $s^{-2}$ |
| $\eta_{air}$ | Viscosity of air | Kays and Crawford (1980) |
| $\eta_{erupt}$ | Lava viscosity at eruption temperature | 1000 Pa s[d] |
| $\kappa_{air}$ | Cubic expansivity of air | Kays and Crawford (1980) |
| $L_{cryst}$ | Latent heat of crystallization | $3.5\pm0.7\times10^5$ J $kg^{-1}$ |
| $L_{H2O}$ | Latent heat of vaporization plus heat needed to raise water temperature to 100°C | $2.8\times10^6$ J $kg^{-1}$ |
| $\rho_{air}$ | Density of air | 0.4412 kg $m^{-3}$ |
| $\rho_{H2O}$ | Density of water at 100°C | 958 kg $m^{-3}$ |
| $\rho_{lava}$ | Density of basalt[c] | 2600 kg $m^{-3}$ |
| $\sigma$ | Stefan-Boltzmann constant | $5.67\times10^{-8}$ W $m^{-2}$ $K^{-4}$ |

## Harris & Rowland(2001)

**Table 5** Summary of the hot and cool end-member models used to run FLOWGO, with input parameters used in our simulations of the Mauna Loa 1984, Pu'u 'Ō'ō 16 May 1997, and Etna 11–12 October 1998 flows

| Parameter | Model | | Mauna Loa[b] | | Pu'u 'O'o[c] | | Etna[d] | |
|---|---|---|---|---|---|---|---|---|
| | Cool | Hot | Cool | Hot | Cool | Hot | Cool | Hot |
| w | | | 5.5 m | 5.5 m | 5.0 m | 5.0 m | 5.0 m | 5.0 m |
| d | | | 5.5 m | 5.5 m | 3.0 m | 3.0 m | 1.25 m | 1.25 m |
| | Cool: | Hot: | | | | | | |
| $T_{air}$ | Min. $T_{air}$ | Max. $T_{air}$ | 10 °C | 30 °C | 10 °C | 30 °C | −10 °C | 0 °C |
| $T_{erupt}$ | Min. $T_{erupt}$ | Max. $T_{erupt}$ | 1137 °C | 1143 °C | 1150 °C | 1150 °C | 1080 °C | 1090 °C |
| $T_{solid}$ | Min. $T_{solid}$ | Max. $T_{solid}$ | 970 °C | 990 °C | 970 °C | 990 °C | 970 °C | 990 °C |
| | High crystallinity | Low crystallinity | | | | | | |
| $\phi_{phen}$[e] | Max. $\phi_{phen}$ | Min. $\phi_{phen}$ | 0.15 | 0.00 | 0.00 | 0.00 | 0.34 | 0.27 |
| $\phi_{post}$ | | | 0.45 | 0.45 | 0.45 | 0.45 | 0.41 | 0.41 |
| | Cool crust: | Hot crust: | | | | | | |
| $T_{crust}$ (av) | Min. $T_{crust}$ | Max. $T_{crust}$ | 425 °C | 675 °C | 425 °C | 675 °C | 425 °C | 675 °C |
| $T_{hot}$[a] | Min. $T_{hot}$ | Max. $T_{hot}$ | y=140 | y=0 | y=140 | y=0 | y=140 | y=0 |
| $T_{base}$ | [illegible] | [illegible] | [illegible] | [illegible] | 500 °C | 900 °C | 500 °C | 900 °C |
| $H_b$ | [illegible] | [illegible] | [illegible] | [illegible] | 19% | 1% | 19% | 1% |
| Ves | [illegible] | [illegible] | [illegible] | [illegible] | 23% | 23% | 13% | 25% |




## まとめ

- 基礎方程式(質量・運動量・エネルギー保存)についてはほぼ共通。
- 熱の取り扱いもある程度固まっているが、表面の冷えたスラブの内部への取り込み・冷却の扱いを進める必要。冷却観測を参照。
- 粘性係数、降伏応力の評価は岩石学的な面からは不一致が見られる。脱ガス・過冷却からの結晶作用を考慮することが必要。