Supplement 5A: Review of Type I models

Table 5A.1. Review of Type I (thermo-rheologically based) models for terrestrial lava flows and the lava flow physical parameters addressed by each

Model (source reference)	Approach		Parameters considered and/or used by model					Flow type		
	Theo.	**Lab.**	**Heat sink**	**Heat source**	**Cooling**	**Rheology**	**Flow dynamics**	**Chnl.**	**Tube**	**Other/Notes**
Baloga (1987)	✓					η	X, h, w, u			Lava flow as kinematic wave
Baloga and Pieri (1986)	✓		q_{rad}			η	X, h, u, E_r, t			Time-dependent flow profile
Baloga *et al.* (1995)	✓					η	θ, h, w, u, E_r, Re	✓		High velocity flow
Baum *et al.* (1989)	✓					η	u			Rhyolite: folds and Taylor instability
Blake and Bruno (2000)		✓	q_{conv}, q_{rad}		✓	η	h, E_r, Pe			Compound flow emplacement
Borgia and Linneman (1990)	✓					η, τ_0	θ, X, h, E_r, t	✓		Channel fed flow field growth
Borgia *et al.* (1983)			heat, kinetic and potential energy			η, τ_0	X, u, ε	✓		Channel fed flow emplacement
Bruno *et al.* (1996)	✓					η	θ, X, h, u, E_r			Gravity-driven flow
Burkhard (2003)		✓	q_{cond}	L	✓					Pahoehoe lobe thermal interaction
Bussey *et al.* (1997)	✓		q_{cond}		✓			✓		Substrate heating and thermal erosion
Cashman *et al.* (1999)	✓		q_{rad}	L	✓	ϕ, η		✓		Lava cooling and crystallization. See also: Blake (2000)
Cashman *et al.* (2006)		✓			✓		w, u, Ra	✓	✓	Crust formation in channels
Cigolini *et al.* (1984)	✓					ϕ, η	θ, h, w, u	✓		Flow velocity profile
Crisp and Baloga (1990)	✓		q_{rad}	q_{adv}	✓		t	✓		Surface thermal structure and q_{rad}
Crisp and Baloga (1994)	✓		q_{rad}, q_{ent}	q_{adv}, L	✓	ϕ		✓		Thermal effects of entrainment and L
Daneš (1972)	✓		q_{rad}		✓	T, η	h, u, Re	✓		Flow cooling and velocity
Dragoni (1989)	✓		q_{rad}		✓	T, η, τ_0	$\theta, h, u, E_r, \varepsilon$	✓		T-dependent rheology and velocity
Dragoni and Tallarico (1994)	✓		q_{rad}			T, ϕ, η, τ_0	θ, h, u	✓		ϕ-dependent rheology and velocity
Dragoni and Tallarico (1996)	✓				✓		ε	✓		Flow front breakout
Dragoni and Tallarico (2008)	✓		q_{cond}		✓				✓	Tube temperature field / heat flow
Dragoni *et al.* (1986)	✓					η, τ_0	$\theta, h, w, u, E_r, \varepsilon$, Re	✓		Velocity profile for laminar flow
Dragoni *et al.* (1992)	✓		q_{rad}		✓	T, η, τ_0	u, ε	✓		Velocity profile for laminar flow
Dragoni *et al.* (1995)	✓		q_{cond}		✓	η, τ_0	$\theta, h, u, \varepsilon$	✓	✓	Roofing over of a channel
Dragoni *et al.* (2002)	✓				✓	η	θ, w, u		✓	Tube temperature field / heat flow
Dragoni *et al.* (2005)	✓					η, τ_0	θ, h, w, u, E_r			Flow front motion
Fagents and Greeley (2001)	✓		q_{cond}		✓		u, Pr		✓	Substrate heating and thermal erosion
Fink (1980)	✓					η	ε			Flow surface folding
Fink and Griffiths (1992)		✓	q_{conv}		✓		u, Pe			Flow surface morphology
Gregg and Fink (2000)		✓	q_{conv}	q_{adv}	✓	η	θ, u, E_r			Effect of θ on morphology
Gregg and Fornari (1998)	✓		q_{rad}, q_{conv}	L		ϕ, η	u			Submarine flow heat loss model

Gregg and Keszthelyi (2004)		✓				η	u, E_r, ε			Controls on pahoehoe emplacement
Gregg *et al.* (1998)		✓			✓	η	E_r, ε			Flow surface folding
Griffiths (2000)		✓	q_{rad}, q_{conv}		✓	T, ϕ, η, τ_0	$\theta, h, u, \varepsilon$, Re			Review of flow dynamics
Griffiths *et al.* (2003)		✓	q_{conv}		✓		θ, u, E_r, Ra, Pr	✓	✓	Crust solidification in channels
Harris *et al.* (1998)	✓		heat budget	q_{adv}, L	✓		E_r		✓	Tube-fed pahoehoe and ocean-entry
Harris *et al.* (2002)	✓		heat budget	q_{adv}, L	✓	η, τ_0	$\theta, h, w, u, E_r, \varepsilon$, Re			Silicic flow thermo-rheology model
Harris *et al.* (2005)	✓		heat budget	q_{adv}, L	✓	T, ϕ, η, τ_0	θ, h, w, u	✓		Channel flow thermo-rheology model
Heslop *et al.* (1989)	✓					η, τ_0	$\theta, h, w, u, E_r, \varepsilon$, Re	✓		Super-elevated flow
Hulme (1974)		✓				τ_0	u, E_r, ε			Rheology and surface morphology
Huppert *et al.* (1984)	✓		q_{cond}	q_{adv}, L	✓	η	E_r, Re, Pr	✓		Komatiite emplacement and cooling
Kerr (2001)		✓	q_{cond}				u, E_r, Re, Pe	✓		Substrate heating and thermal erosion
Kerr *et al.* (2006)		✓				τ_0	θ, w, u, E_r, Pe, Ra	✓	✓	Channel formation
Keszthelyi (1994)	✓		q_{rad}		✓		Ra			Effect of vesicles on cooling
Keszthelyi (1995)	✓		heat budget	q_{adv}, L	✓		E_r			Tube heat budget
Keszthelyi and Denlinger (1996)	✓		heat budget	q_{adv}, L	✓					Pahoehoe heat budget
Keszthelyi and Self (1998)	✓		heat budget	q_{adv}, L	✓	η	θ, h, u, Re	✓	✓	Flow heat budget / cooling rate
Klingelhöfer *et al.* (1999)	✓		heat budget		✓	ϕ, η	u			Submarine flow heat loss model
Lyman and Kerr (2006)		✓			✓	τ_0	$\theta, X, h, u, t_{stop}$			Flow emplacement on a slope
Lyman *et al.* (2005)		✓			✓	τ_0	X, h, t			Flow run out length
Manley (1992)	✓				✓	ϕ, η	u			Silicic flow thermo-rheology model
Moore (1987)	✓					τ_0, η	θ, h, w, u, E_r			Channel flow and rheological model
Miyamoto and Crown (2006)		✓				η	h, u			Pahoehoe “self-confinement”
Neri (1998)	✓		q_{rad}, q_{conv}							Convective heat transfer
Oppenheimer (1991)	✓		heat budget		✓			✓		Flow heat loss model
Park and Iversen (1984)	✓		q_{rad}		✓	τ_0, η	θ, h, u	✓		Dynamics of Bingham fluid
Patrick *et al.* (2004)	✓		heat budget	L	✓					Flow cooling in time
Patrick *et al.* (2005)	✓		heat budget	L	✓					Flow cooling in time
Pieri and Baloga (1986)	✓		q_{rad}	q_{adv}	✓		E_r, X			E_r and cooling controls on flow area
Pinkerton and Wilson (1994)	✓				✓	η, τ_0	θ, h, L, E_r, Gz			Flow length versus E_r
Quareni *et al.* (2004)	✓		q_{cond}		✓			✓		Levee temperature field / heat flow
Sakimoto and Gregg (2001)		✓				τ_0, η	θ, h, w, u, E_r	✓		Channelized flow dynamics
Sakimoto and Zuber (1998)	✓		heat budget		✓		u, E_r, Re, Pr, Pe		✓	Tube flow and convective cooling
Tallarico and Dragoni (1999)	✓					η, τ_0	$\theta, h, u, E_r, \varepsilon$	✓		Channelized laminar flow velocity
Tallarico *et al.* (2006)	✓					η, τ_0	θ, h, u, E_r	✓		E_r and μ for 2- and 3-D Bingham flow
Williams *et al.* (1998)	✓		q_{cond}		✓	ϕ, η	u, Re, Pr			Substrate heating and thermal erosion
Wilson *et al.* (2007)	✓					η, τ_0	u, E_r, Re	✓		Channelized flow conditions
Witter and Harris (2007)	✓		heat budget		✓		u, E_r		✓	Tube (skylight) heat budget

Woodcock and Harris (2006)	✓			η	h, w, u, E_r, Re	✓	Super-elevated flow
Wooster *et al.* (1997)	✓	heat budget	✓				Flow heat loss model
Wright *et al.* (2000)	✓	heat budget	✓				Flow heat loss model
Zhu *et al.* (2002)	✓			η	θ, E_r		Submarine lava terraces

Table 5A.2. Parameters and symbols used in Table 5A.1.

Parameter	**Definition**	**Units**
h	flow depth	M
E_r	effusion rate	$m^3\ s^{-1}$
L	latent heat of crystallization	$J\ kg^{-1}$
q_{adv}	advected heat flux	$W\ m^{-2}$
q_{cond}	conductive heat loss	$W\ m^{-2}$
q_{conv}	convective heat loss	$W\ m^{-2}$
q_{ent}	heat loss due to entrainment	$W\ m^{-2}$
q_{rad}	radiative heat loss	$W\ m^{-2}$
t	emplacement time	s
t_{stop}	flow stopping time	s
T	flow core temperature	K
u	velocity	$m\ s^{-1}$
w	channel width	m
X	flow length	m
$\dot{\varepsilon}$	strain rate	s^{-1}
ϕ	crystallinity	% (or volume fraction)
η	viscosity	Pa s
θ	slope	degrees
τ_0	yield strength	Pa

Table 5A.3. Summary of dimensionless numbers parameters used in modeling and their constitutive parameters.

Parameter	Definition	Derivation / Units
Gr	Grashof number: ratio of buoyancy to viscosity	$\mathrm{Gr} = g\beta(T_1 - T_0)\, L^{*3}/\upsilon^2$
Gz	Grätz number: balance between mass diffusivity and thermal diffusivity	$\mathrm{Gz} = ud_e^{\,2}/\kappa L^*$
Pe	Peclet number: ratio of energy transport by convection to that by conduction	$\mathrm{Pe} = \mathrm{Re}\ \mathrm{Pr}$ $\mathrm{Pe} = uL^*/\kappa$
Pr	Prandtl number: ratio of momentum diffusivity and to thermal diffusivity	$\mathrm{Pr} = \upsilon/\kappa$
Ra	Rayleigh number: describes the relationship between buoyancy forces and thermal and momentum diffusivities. Below a critical Ra heat transfer is conduction dominated, above the critical Ra heat transfer is convection dominated	$\mathrm{Ra} = \mathrm{Gr}\ \mathrm{Pr}$ $\mathrm{Ra} = (g\beta/\kappa\upsilon)\,(T_1 - T_0)$
Re	Reynolds number: ratio of inertial forces to viscous forces. Below a critical Re flow is laminar, above the critical Re flow is turbulent	$\mathrm{Re} = uL^*/\upsilon$
c_p	specific heat capacity	J kg^{-1} K^{-1}
$d_e = 2wd/(w+d)$	flow equivalent diameter	m
g	acceleration due to gravity	m^2 s^{-1}
k	thermal conductivity	W m^{-1} K^{-1}
L^*	characteristic length scale	m
T_1	hot fluid temperature	K
T_0	cold reference temperature (surrounding cool medium)	K
u	velocity	m s^{-1}
w	flow width	m
β	thermal expansion coefficient	K^{-1}
$\kappa\ \ (= k/\rho\, c_p)$	thermal diffusivity	m^2 s^{-1}
η	viscosity	Pa s
ρ	density	kg m^{-3}
$\upsilon\ (= \eta/\rho)$	kinematic viscosity	m^2 s^{-1}

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