 SlugSed, A One-Dimensional Numerical Model of Fluid and Heat Transport

Technical Reference and Cookbook

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1. Overview

SlugSed is a one-dimensional numerical model of fluid and heat transport coded in Matlab. In its most basic form, the model calculates the temperature distribution within a medium of finite thickness and known thermal conductivity and heat capacity given appropriate initial and boundary conditions. The initial conditions consist of depth, temperature, rate(s) of radiogenic heat production or loss, and thermal conductivity for discrete points within the medium. The boundary conditions must be specified as temperature at the top of the medium and either temperature or heat flux at the bottom, and both can be time-variant. SlugSed can accommodate multiple distinct basement layers, each having independent property sets. In the case of sedimentation, the depth-variant physical and thermal properties within the accumulating sediment layer are derived from a user-specified porosity versus depth function. The thermal properties of basement layers (when in use) can be specified in bulk (i.e., applied to all points within the layer) or individually. Seepage of fluids within the sediment layer can be driven by compaction and consolidation, fluid overpressures in basement, or imposed directly.

2. The Physical Model

The transient thermal effects of sedimentation and seepage on the thermal structure of an idealized section of ocean crust having uniform basal heat flow are shown schematically in figure 1. In the absence of fluid seepage, steady-state conductive heat transport through a sedimented ridge flank generally results in a thermal gradient (T vs. z) that decreases with depth, because deeper sediments usually have lower porosity and higher thermal conductivity than shallower sediments. The thermal conductivity of upper
oceanic basement also tends to increase with depth, but the variations are often associated with abrupt lithologic transitions, for example from extrusive basalt pillows to more massive flows or sills [e.g., Bartetzko et al., 2001; Busch et al., 1992; Karato, 1983]. Within a purely conductive system, the thermal gradient through sediments is usually greater than that within basement because sediment thermal conductivity tends to be lower than that within uppermost basaltic crust (Fig. 1). Rapid sedimentation results in the heat flux through sediments and upper basement being suppressed relative to steady-state for an equivalent sediment thickness, with the magnitude and depth extent of suppression depending on the sedimentation history (magnitude, duration), and the thermal and physical properties of sediment and basement. Upward fluid seepage through sediments causes the thermal gradient to be elevated in the shallow subsurface (Fig. 1).

Analytical studies of sedimentation and heat transport are often based on a semi-infinite half-space with constant heat flux at depth and a moving upper boundary that represents accumulating sediment [e.g., Benfield, 1949; Von Herzen and Uyeda, 1963]. Hutchison [1985] and Wang and Davis [1992] developed numerical models using a thick (but finite) plate, most of which comprised crustal basement, that "fell away" from the upper boundary, allowing for the deposition of sediments. The sediments consolidated after deposition and burial according to a series of property-depth relations. We extend the methods developed for these earlier models with the approach and modifications described in the rest of this section.

The accumulating sediment layer follows a porosity-depth function, $\phi(z)$, with bulk sediment thermal conductivity ($\lambda$) and permeability ($k$) depending on porosity. This approach is based on the assumption that sediment porosity decreases with depth only,
independent of sedimentation rate or total elapsed time, and that the compressibility of pore water and sediment grains is smaller by several orders of magnitude than bulk sediment compressibility.

The sediment section is underlain by a crustal aquifer through which heat transfer may be dominated by advection, and by basement layers through which heat is transferred purely by conduction (Fig. 2A). The use of multiple conductive basement layers allows representation of distinct lithologic regions (having different thermal properties), whereas having a separate basement aquifer allows representation of several aspects of heat transport accompanying hydrothermal circulation in upper basement. Hydrothermal circulation can extract significant quantities of lithospheric heat on a regional basis through (dominantly) rapid lateral fluid transport in the upper crust [e.g., Davis et al., 1992; Fisher and Becker, 2000; Langseth et al., 1984]. This process can be simulated by distributing heat sinks within the basement aquifer, where the collective magnitude of the heat sinks removes a desired fraction of lithospheric heat before it can reach the thickening (overlying) sediment layer.

In addition, vigorous convection can homogenize basement temperatures on a local basis. This processes can be represented using a high Nusselt number (Nu) approximation [e.g., Davis et al., 1997; Spinelli and Fisher, 2004], whereby the effective thermal conductivity of the basement aquifer is increased. Within a two- or three-dimensional crustal system, high-Nu convection can elevate the seafloor heat flux above buried basement highs, and lower the heat flux above buried basement lows. Within this one-dimensional model, only the increase in vertical heat transport associated with vigorous, local convection is simulated. Regional heat extraction and local heat
redistribution can occur simultaneously on ridge flanks within a "well-mixed" aquifer [e.g., Davis et al., 1999; Langseth and Herman, 1981; Rosenberg et al., 2000; Stein and Fisher, 2001], and both processes can be represented independently with SlugSed.

3. The Numerical Model

The numerical model employs a deforming finite-difference grid to model heat transport within a lithospheric plate upon which sediment is added, using mixed Eulerian and Lagrangian reference frames for the sediment and basement sections, respectively (Fig. 2B). As with other one-dimensional sedimentation models using a deforming mesh to simulate heat transport [e.g., Hutchison, 1985; Lucazeau and Le Douaran, 1985; Wang and Davis, 1992], we first determine the kinematics of the mass movement and then solve the heat transfer problem.

The model domain evolves with time through the creation of space at the sediment-basement interface, with depths referenced to the seafloor \((z = 0)\). Time-dependent sedimentation causes the sediment-basement interface \((z = B)\) to move downward, and the grid near this interface is deformed and extended through the addition of nodes according to a series of user-specified rules.

Conservation of mass allows sediment and fluid velocities to be uniquely determined from the porosity-depth profile. For a pair of adjacent nodes at depths \(z_1\) and \(z_2\) [Wang and Davis, 1992]:

\[
\begin{align*}
 v_s(z_1,t)(1 - \phi(z_1)) &= v_s(z_2,t)(1 - \phi(z_2)) \\
 v_w(z_1,t)\phi(z_1) &= v_w(z_2,t)\phi(z_2)
\end{align*}
\]

(1)

where \(\phi\) is porosity, \(v\) is velocity, and the subscripts \(w\) and \(s\) denote the water and sediment phases, respectively. Sediment and fluid velocities associated with deposition...
and compaction vary spatially and temporally based on user-specified rates of sediment accumulation and/or deposition (Fig. 3). When the user specifies a rate of sediment accumulation, the velocity of basement is known: \[ v_b = v_s(B_t) = v_w(B_t) \], leading to direct calculation of basement depth with time \[ \frac{dB}{dt} = v_b \]. Because of compaction, the velocity of sediment grains entering the model domain \[ v_o = v_s(0_t) \] must increase with time in order to keep the domain filled with sediment. In the case of a specified deposition rate, the velocity of sediment entering the model domain is known and \( B \) is determined by boot-strapping along the porosity-depth profile. In this situation, \( v_b \) decreases as sediment thickness increases.

Sediment porosity decreases with depth using a flexible analytical representation, including (if desired) constant, linear, polynomial, exponential, and logarithmic terms. Bulk thermal conductivity \( (\lambda_b) \) is determined using a geometric mean mixing model, \( \lambda_b = \lambda_w \phi \lambda_s^{1-\phi} \), where the subscripts \( w \) and \( s \) denote water and sediment phases, respectively. Sediment permeability \( (k) \) is calculated using an empirical analytical relation for the particular lithology of interest, once again including (if desired) constant, linear, polynomial, exponential, and logarithmic terms [e.g., Spinelli et al., 2004].

Heat transfer is modeled using a standard conduction-advection equation:

\[
\frac{\rho c}{\partial t} = \frac{\partial}{\partial z} \lambda_b \frac{\partial T}{\partial z} - \rho c v \frac{\partial T}{\partial z} + Q
\]  

(2)

where \( \rho c \) is the specific heat capacity (density times specific heat), \( v \) is velocity, \( T \) is temperature, \( t \) is time, \( z \) is depth, and \( Q \) is heat production or loss rate. The bar above selected parameters denotes average properties for the fluid-grain mixture. We extend
this standard equation to include a separate fluid seepage term (independent of compaction) by specifying:

\[
\bar{\rho}c = \rho c_w \phi + \rho c_s (1 - \phi), \\
\bar{\rho}cv = \rho c_w v_w \phi + \rho c_w v_{seep} + \rho c_s v_s (1 - \phi)
\] (3)

It is implicit in this formulation that fluid seepage does not alter the porosity-depth profile. This representation of fluid seepage includes no local fluid storage within the sediment column, and permits time-varying fluid seepage set at arbitrary (user specified) rates or based on excess fluid pressure in basement.

When vertical fluid seepage is driven by an overpressure (\(\Delta P\), pressure in excess of hydrostatic), the model first determines the hydraulic impedance, \(I\), of the existing sediment column [Karato and Becker, 1983]:

\[
I = \int_0^{z_B} \frac{dz}{k(z)}
\] (4)

The seepage flux, \(q\), is calculated according to Darcy’s Law:

\[
q = -\frac{k_{eff}}{\mu} \frac{\Delta P}{B}
\] (5)

where \(k_{eff} = B/I\) and \(\mu\) is dynamic fluid viscosity. Although \(\mu\) and \(\rho\) vary slightly with the range of temperatures typically encountered on ridge flanks, changes in \(\rho\) are generally negligible and SlugSed uses the minimum temperature within the sediment column to calculate the maximum value \(\mu\), minimizing the rate of pressure-driven seepage (as will occur in the natural system).

Using the standard heat conduction-advection equation (2), we perform the following discretization where the superscripts \(k\) and \(k+1\) denote the current and next
time, respectively, and the subscripts refer to the node positions: We use a positive-down reference frame, such that node $i-1$ is above node $i$, and node $i+1$ is below node $i$ (Fig. 2).

\[
\frac{\rho c}{\Delta t} (T_{i+1}^k - T_i^k) = \frac{\lambda_{i+1} (T_{i+1}^k - T_i^k) - \lambda_i (T_i^k - T_{i-1}^k)}{\Delta z_{i+1} + \Delta z_i} - \frac{\rho cv (T_{i+1}^k - T_{i-1}^k) + Q_i}{2}
\]  

(6)

The time step length is $\Delta t$, and the differential thickness between nodes is $\Delta z$. By expanding terms, grouping, and including an implicitness weighting-factor $\theta$, we arrive at this mixed implicit/explicit formulation:

\[
T_{i+1}^{k+1} - T_i^k = \left( \frac{2}{\Delta z_{i+1} + \Delta z_i} \right) \frac{\Delta t}{\rho c} \theta \left[ T_{i+1}^k (\frac{\lambda_{i+1}}{\Delta z_{i+1}}) + T_i^k (\frac{-\lambda_{i+1}}{\Delta z_{i+1}}) + T_{i+1}^{k+1} (\frac{\lambda_i}{\Delta z_i}) + T_i^{k+1} (\frac{-\lambda_i}{\Delta z_i}) + T_{i+1}^{k+1} (\frac{-\rho cv}{2}) + T_i^{k+1} (\frac{-\rho cv}{2}) \right]
\]

\[
+ \left( \frac{2}{\Delta z_{i+1} + \Delta z_i} \right) \frac{\Delta t}{\rho c} (1 - \theta) \left[ T_{i+1}^k (\frac{\lambda_{i+1}}{\Delta z_{i+1}}) + T_i^k (\frac{-\lambda_{i+1}}{\Delta z_{i+1}}) + T_{i+1}^k (\frac{-\lambda_i}{\Delta z_i}) + T_i^k (\frac{\lambda_i}{\Delta z_i}) + T_{i+1}^k (\frac{-\rho cv}{2}) + T_i^k (\frac{-\rho cv}{2}) \right]
\]

(7)

Rearranging with terms for the current time on the left-hand side, and terms for the next time on the right-hand side yields:

\[
T_{i+1}^{k+1} - \left( \frac{2}{\Delta z_{i+1} + \Delta z_i} \right) \frac{\Delta t}{\rho c} \theta \left[ T_{i+1}^k (\frac{\lambda_{i+1}}{\Delta z_{i+1}}) + T_i^k (\frac{-\lambda_{i+1}}{\Delta z_{i+1}}) + T_{i+1}^{k+1} (\frac{\lambda_i}{\Delta z_i}) + T_i^{k+1} (\frac{-\lambda_i}{\Delta z_i}) + T_{i+1}^{k+1} (\frac{-\rho cv}{2}) + T_i^{k+1} (\frac{-\rho cv}{2}) \right]
\]

\[
= T_i^k + \left( \frac{2}{\Delta z_{i+1} + \Delta z_i} \right) \frac{\Delta t}{\rho c} (1 - \theta) \left[ T_{i+1}^k (\frac{\lambda_{i+1}}{\Delta z_{i+1}}) + T_i^k (\frac{-\lambda_{i+1}}{\Delta z_{i+1}}) + T_{i+1}^k (\frac{-\lambda_i}{\Delta z_i}) + T_i^k (\frac{\lambda_i}{\Delta z_i}) + T_{i+1}^k (\frac{-\rho cv}{2}) + T_i^k (\frac{-\rho cv}{2}) \right]
\]

(8)

Assigning $\theta = 0$ will result in the fully explicit formulation, whereas a value of 1 will yield the fully implicit scheme. A value of 0.5 yields the Crank-Nicholson scheme. By assigning the following constants:
\[ a = \left( \frac{2}{\Delta z_{i+1} + \Delta z_i} \right) \left( \frac{\Delta t}{\rho c} \right) \]
\[ b = \frac{\lambda_{i+1}}{\Delta z_{i+1}} \]
\[ c = \frac{\rho cv}{2} \]
\[ d = \frac{\lambda_i}{\Delta z_i} \]
\[ e = (-a)\theta(b - c) \]
\[ f = 1 - (a)\theta(-b - d) \]
\[ g = (-a)\theta(d + c) \]
\[ h = (a)(1 - \theta)(b - c) \]
\[ m = 1 + (a)(1 - \theta)(-b - d) \]
\[ n = (a)(1 - \theta)(d + c) \]

we arrive at the following linear equation
\[ T_{i-1}^{k+1} g + T_i^{k+1} f + T_{i+1}^{k+1} e = T_i^k h + T_{i+1}^k m + T_{i+1}^k h + aQ_i \] (9)

SlugSed puts the linear system into matrix form \( Ax = b \), where the matrix \( A \) contains the coefficients \((g,f,e,n,m,h,a)\), vector \( x \) holds the unknown temperatures at time \( k+1 \), and vector \( b \) contains the knowns (i.e., temperatures at time \( k \) as well as boundary values at time \( k+1 \)).

4. Boundary Conditions

There are several complexities with the use of a constant heat flux lower boundary condition, which we now address. Because the basic heat conduction-advection equation is of second order, we establish a temperature gradient across the lowermost node that gives the prescribed heat flux. To accomplish this, SlugSed employs a phantom node below the lower boundary spaced equidistant from the deepest
node above the boundary. If the model simulation does not incorporate a basement layer, the thermal conductivity of the phantom node is assigned the same value as the node at the boundary. If the model does contain basement, then the conductivity of basement is assigned. The thermal conductivities of the elements above and below the boundary are calculated as the harmonic mean of the conductivities of the three enclosing nodes, and the thermal conductivity of the entire block encompassing the boundary node is calculated as the harmonic mean of the enclosing blocks. Since the temperature of the node above the boundary is known, the temperature of the phantom node can be calculated based on the prescribed heat flux and conductivity of the material in between.

5. Data Storage and Output

SlugSed saves variables in the current workspace as a Mat file and also dumps data in text format to a Log file. The Log file is created at the beginning of the simulation and contains a copy of the entire input deck, whereas the Mat file is created at the end of the first stress period and updated thereafter. Both of these processes occur by default, and the user can specify time increments for additional output.

Variables stored in the Mat file include timing information, temperature, depth, heat flux, thermal conductivity, porosity, heat production or loss amount, execution time, fluid and grain velocities, and times when nodes were added or removed. These are described in more detail in the variables section.

Considerably more data output is directed to the text Log file, including detailed information from most of the individual function calls and any warning messages generated during code execution. Data is appended to the Log file during the model
simulation, and the file may become extremely large if high-resolution Log output is requested. Log file output increases execution time, and should be used sparingly.

6. Heat Production or Extraction

Heat can be produced or extracted from any node in order to model processes occurring within the plate. As currently configured, the rate of heat production/extraction has units of W/m². This formulation is ideal for modeling advective heat extraction from the basement sections of the model domain where the grid is not deforming and the volume of basement material is not changing with time. This is not necessarily the case within the accumulating sediment column, where compaction acts to change the volume of material between enclosing nodes if the user-specified porosity versus depth profile is not constant. It may be worthwhile to modify the code in the future to allow heat production in sediments and basement using units of W/kg.

7. Description of the Input Deck

The input deck includes initial conditions, parameters and parameter distributions, timing information, and filenames for external function calls. General parameters that are held constant occupy one portion of the input deck, and transient conditions are accommodated by dividing the model simulation into individual stress periods. The general parameters include the model type, number of stress periods, basement layer parameters (conductivity, thermal capacity, porosity), water and sediment thermal capacity and conductivity, parameters used to calculate sediment porosity variability with depth, parameters for calculating permeability as a function of porosity, weighting factor for implicit-to-explicit temperature solutions, distance over which surface heat flux is
calculated, and node removal and data output information. Each individual stress period contains timing information, boundary condition types and values, sedimentation rate, seepage type and rate, node addition information, heat production or loss rate at selected nodes during the stress period, and timing for data output. Node parameters include initial node depths, temperatures, heat production or loss terms, and conductivities.

8. The Input Deck: Line-by-Line

Several special characters are used to define and separate portions of the input deck, and need to be used with care. These include the star (*), semicolon (:), and blank lines. General parameters that are held constant are contained between the first and second occurrences of ‘*’. Stress period parameters are contained between the second and third occurrences of ‘*’, and each stress period is separated from the previous one by one blank line. Initial node parameters follow the last occurrence of ‘*’. The semicolon (:) is used to separate the parameters from text describing their function.

The sections that follow describe the function of each line, and examples are given in boxes. Multiple parameters are labeled A-X, with the labeled value corresponding to the parameter position within the input line.

Header

The header encompasses all text up to the first occurrence of ‘*’.

General Parameters

Parameters and functions for the entire simulation occupy the next 17 lines, until the next occurrence of ‘*’.
Type of model. The allowable choices are ‘sub’ or ‘sed’, specifying either subsidence and accumulation or sediment deposition, respectively, during each stress period.

| sub |

| sed |

Number of stress periods (integer)

| 5 |

Basement Layer1 parameters (A-D). If a basement layer is in use, the depth of the sediment-basement interface (SBI) must be defined, and must correspond to a node depth in the node parameters section of the input deck.

A. depth of the node at the SBI (m)
B. basement conductivity (W/m-k)
C. basement thermabl capacity (J/m$^3$ K)
D. porosity (decimal)

| 606 2.9 3.21e6 0 |

If no basement layer is in use, include square brackets (Matlab’s equivalent to “empty-set”):
Line 4
Basement Layer 2 parameters (A-D). Same as Line 3, except the layer1/layer2 interface (rather than the SBI) is in (A). The depth of the node at the layer1/layer2 interface must correspond to a node depth in the node parameters section of the input deck.

Line 5
Thermal capacity of water (J/m³-K)

4.30e6

Line 6
Thermal capacity of sediment (J/m³-K)

2.65e6

Line 7
Thermal conductivity of water (W/m-K)

0.6

Line 8
Thermal conductivity of sediment grains (W/m-K)

2.3e6
**Line 9**

Surface sediment porosity (decimal) explicitly defined for the boundary node. Because the formula for calculating porosity as a function of depth (line 10) relies on a flexible analytical representation using a combination of constant, linear, polynomial, exponential, and logarithmic terms, calculation at the seafloor node at \( z = 0 \) may not yield the correct porosity

\[
\phi = A + Bz + Cz^2 + Dz^3 + Elnz + Fe^{(Gz^2)} + H^{(Iz)}
\]

| 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 7 -8.333e-4 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 909 -0.073 |

**Line 10**

Constants for calculating porosity (\( \phi \)) as a function of depth (\( z \)) (A-I):

**Line 11**

Defines porosity function as being in either meters ‘m’ or kilometers ‘km’

| m |

**Line 12**

Minimum allowable sediment porosity (decimal)
**Line 13**

Constants (A, B) for calculating sediment permeability ($k$) as a function of porosity ($\phi$) when seepage type (*stress period parameters*, line 6) is defined as an overpressure ‘p’.

$$k = Ae^{B(\phi/(1-\phi))}$$

| 0.3
|---

**Line 14**

Implicitness factor ($\theta$) for temperature solution. A factor of 0 yields the fully explicit scheme, whereas a factor of 1 yields the fully implicit scheme. A value of 0.5 results in the Crank-Nicholson scheme.

| 0.5
|---

**Line 15**

Calculate heat flux between surface and this node number (int). The seafloor node at $z=0$ is node 1. A value of 2 uses the first node below the seafloor, a value of 3 uses the second, etc. Thermal conductivity is calculated as the harmonic mean of conductivities of the intervening nodes.

| 2
|---
Line 16
The flag to allow the removal of basement nodes must be specified as ‘no’ or ‘yes’. If
basement node removal is allowed, ‘yes’ must be followed by the maximum number of
nodes to remove.

| yes 5 |

| no 0 |

| no |

Line 17
The flag to allow output to a text (Log) file must be specified as either ‘yes’ or ‘no’. The
data from the input deck is written to the Log file regardless.

| yes |

Stress Period Parameters

Line 1
Timing parameters for this stress period (A-E). Square brackets ‘[ ]’ indicate empty sets,
and must be included for parameters C-D if constant timing is being used. When variable
timing is used, time steps are calculated using the stress period length, initial time step,
number of time steps, and initial guess at scaling factor.

A. stress period length: \( \Delta t_{\text{total}} \) (years)

B. maximum time step: (years)
C. initial time step: $\Delta t_o$ (years)

D. number of time steps: $n$ (int)

E. initial guess at scaling factor: $F$(int $> 1$)

**Constant time stepping:**

$$1.0e6 \ 1000 \ [] \ [] \ [] \ []$$

**Variable time stepping:**

The final scaling factor is iteratively solved for

$$F = \sqrt{\frac{\Delta t_{total} - \Delta t_o}{\Delta t_o}(F - 1) + 1}$$

such that $\Delta t_{total} = \Delta t_o F^n$.

Any values greater than the maximum time step ($B$) calculated in this manner are set equal to the maximum, and time will increment by the maximum allowed until the end of the stress period.

$$0.2e6 \ 2000 \ 0.1 \ 10 \ 1.1$$

**Line 2**

Lower boundary condition type for this stress period must be specified as temperature ‘T’ or heat flux ‘q’.

$q$
Parameters for calculating the value at lower boundary for this stress period (A-D) or a filename containing time and value data. If the lower boundary condition type (line 2) is temperature, the value is in °C. If specified as heat flux, the value is in W/m². If a filename is given, the file must have two columns of data: time (space) value. Data in the time column must be consistent with timing data (line 1) for this stress period (i.e., data must exist in the file for each time step). SlugSed will examine the file and look for a time value that corresponds to the current time in the model simulation. Roundoff errors are avoided by not doing a direct comparison, but rather using a roundoff tolerance of 1.e-7 yrs. If SlugSed cannot find a time value in the file that is within the roundoff tolerance, a warning is displayed and the closest time value is used. When parameters are used, the value is calculated as

\[
value = A + Bt + \frac{C}{\sqrt{Dt}}
\]

The beginning of an input file using variable timing may look like the following:

<table>
<thead>
<tr>
<th>Time (yrs)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>6.3399</td>
</tr>
<tr>
<td>0.2</td>
<td>6.3395</td>
</tr>
<tr>
<td>0.3</td>
<td>6.3392</td>
</tr>
<tr>
<td>0.4</td>
<td>6.3390</td>
</tr>
<tr>
<td>0.5</td>
<td>6.3387</td>
</tr>
<tr>
<td>0.6</td>
<td>6.3385</td>
</tr>
</tbody>
</table>
Line 4
Temperature that the upper boundary is held at (°C).

2

Line 5
Basement subsidence or sediment deposition rate (m/yr)

0.000500

Line 6
Seepage in the sediment column in addition to any that might result from compaction and consolidation (A,B). Square brackets ‘[ ]’ indicate empty sets, and must be included if no additional seepage is to be included. Since SlugSed employs a positive down reference scheme, negative values for parameter B indicate upward seepage and overpressure, respectively.

A. Seepage type must be specified as either ‘s’ for constant seepage, or ‘p’ seepage driven by overpressure in basement. If type ‘p’ is used, the effective permeability of the sediment column is calculated as per General Parameters, line 13, and the fluid seepage is calculated accordingly.

B. If seepage type is ‘p’, this is the pressure in at the sediment-basement interface (kPa). If seepage type is ‘s’, this is the flux of seeping fluids at all nodes within the sediment section (m/yr)

[ ] [ ]
Line 7

Heat production or sink rate for nodes added during this stress period (W/m²)

0

Line 8

Name of file containing node depths and constants for calculating heat production or sink terms (W/m²) as a function of time (yrs) during this stress period. This line must contain square brackets ‘[]’ if no file is to be used. If a filename is given, the file format is as follows:

No blank lines are allowed, and all header lines must begin with ‘%’. Following the header are ten columns of data, containing the node depths in the first column followed by constants A-I used in calculating the heat production or sink term (Q) for the specified node:

\[ Q = A + Bt + C t^2 + D t^3 + E \ln(t) + F e^{(G t^r)} + H^{(Ir)} \]

where \( t \) is time in years. For basement nodes (which may subside during the simulation), node depths are referenced to the original starting depths in the input deck. Do not apply variable production or sink terms to boundary nodes or sediment-basement interface node.
An example of a file where heat sinks at node depths 8, 10, and 12 are ramped down linearly may look like the following:

% ----------- Begin Header ------------
%
% This file contains constants for calculating production/sink terms as a function
% of time
% The equation in use is:
% Q=A+Bt+Ct^2+Dt^3+Elnt+Fexp(G*t)+H^(It)
%
% where t is time in years, and A-->I are constants.
%
% The first value in the line is the node depth, followed by the constants
%
% For basement nodes (whos spacing is constant but subside during the model
% simulation), depths are referenced to the ORIGINAL starting depth in the input
% deck.
%
% Note: Do not apply to boundary nodes or Sediment-Basement-Interface node!
% ----------- End Header ------------

8   -0.00356744704570792   8.9186176142698e-10   0 0 0 0 0 0 0
10   -0.00356744704570792   8.9186176142698e-10   0 0 0 0 0 0 0
12   -0.00535117056856188   1.33779264214047e-09   0 0 0 0 0 0 0
Parameters for handling node addition during this stress period (A-C). If no nodes are to be added, (A-C) must be zeros. Nodes can be added at either fixed or variable depth intervals. In order to avoid numerical instabilities that may arise when the block created through node addition is exceedingly small, basement must move an additional fractional length (B) beyond the interval specified (A) in order for a node to be added.

A. Minimum distance (m) for addition of a new node at fixed depth intervals. If this value is –1, node addition will be at variable depth intervals scaled by (C).

B. Fractional length (m)

C. Scaling Factor (int)

Constant spacing node addition:

For example, if the node addition criteria is 2 m and the fractional length is 0.5, a node will be added at a depth of 10 m when the distance between the last sediment node at a depth of 8m and the sediment-basement interface is \( \geq (8+2)+(2*0.5) = 11 \) m.

\[ \begin{array}{ccc} 2 & 0.5 & 0 \end{array} \]

Variable spacing node addition:

When variable depth scaling is in use, parameter A must be –1 and nodes are added based on the scaling factor (C) and the distance between the last two sediment nodes (\( \Delta z_i \)), such that the total distance (\( \Delta z_{total} \)) is:

\[ \Delta z_{total} = \Delta z_i + \Delta z_i \left( \frac{C^n - 1}{C - 1} \right) \]
where \( n = 2 \), and the distance for basement to move in order for node addition to be considered must be at least \( \Delta z_{\text{total}} - \Delta z_{i} \). A node will only be added if basement has moved an additional fractional length (B).

\[-1 \quad 0.5 \quad 1.1\]

**Line 10**

Data storage and output parameters (A-C). Data will be stored in a Mat file at the increment specified in (A) and at the end of each stress period. Data will only be written to a text Log file at the increment specified in (B) if the flag to do so (General Parameters, line 17) is set to ‘yes’. To simply Log data at the end of each stress period, (B) can be set at a value >> than the number of time steps during this stress period. An optional parameter can be included to dump user-specified data to an additional text file named `filename.userdata.stressperiod.X.dat` at each timestep, where `filename` is the root name of the input deck, and X is the corresponding stress period. The data to be written must be explicitly defined at the end of the main loop in the body of the SlugSed.m file.

\[2 \quad 100\]

\[10 \quad 1.e6\]

An example of explicitly defining that time and sediment-basement interface temperature are to be dumped to a userdata file at each time step would be

\[2 \quad 1.e6 \quad 1\]
where the following commands are in the User Data Output section of SlugSed:

```
% Userdata variable. Determine temperature at
% sediment-basement interface
userdata_variable = find(Z==B);
fprintf(Fid_userdata,'%16.16f \t 16.16f\n',t_yrs,T(userdata_variable));
```

### Initial Node Parameters

Initial node parameters follow the last occurrence of ‘*’, and make up the remainder of the input deck. The first line gives the number of nodes to be read in. The node data consist of depths (positive down), temperatures (°C), heat production or loss terms (W/m²), and conductivities (W/m-K). The seafloor node must be assigned a depth of 0 m, and at least three nodes are required to initialize a model simulation. If a porosity function is being used to determine conductivity within the sediment section (*General Parameters*, line 10), conductivities will be assigned accordingly when the simulation begins, overriding any values assigned in this section. If basement layers are being used, conductivity values (other than 0) in this section will override the values entered in *General Parameters* lines 3 and 4.

For example, in a simulation containing sediment and two basement layers where sediment thermal conductivity is derived from a porosity function, basement layer 1 thermal conductivity is set at 1.7 W/m-K (*General Parameters*, line 3), basement layer 2 thermal conductivity is set at 2.9 W/m-K (*General Parameters*, line 4), and the depths of the sediment-basement interface and layer1/layer 2 boundary are 6 m and 606 m, respectively, the following node parameters

<table>
<thead>
<tr>
<th>Depth</th>
<th>Temperature</th>
<th>Conductivity</th>
<th>Depth</th>
<th>Temperature</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.42232295</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0.84389952</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1.26473227</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
define a 100 km basement section overlain by 6 m of sediment. Thermal conductivity within the sediment section (0-6 m) will be calculated based on the porosity function. A total of 0.8 W/m$^2$ of heat is being extracted within basement layer 1 (6-606 m) which is assigned a thermal conductivity of 1.7 W/m-K (General Parameters, line 3). Thermal conductivity within basement layer 2 between 806-2006 m is explicitly defined as 2 W/m-K (overriding General Parameters, line 4), and the remainder is assigned the value of 2.9 W/m-K (General Parameters, line 4).
9. Model Structure, Function Calls, and Variables

The model is composed of a main shell script (SlugSed) and numerous external functions (each beginning with the prefix “ss_”), all of which are described in more detail in the following sections. The model can be run with all the external functions placed in Matlab’s search path, or they can be embedded within the body of the main shell script (thus creating a single m-file) as discussed below.

BuildSlugSed

*BuildSlugSed* wraps all the external functions into the body of the main shell script, and can be manually edited to identify which external functions should be embedded. The function filename is written before each embedded function, thus making it explicitly clear which function (or version thereof) is being used. This is advantageous because changes to individual external functions can be easily incorporated and tested without altering or renaming all the function calls within the main shell script. For example, let’s say the user wants to test different schemes of calculating conductivity, which is handled in *ss_conductivity* and called by various other functions. The cleanest way to do this is to copy *ss_conductivity* and give it a new name, say, *ss_conductivity_new*. After modifying the new function to calculate conductivity in a different manner, the user modifies *BuildSlugSed* by changing the name of the function to be embedded from *ss_conductivity* to *ss_conductivity_new*. Now run *BuildSlugSed* and assign a different output name, say *SlugSed_Kdifferent.m* for a main shell script containing the new method of calculating conductivity. If the user examines the body of *SlugSed_Kdifferent.m*, they will find the following
SlugSed

*SlugSed* is the main shell script for running the model, and contains all the function calls for loading and processing data contained within the input deck. The program can be executed directly from the command line or called from another function or application. Typing `>>SlugSed` will prompt the user to locate an input deck, whereas `>>SlugSed('myfile.dat')` will operate on the input deck *myfile.dat*. An illustration of the function calls is shown in Figure 4. The main body of the program is divided into two sections: the first section loads the parameters from the input deck, and the second (main loop) performs the time stepping and numerical calculations.

**Function description: parameter loading and preparation**

*ss_dataload*

*ss_dataload* loads all the parameters from the input deck into discrete variables.

*ss_varqfmt*

*ss_varqfmt* sets flags for each stress period indicating whether or not time-variant heat production or sink terms are to be used.

*ss_vbsmtfmt*

*ss_vbsmtfmt* sets flags for each stress period indicating whether or not user-specified timing and value data for the lower boundary condition are to be used.

*ss_datadisp*

*ss_datadisp* displays a synopsis of the data from the input deck.
**ss_Vbsmt**

*ss_Vbsmt* calculates the value (temperature or heat flux) at the lower boundary.

**ss_bsmtprep**

*ss_bsmtprep* assigns values to basement variables.

**ss_qc**

*ss_qc* performs some basic quality control on timing, seepage flux, node removal, and output interval data.

**ss_timeconv**

*ss_timeconv* converts timing data from years to seconds.

**ss_nts**

*ss_nts* determines the number of time steps in the entire simulation, and when output should be generated between stress periods. This function calls *ss_timestepcalc* and *ss_tvartimecalc* if variable timing is in use.

**ss_initconds**

*ss_initconds* initializes storage vectors, determines initial conditions, and writes the results to the Log file if requested. This function calls *ss_porosity*, *ss_conductivity*, *ss_velocity*, *ss_heatflow*, *ss_resprep*, *ss_store*, and *ss_resfile*.

**Function description: main loop function calls (executed at each time step)**

**ss_currenttime**

*ss_currenttime* determines the current time step, stress period, and boundary condition value for the current time step. This function calls *ss_Vbsmt*, as well as *ss_timestepcalc* and *ss_tvartimecalc* if variable timing is in use.

**ss_check4newnode**

*ss_check4newnode* determines basement depths, and checks to see if a new node needs to be added. If the model type is ‘sed’ (sediment deposition), this function
calls *ss_bootstrap4B* to determine the depth of the sediment-basement interface node.

**ss_varqparams**
*ss_varqparams* extracts node-specific time-variant heat production/sink parameters from a user-specified file.

**ss_porosity**
*ss_porosity* calculates and assigns porosity values to sediment and basement.

**ss_conductivity**
*ss_conductivity* calculates and assigns conductivity values to sediment nodes based on a geometric mean mixing model.

**ss_fluxconv**
*ss_fluxconv* is called when seepage within the sediment column is driven by overpressures in basement. It converts overpressures in kPa to specific discharge by calculating the bulk (effective) permeability of the sediment section.

**ss_velocity**
*ss_velocity* calculates sediment grain and water velocities, based on the model type. Water velocities include both compaction-driven and seepage velocities.

**ss_varq**
*ss_varq* calculates node-specific time-variant heat production/sink values using the parameters extracted by *ss_varqparams*.

**ss_solver**
*ss_solver* calculates temperature solutions using the matrix form \(Ax=b\).

**ss_heatflow**
*ss_heatflow* calculates heat flux. Heat flux is calculated using the average thermal conductivity over the entire sediment section, as well as using the harmonic mean of thermal conductivity over a user-specified depth interval.

**ss_resprep**
*ss_resprep* prepares data for output to the Log file.
**ss_resfile**

*ss_resfile* writes data to the Log file.

**ss_store**

*ss_store* saves the current variables in the Mat file.

**ss_addnode**

*ss_addnode* adds a new node to the sediment column and determines the new node properties. This function calls *ss_porosity*, *ss_conductivity*, *ss_velocity*, and *ss_estimate*.

**ss_estimate**

*ss_estimate* calculates the temperature of nodes being added.

**ss_remnode**

*ss_remnode* removes nodes from the sediment section.

**ss_plotter**

*ss_plotter* plots heat flux, temperature, and sediment thickness data.

**Variables**

The following is a list and brief description of the main variables, and is divided into four sections: input variables, output/storage variables, other variables, and specific variables sent to the Log file. Some functions use additional function-specific variables, which are defined in each function header.

**Input Variables and a Brief Description**

- **add_node**: Subsidence distance for a node to be added (m)
- **AddNodeTol**: Tolerance for node addition (0-1)
- **bctype**: Lower boundary condition type: [T] or [q]
- **F**: Scaling factor for variable node addition depths
- **fid_status**: File identifier for output to Log file
- **hf_node**: Calculate heat flux between surface and this node NUMBER (not depth)
- **interval**: Maximum or fixed timestep during stress period. Originally in years, converted to seconds
- **K**: Node Thermal conductivity (W/m-K)
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_s)</td>
<td>Sediment grain thermal conductivity (W/m-K)</td>
</tr>
<tr>
<td>(\lambda_w)</td>
<td>Water thermal conductivity (W/m-K)</td>
</tr>
<tr>
<td>Layer</td>
<td>Flag for layers [yes] or [no]</td>
</tr>
<tr>
<td>log_count</td>
<td>Counter - output to Log file, one entry per stress pd</td>
</tr>
<tr>
<td>LogFlag</td>
<td>Flag for writing output to Log and Mat files. Gets converted to a 3-element character vector. The first entry will indicate whether or not the user wants data written to the log file. The second entry will be set to 'yes' only when the user-defined timesteps for model storage in MAT file are reached, and is set to 'yes' initially so that all original input data is written to the MAT file. The third entry indicates whether or not data will be written to the LOG file.</td>
</tr>
<tr>
<td>mtype</td>
<td>Model type: [sub] or [sed]</td>
</tr>
<tr>
<td>n</td>
<td>Initial number of nodes</td>
</tr>
<tr>
<td>num_stress_pds</td>
<td>Number of stress periods</td>
</tr>
<tr>
<td>PermCon1</td>
<td>Constant for calculating permeability=f(porosity)</td>
</tr>
<tr>
<td>PermCon2</td>
<td>Constant for calculating permeability=f(porosity)</td>
</tr>
<tr>
<td>(\phi_{\text{min}})</td>
<td>Minimum allowable porosity (decimal)</td>
</tr>
<tr>
<td>phi_params</td>
<td>Parameters for calculating porosity=f(depth)</td>
</tr>
<tr>
<td>phi_surface</td>
<td>Surface porosity at first node :z=0 (decimal)</td>
</tr>
<tr>
<td>phi_type</td>
<td>Porosity function type as meters or kilometers [m] or [km]</td>
</tr>
<tr>
<td>prod_snk</td>
<td>Production/sink term for nodes being added (W/m^2), one value per stress pd.</td>
</tr>
<tr>
<td>Q</td>
<td>Heat production/sink term (W/m^2), one value per node</td>
</tr>
<tr>
<td>remnodeflag</td>
<td>Flag for removal of nodes [0/1]</td>
</tr>
<tr>
<td>remnodemax</td>
<td>Maximum number of nodes allowed to be removed</td>
</tr>
<tr>
<td>rhoc_sed</td>
<td>Thermal capacity of sediment (J/m^3-K)</td>
</tr>
<tr>
<td>rhoc_water</td>
<td>Thermal capacity of water (J/m^3-K)</td>
</tr>
<tr>
<td>RunFlag</td>
<td>Flag to run [0/1]</td>
</tr>
<tr>
<td>subsed</td>
<td>Subsidence or sedimentation rate (m/yr), one value per stress pd.</td>
</tr>
<tr>
<td>T</td>
<td>Initial temperatures (deg C)</td>
</tr>
<tr>
<td>T0</td>
<td>Upper boundary temperature (deg C)</td>
</tr>
<tr>
<td>tend</td>
<td>Stress period length, one value per stress pd.</td>
</tr>
<tr>
<td>theta</td>
<td>Scaling factor for Crank-Nicholson solution (0-1)</td>
</tr>
<tr>
<td>timeout</td>
<td>Number of timesteps to increment before storing to Mat File</td>
</tr>
<tr>
<td>userdata</td>
<td>Flag to output additional user-specified data [0/1]. Gets converted to two entries per stress pd. First entry indicates whether or not to output data [0/1], and second entry indicates whether an output file has already been opened [0/1]</td>
</tr>
<tr>
<td>VarQ_fn</td>
<td>Filename for calculating Q=f(t) for selected nodes, one entry per stress pd.</td>
</tr>
</tbody>
</table>
Vartime_params  Variable timing parameters: three entries per stress pd [ initial time step (yrs), # of time steps, scaling factor (initial guess)]

VartimeFlag  Flag for variable timing [0/1], one entry per stress pd.

Vbsmt_params  Parameters for calculating basement boundary condition value [A,B,C,D,E,F]
where value = A+Bt+Ct^2+Dt^3+E/sqrt(F*t) and time (t) is in years. Can also contain a filename, which must contain two columns: time, value.

vflux  Seepage flux or driving pressure in kPa. Flux originally in m/yr, converted to m/s

vflux_type  Seepage flux type: [s] constant seepage or [p] pressure

Z  Vector of depths

Z_l1l2  Depth of Layer1 / Layer2 interface (m)

Z_sbi  Depth of sediment-basement interface (m)

Zb1_K  Conductivity of Layer1 (W/m-K)

Zb1_phi  Porosity of Layer1 (decimal)

Zb1_rhoc  Thermal capacity of Layer1 (J/m^3-K)

Zb2_K  Conductivity of Layer2 (W/m-K)

Zb2_phi  Porosity of Layer2 (decimal)

Zb2_rhoc  Thermal capacity of Layer2 (J/m^3-K)

Output/Storage Variables and a Brief Description

A_store  Matrix of basement temperatures (deg C)

addnode_store  Vector of times when nodes were added (yr)

B  Basement depth (m)

b_store  Vector of SBI depths, one entry per time step (m)

btmlp_store  Vector of SBI temps, one entry per time step (deg C)

filename  Character array containing filename

Ha_store  Vector of heat flux: average over entire sediment column (W/m^2)

Hh_store  Vector of heat flux: harmonic mean over user-specified depth range (W/m^2)

K  Vector of conductivities from final time step (W/m-K)

K_store  Matrix of conductivities, one column/time step (W/m-K)

LoopTime  Vector of loop execution time (s)

P_store  Matrix of porosities, one column/time step (decimal)

Q  Vector of production/sink terms from final time step (W/m^2)

remnode_store  Vector of times when nodes were removed (yr)
S_store  Matrix of sediment velocities, one column/time step (m/s)
T       Vector of temperatures from final time step (deg C)
T_store Matrix of temperatures, one column/time step (deg C)
t_store Vector of time (yr)
Vbsmt_store Vector of lower BC value (deg C or W/m^2)
vflux_store Vector of seepage flux (m/s)
W_store  Matrix of sediment water velocities, one col/time step (m/s)
Z       Vector of depths from final time step (m)
Z_store Vector of depths (m)
Zb_store Vector of basement depths (m)

Other Variables and a Brief Description

a       Placeholder
b       Main loop counter
Boriginal Original sediment-basement interface depth (m)
dt      Current timestep (s)
dzB     Distance basement has moved during the current timestep (m)
ElapsedTime Elapsed time for current loop (from internal clock)
errorstring Error message
foo     Exactly
H_wait  Handle for waitbar
i       Counter typically used in functions
lnode   Depth of last sediment node (m)
logout_count Counter: solution output to Log file
LoopTimeStart Starting time for current loop (from internal clock)
num_timesteps Number of time steps for entire simulation
out_count Counter for output. This forces output to the MAT file
overpressure Clone of vflux (vflux will change if driven by overpressure)
pathname Current path
pd_count Counter: stress period
phi     Vector of porosity (decimal)
PS      Previous temperature solutions before sending to solver
qa      Heat flux in W/m^2, average
qh      Heat flux in W/m^2, Harmonic mean
remnodecounter Counter for node removal
sidyr2sec Conversion factor for years to seconds:
              1 year = 3.1536e7 seconds
sol_count Counter: solution storage to Mat file
stress_pd Current stress period
subsed_rate Subsidence or sedimentation rate in m/s
t
Current time (s)
t_vartime
Variable time (s)
t_vartime
Vector of times if variable timing is in use (s)
t_yrs
Current time (yrs)
userdatafile
File for output of user-specified data. One file per stress pd. Naming format is
[inputfilename].userdata.stressperiod.[stress pd.]
userdatavariable
User-specified variable
VarQ_params
Parameters for calculating variable production/sink values
VarQ_Z
Node depths where variable production/sink values are to be applied
VarQFlag
Flag for variable production/sink with two entries per stress pd. First column indicates whether or not a file exists [0/1], the second indicates whether parameters and node depths have been extracted from the file [0/1]
VartimeCounter
Counter for variable time vector
Vbsmt
Lower BC value for current timestep (W/m² or deg C)
Vbsmt_time
Vector of times when variable lower BC is in use, or current time if standard (yrs)
Vbsmt_value
Vector of values for lower BC when variable lower BC is in use, or current value if standard (deg C or W/m²)
VbsmtFlag
Flag for variable lower BC value, with two entries per stress pd. First column indicates whether or not a file exists [0/1], the second indicates whether times and values have been extracted [0/1]
Vs
Vector of sediment velocity (m/s)
Vw
Vector of water velocity (m/s)
Zb1
Vector of basement Layer1 node depths (m)
Zb2
Vector of basement Layer2 node depths (m)
Znewnode
Depth of node being added (m)
Zoriginal
Vector of original sediment and basement node depths (m)

List of Variables Sent to Results (Log) File

temps
clone of T
depths
[Z;B]
sediment
sed. velocity (m/yr)
water
water velocity (m/yr)
conduct
conductivity (W/m-K)
porosity
decimal
10. Example Input Decks

Comparison to analytical solutions: Linear flow of heat in the solid bounded by two parallel planes

**Case 1: The region 0<x<L. Ends kept at zero temperature. Initial temperature \( f(x) = V_0 \), constant.**

The following input deck can be used to validate SlugSed against the analytical solution presented in Carslaw and Jaeger, 1959, page 96 equation 6. This simulation uses a 100 m thick slab with the ends at zero degrees, and an initial temperature throughout the remainder of the slab at 100 degrees. Properties are uniform throughout. The simulation runs for 500 years using variable timing and a maximum time step of 1 year. Data are stored every time step in the Mat file, and output to the Log file at the end of the model run. Figure 5 shows selected model results.

Validate the model against the analytical solution from Carslaw and Jaeger, 1967, page 96, equation 6.

Create a slab (0-100 m). Ends at zero, initial temperature of 100 degrees

m-file analytical1.m creates the analytical solution for comparison

```
**************
sub :type of model, subsidence [sub] or sedimentation [sed]
1 :number of stress periods
[ ] [ ] [ ] [ ] :layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
[ ] [ ] [ ] [ ] :layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
2.65e6 :parameter, thermal capacity of water (J/m^3-K)
2.65e6 :parameter, thermal capacity of sediment (J/m^3-K)
1 :parameter, thermal conductivity of water (W/m-K)
1 :parameter, thermal conductivity of sediment grains (W/m-K)
```
0.00000 :parameter, surface sediment porosity (decimal)
0 0 0 0 0 0 0 0 0 0 0 0 :parameter, constants for porosity = f(z).
A+Bz+Cz^2+Dz^3+Elnz+Fexp(G*z)+H*(Iz)^2
km
0 0 0 0 0 :parameter, minimum allowable sediment porosity
(decimal)
0 0 0 0 :parameter, constants for permeability = f(phi)
when pressure term is used to drive seepage;
perm = Aexp(B*(porosity/(1-porosity)))
0.5 :parameter, scaling factor theta (for crank-
nicholson solution; 0-1) 0=explicit, 1=implicit,
0.5=mixed
2 :parameter, calculate heat flow between surface
and this node
no 0 :Flag, allow the removal of nodes from upper
basement [yes/no] followed by maximum number of
nodes to remove. Will remove a basement node when
a sediment node is added
yes :Flag, write output to a text Log file [yes/no]
(Will write input-file data regardless)
***************
500 1 0.001 1000 1 1 :time, length of this stress period (in yrs)
followed by maximum time step (in yrs), Variable
params; initial timestep (yrs), # timesteps,
scaling factor (initial guess)
T :boundary condition (lower), ([T] for Temperature
(degrees C), [q] for heat flow (W/m^2))
0 0 0 0 0 0 :boundary condition parameters for lower boundary;
[T] or [q] = f(time in yrs);
A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)
0 :boundary condition (upper), temperature in
degrees C that boundary is held constant at.
0.00000 :parameter, basement subsidence rate or
sedimentation rate during this stress period in
m/yr
[ ] [ ] :parameter, [s] seepage followed by value in m/yr
or [p] lower boundary pressure followed by value
in (kPa) ; (+) down/underpressure
0.0 :parameter, production/sink term for additional
nodes during this stress period in (W/m^2)
[ ] :filename containing constants for calculating
production/sink (Q=f(t)) values for selected nodes
0 0 0 :parameter, subsidence distance (m) for addition
of a new node followed by tolerance (0-1). If
param 1 ==-1, variable node
addition depth scaled by param. 3
1 1.e6 :parameter, number of time steps to increment
before storing data in Mat File followed by
writing to Log File (Flag to write
must be set to [yes] for writing to Log file)
***************
101 :node, number of nodes. Following are node depths
(m), initial temps (deg C), radiogenic
production/sink (W/m^2), [optional] conductivity
(W/m-K)
Case 2: The region $-L < x < L$. Initial temperature =0, ends at constant temperature

The following input deck can be used to validate SlugSed against the analytical solution presented in Carslaw and Jaeger, 1959, page 100 equation 2. This simulation uses a 100 m thick slab with the ends at 100 degrees, and an initial temperature of 0 degrees throughout the remainder. Properties are uniform throughout. The simulation runs for 500 years using variable timing and a maximum time step of 1 year. Data are stored every time step in the Mat file, and output to the Log file at the end of the model run. Figure 6 shows selected model results.

Match the analytical solution from C&J (1967) pg 100 for a region $-L < X < L$ with ends held at constant temperature, and initial temperatures throughout at zero

run mfile analytical2.m for analytical solution

**************
sub :type of model, subsidence [sub] or sedimentation [sed]
1 :number of stress periods
[ ] [ ] [ ] [ ] :layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
[ ] [ ] [ ] [ ] :layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
2.65e6: parameter, thermal capacity of water (J/m^3-K)
2.65e6: parameter, thermal capacity of sediment (J/m^3-K)
1: parameter, thermal conductivity of water (W/m-K)
1: parameter, thermal conductivity of sediment grains (W/m-K)
0: parameter, surface sediment porosity (decimal)
0 0 0 0 0 0 0 0 0 0 0: parameter, constants for porosity = f(z).
A+Bz+Cz^2+Dz^3+Elnz+Fexp(G+Z)+H^Iz
km: parameter, porosity = f(z) where z is in [m] or [km]
0: parameter, minimum allowable sediment porosity (decimal)
0 0: parameter, constants for permeability = f(phi) when pressure term is used to drive seepage;
perm = Aexp(B*(porosity/(1-porosity)))
0.5: parameter, scaling factor theta (for crank-nicholson solution; 0-1)
0 = explicit, 1 = implicit, 0.5 = mixed
2: parameter, calculate heat flow between surface and this node
no 0: Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added
yes: Flag, write output to a text Log file [yes/no] (Will write input-filedata regardless)
**************
500 1 0.001 1000 1.1: time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
T: boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
100 0 0 0 0 0: boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)
100: boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.00000: parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ]: parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa) ; (+) down/underpressure
0.0: parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ]: filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
0 0 0: parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3
1 1.6e6: parameter, number of time steps to increment before storing data in Mat File followed by
before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

**************
101

:node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic production/sink (W/m^2), [optional] conductivity (W/m-K)

<p>| | | | |</p>
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**Case 3: The region -L<x<L. Zero Initial temperature. Heat production constant.**

The following input deck can be used to validate SlugSed against the analytical solution presented in Carslaw and Jaeger, 1959, page 130 equation 7. This simulation uses a 100 m thick slab with uniform properties throughout, and an initial temperature of zeros degrees. Heat production within the slab is 0.1 W/m^2 at each node (excluding boundary nodes) for 500 years. Time stepping is variable, with an initial time step of 0.1 years and a maximum of 1 year. Data are stored every time step in the Mat file, and output to the Log file at the end of the model run. Figure 7 shows selected model results.

header
The region -L<x<L with zero surface temperature, zero initial temperature, and heat production of 0.1 W/m2 for t>0
run mfile analyticalheat.m for analytical solution

**************
sub :type of model, subsidence [sub] or sedimentation [sed]
1 :number of stress periods
[ ] [ ] [ ] [ ] :layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
[ ] [ ] [ ] [ ] :layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
2.65e6 :parameter, thermal capacity of water (J/m$^3$-K)
2.65e6 :parameter, thermal capacity of sediment (J/m$^3$-K)
1 :parameter, thermal conductivity of water (W/m-K)
1 :parameter, thermal conductivity of sediment grains (W/m-K)
0. :parameter, surface sediment porosity (decimal)
0 0 0 0 0 0 0 0 :parameter, constants for porosity = f(z).
0 A+Bz+Cz^2+Dz^3+Elnz+Fexp(G*Z)+H^Iz
km :parameter, porosity = f(z) where z is in [m] or [km]
0 :parameter, minimum allowable sediment porosity (decimal)
0 0 :parameter, constants for permeability = f(\phi) when pressure term is used to drive seepage; perm = Aexp(B*porosity/(1-porosity))
0.5 :parameter, scaling factor theta (for crank-nicholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed
2 :parameter, calculate heat flow between surface and this node
no 0 :Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added
yes :Flag, write output to a text Log file [yes/no] (Will write input-file data regardless)
**************
500 1 0.1 1000 1.1 :time, length of this stress period (in yrs)
followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
T :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m$^2$))
0 0 0 0 0 0 :boundary condition parameters for lower boundary;
[T] or [q] = f(time in yrs);
A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.00000 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa) ; (+) down/underpressure
0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m$^2$)
[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
0 0 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param. 3
1 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for
writing to Log file)

***************
101 :node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic production/sink (W/m^2), [optional] conductivity (W/m-K)

0 0 0 0
1 0 0.1 0
2 0 0.1 0
...
98 0 0.1 0
99 0 0.1 0
100 0 0 0

Comparison to Benfield 1949 analytical solution

The following input deck can be used to validate SlugSed against the analytical solution for heat transfer shown in Benfield, 1949. This simulation begins with a 50 m thick layer on top of a 29,950 m thick basement layer, but the distinction between sediment and basement is trivial because constant properties are assigned throughout. Sediment accumulates at a rate of 50 m/M.y. for 1 M.y., and basal heat flux is constant at 1 W/m^2.

Variable timing is used, with a maximum time step of 1000 years and an initial time step of 0.001 years. Nodes are added every 2 m, variables are stored in the Mat file every time step, and data are written to the Log file at the end of the stress period. Figure 8 shows selected model results.

Use Variable timing to match Benfield analytical solution

Start with 50 meters of sediment (doesn't matter because properties are uniform)
Subsidence at 50 m/M.y.
Match with analytical solution from Benfield, 1949
M-file BENFIELD gives analytical solution to the above equation.
conductivity is 1
thermal capacity is 2.65e6
measure heat flux over top meter
Qbase = 1 W/m²

**************

sub : type of model, subsidence [sub] or sedimentation [sed]
1 : number of stress periods
50 1 2.65e6 0 : layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m³-K), porosity (decimal)
[ ] [ ] [ ] [ ] : layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m³-K), porosity (decimal)
2.65e6 : parameter, thermal capacity of water (J/m³-K)
2.65e6 : parameter, thermal capacity of sediment (J/m³-K)
1 : parameter, thermal conductivity of water (W/m-K)
1 : parameter, thermal conductivity of sediment grains (W/m-K)
0 : parameter, surface sediment porosity (decimal)
0 0 0 0 0 0 0 0 : parameter, constants for porosity = f(z). A+Bz+Cz²+Dz³+Elnz+Fexp(G*z)+H^(Iz)
km : parameter, porosity = f(z) where z is in [m] or [km]
0.0 : parameter, minimum allowable sediment porosity (decimal)
[ ] [ ] : parameter, constants for permeability = f(phi) when pressure term is used to drive seepage; perm = Aexp(B*(porosity/(1-porosity)))
0.5 : parameter, scaling factor theta (for crank-nicholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed
3 : parameter, calculate heat flow between surface and this node
no 0 : Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added
yes : Flag, write output to a text Log file [yes/no] (Will write input-file data regardless)

**************

100000 1000 0.001 : time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
5000 1.10 : time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
q : boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m²))
1 0 0 0 0 0 : boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C(time²)+D(time³)+E/sqrt(F*time)
0 : boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000050 : parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ] : parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure
0.0 : parameter, production/sink term for additional nodes during this stress period in (W/m²)
Comparison to Bredehoeft and Papadopulos 1965 analytical solution for seepage

The following input deck can be used to validate SlugSed against the analytical solution for heat transfer due to fluid seepage shown in Bredehoeft and Papadopulos, 1965, equation 4, page 326. This simulation uses a 100 m thick layer with constant properties throughout. Variable timing is used, with a maximum time step of 10 years and an initial time step of 0.1 years. Temperatures are held constant at 0 °C and 100 °C for the upper and lower boundaries, respectively, and the initial thermal gradient is linear. Seepage is constant at ±0.1-1.0 m/yr. Variables are stored in the Mat file every time step, and data are written to the Log file at the end of the stress period. Figure 9 shows selected model results.

Test file created July 3, 2006
Test seepage against the Bredehoeft & Papadopulos 1965 analytical solution

Water Resources Research, Vol. 1 No. 2, equation 4, page 326

Seepage = -0.5 m/yr (up)

Use 100 meters of sediment with constant properties

m-file SEEPAGE.M gives analytical solution

***************
sub
1
[ ][ ][ ][ ][ ] :layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
[ ][ ][ ][ ][ ] :layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
2.65e6 :parameter, thermal capacity of water (J/m^3-K)
2.65e6 :parameter, thermal capacity of sediment (J/m^3-K)
1 :parameter, thermal conductivity of water (W/m-K)
1 :parameter, thermal conductivity of sediment grains (W/m-K)
0. :parameter, surface sediment porosity (decimal)
0 0 0 0 0 0 0 0 0 0 0 :parameter, constants for porosity = f(z). A+Bz+Cz^2+Dz^3+Elnz+Fexp(G*Z)+H^Iz
km :parameter, porosity = f(z) where z is in [m] or [km]
0 :parameter, minimum allowable sediment porosity (decimal)
0 0 :parameter, constants for permeability = f(phi) when pressure term is used to drive seepage; perm = Aexp(B*(porosity/(1-porosity)))
0.5 :parameter, scaling factor theta (for crank-nicholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed
2 :parameter, calculate heat flow between surface and this node
no 0 :Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added
yes :Flag, write ouput to a text Log file [yes/no] (Will write input-file data regardless)
***************
500 10 0.1 1000 1.1 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps,
scaling factor (initial guess)

T :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
100 0 0 0 0 :boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs);
               A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.00000 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
s -0.5 :parameter, [s] seepage followed by value in m/yr
        or [p] lower boundary pressure followed by value in (kPa) ; (+) down/underpressure
0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
0 0 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If
        param 1 ==-1, variable node addition depth scaled by param. 3
1 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by
        writing to Log File (Flag to write must be set to [yes] for writing to Log file)

**************

101 :node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic
      production/sink (W/m^2), [optional] conductivity (W/m-K)
0 0 0 0
1 1 0 0
2 2 0 0
...
99 99 0 0
100 100 0 0

Constant Sediment Accumulation and variable porosity, uniform basement properties

The following input deck is used to model constant sediment accumulation at the rate of
100 m/M.y. Initial sediment thickness is 6 m, basement layer 1 is 600 m thick and
basement layer 2 is 99.4 km thick. Basal heat flux is 1 W/m^2 and the initial thermal
gradient is uniform. Porosity decreases with depth defined by \( \phi = 0.7e^{-z/1200} \) where depth
(z) is in meters. Total runtime is 20 M.y. with variable timing during each stress period, and increases to a maximum of 8 kyr during stress period 5. Nodes are initially added every 2 m, increasing to a maximum of 4 m during stress period 5. Data are stored in the Mat file every 3 time steps during stress periods 1-3, and every 10 time steps during stress periods 4 and 5. Data are written to the Log file every 100 time steps during stress periods 1-3, and every 500 time steps during stress periods 4 and 5. Figure 10 shows selected model results.

Header

Test how sensitive the results are to the choice of conductivity for lowermost basement. This simulation uses a lower basement value of 2 W/m-K

Basal heat flux = 1 W/m^2
100 km thick lower basement
Subsidence at 100 m/M.y. for 20 M.y. to accumulate 2000 m of sediment
Sediment-basement-interface at depth of 6 m
Variable timing in use
No Node removal allowed
Use porosity function from Davis et al., 1999 JGR

**************
sub :type of model, subsidence [sub] or sedimentation [sed]
5 :number of stress periods
6 2.0 3.86e6 0 :layer1 parameters, depth of node at SBI (m), basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
606 2.0 3.86e6 0 :layer2 parameters, depth of node at layer1/layer2 interface, basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
4.30e6 :parameter, thermal capacity of water (J/m^3-K)
2.65e6 :parameter, thermal capacity of sediment (J/m^3-K)
0.6 :parameter, thermal conductivity of water (W/m-K)
2.74 :parameter, thermal conductivity of sediment grains (W/m-K)
0.7 :parameter, surface sediment porosity (decimal)
parameter, constants for porosity = f(z).

A+Bz+Cz^2+Dz^3+Elnz+Fexp(G*Z)+H^(Iz)

parameter, porosity = f(z) where z is in [m] or [km]

parameter, minimum allowable sediment porosity (decimal)

parameter, constants for permeability = f(phi) when pressure term is used to drive seepage; perm = Aexp(B*(porosity/(1-porosity)))

parameter, scaling factor theta (for crank-nicholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed

parameter, calculate heat flow between surface and this node

Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added

Flag, write output to a text Log file [yes/no] (Will write input-file data regardless)

:time, length of this stress period (in yrs)
followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)

:boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

:boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)

:boundary condition (upper), temperature in degrees C that boundary is held constant at.

:parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

:parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure

:parameter, production/sink term for additional nodes during this stress period in (W/m^2)

:filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

:parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param. 3

:parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

:time, length of this stress period (in yrs)
followed by maximum time step (in yrs), Variable params

:boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
(degrees C), [q] for heat flow (W/m^2))

1 0 0 0
:boundary condition parameters for lower boundary
0
:boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100
:parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ]
:parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)
0.0
:parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ]
:filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
2 0.5 0
:parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param. 3
3 100
:parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

2.e6 4000 4000 100 1.1
:time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params
q
:boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0
:boundary condition parameters for lower boundary
0
:boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100
:parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ]
:parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)
0.0
:parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ]
:filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
2 0.5 0
:parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param. 3
3 100
:parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

5.e6 4000 4000 100 1.1
:time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params
**q** boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 :boundary condition parameters for lower boundary

0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)

0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

3 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3

10 500 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

10.e6 8000 4000 100 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params

1.1

**q** boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 :boundary condition parameters for lower boundary

0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)

0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

4 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3

10 500 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

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42 :node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic
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Constant sediment accumulation, variable porosity, high Nu basement aquifer, and variable conductivity lower basement

The following input deck is used to model constant sediment accumulation at the rate of 100 m/M.y. Initial sediment thickness is 6 m, basement layer 1 is 600 m thick and
basement layer 2 is 99.4 km thick. The thermal conductivity of basement layer 1 is elevated by a factor of 1000 above the true conductivity in order to simulate the thermal effect of vigorous local hydrothermal heat redistribution. The upper 2 km of basement layer 2 has a conductivity of 2 W/m² (specified directly in the node properties section of the input deck), and the remainder has a value of 2.9 W/m² (specified in the general parameters section of the input deck, line 4). Basal heat flux is 1 W/m² and the initial thermal gradient is uniform. Porosity decreases with depth defined by \( \phi = 0.7e^{-z/1200} \) where depth \( (z) \) is in meters. Time stepping is variable, and data are only written to the Log file at the end of each stress period. Figure 11 shows selected model results.

Header
Basal heat flux = 1 W/m²
100 km thick lower basement
Subsidence at 100 m/M.y. for 20 M.y. to accumulate 2000 m of sediment
Sediment-basement-interface at depth of 6 m
No Node removal allowed
Use porosity function from Davis et al., 1999 JGR

***************
sub :type of model, subsidence [sub] or sedimentation [sed]
6 :number of stress periods
6 1700 3.86e6 0 :layer1 parameters, depth of node at SBI (m),
basement conductivity (W/m-K), thermal capacity
(J/m³-K), porosity (decimal)
606 2.9 3.86e6 0 :layer2 parameters, depth of node at layer1/layer2
interface, basement conductivity (W/m-K), thermal capacity
(J/m³-K), porosity (decimal)
4.30e6 :parameter, thermal capacity of water (J/m³-K)
2.65e6 :parameter, thermal capacity of sediment (J/m³-K)
0.6 :parameter, thermal conductivity of water (W/m-K)
2.74 :parameter, thermal conductivity of sediment grains
(W/m-K)
0.7 :parameter, surface sediment porosity (decimal)
0 0 0 0 0 0.7 - :parameter, constants for porosity = f(z).
8.333e-4 0 0 A+Bz+Cz²+Dz³+Elnz+Fexp(G*Z)+H*(Z)
m :parameter, porosity = f(z) where z is in [m] or
[km]
0.0 :parameter, minimum allowable sediment porosity
(decimal)
0 0 :parameter, constants for permeability = f(\phi) when pressure term is used to drive seepage; perm = A exp(B*(\text{porosity}/(1-\text{porosity})))

0.5 :parameter, scaling factor \( \theta \) (for crank-nicholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed

2 :parameter, calculate heat flow between surface and this node

no :Flag, allow the removal of nodes from upper basement [yes/no] followed by maximum number of nodes to remove. Will remove a basement node when a sediment node is added

yes :Flag, write ouput to a text Log file [yes/no] (Will write input-file data regardless)

***************

1.e6 5 0.1 2000 1.1 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)

q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 :boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C(time^2)+D(time^3)+E/sqrt(F*time)

0 :boundary condition (upper) , temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa) ; (+) down/underpressure

0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

2 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.

3 2000 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

2.6 50 5 100 1.1 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params

q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 :boundary condition parameters for lower boundary

0 :boundary condition (upper) , temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in
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<th>Description</th>
</tr>
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<td>parameter, production/sink term for additional nodes during this stress period in (W/m^2)</td>
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<td>parameter, production/sink term for additional nodes during this stress period in (W/m^2)</td>
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</table>
filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

2 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3

20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

5.e6 5000 1000 100 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params

q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0 :boundary condition parameters for lower boundary
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)

0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

3 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3

20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

5.e6 5000 5000 100 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params

q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0 :boundary condition parameters for lower boundary
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa)

0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

3 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1
a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.

3

20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

**************

42 :node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic production/sink (W/m^2), [optional] conductivity (W/m-K)

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Constant sediment accumulation, variable porosity, high Nu basement aquifer, variable conductivity lower basement, and heat sinks that shut down linearly

The following input deck is used to model constant sediment accumulation at the rate of 100 m/M.y. Initial sediment thickness is 6 m, basement layer 1 is 600 m thick and basement layer 2 is 99.4 km thick. The thermal conductivity of basement layer 1 is elevated by a factor of 1000 above the true conductivity in order to simulate the thermal effect of vigorous local hydrothermal heat redistribution. The upper 2 km of basement layer 2 has a conductivity of 2 W/m² (specified directly in the node properties section of the input deck), and the remainder has a value of 2.9 W/m² (specified in the general parameters section of the input deck, line 4). Basal heat flux is 1 W/m² and the initial thermal gradient is uniform. Porosity decreases with depth defined by $\phi = 0.7e^{-z/1200}$ where depth ($z$) is in meters. Time stepping is variable, and data are only written to the Log file at the end of each stress period. Initial conditions consist of 80% of the lithospheric heat being extracted in the aquifer, and this continues for the first 5 M.y. as sediment accumulates. The heat sinks within the aquifer are then shut down linearly from 80-0% over the next 5 M.y. Figure 12 shows selected model results.

Header

This simulation uses two basement layers, with the upper one corresponding to a 600 m-thick basement aquifer ($K=1700$ W/m·K; $Nu=1000$) and the lower one having a MIXED conductivity; 2.0 W/m-K extends from the base of the aquifer for to a depth of 2000 m, and the remainder has a conductivity of $K=2.9$ W/m-K (the default)

Heat sinks are evenly distributed in the aquifer
Basal heat flux = 1 W/m²
100 km thick lower basement
Subsidence at 100 m/M.y. for 20 M.y. to accumulate 2000 m of sediment
Heat sinks are active for the first 5 M.y. (extracting 80%), then
ramp down linearly over the following 5 M.y.

Sediment-basement-interface at depth of 6 m

No Node removal allowed

Use porosity function from Davis et al., 1999 JGR

**************
sub : type of model, subsidence [sub] or sedimentation [sed]
6 : number of stress periods
6 1700 3.86e6 0 : layer1 parameters; depth of node at SBI (m),
basement conductivity (W/m-K), thermal capacity (J/m^3-K), porosity (decimal)
606 2.9 3.86e6 0 : layer2 parameters; depth of node at layer1/layer2
interface, basement conductivity (W/m-K), thermal
capacity (J/m^3-K), porosity (decimal)
4.30e6 : parameter, thermal capacity of water (J/m^3-K)
2.65e6 : parameter, thermal capacity of sediment (J/m^3-K)
0.6 : parameter, thermal conductivity of water (W/m-K)
2.74 : parameter, thermal conductivity of sediment grains
(W/m-K)
0.7 : parameter, surface sediment porosity (decimal)
0 0 0 0 0.7 - : parameter, constants for porosity = f(z).
8.333e-4 0 0 A+Bz+Cz^2+Dz^3+Elnz+Fexp(G*Z)+H^(Iz)
m : parameter, porosity = f(z) where z is in [m] or [km]
0.0 : parameter, minimum allowable sediment porosity
(decimal)
0 0 : parameter, constants for permeability = f(ffi)
when pressure term is used to drive seepage; perm =
Aexp(B*(porosity/(1-porosity)))
0.5 : parameter, scaling factor theta (for crank-
icholson solution; 0-1) 0=explicit, 1=implicit, 0.5=mixed
2 : parameter, calculate heat flow between surface and
this node
no : flag, allow the removal of nodes from upper
basement [yes/no] followed by maximum number of
nodes to remove. Will remove a basement node when a
sediment node is added
yes : flag, write output to a text Log file [yes/no]
(Will write input-file data regardless)
**************
1.e6 5 0.1 2000 1.1 : time, length of this stress period (in yrs)
followed by maximum time step (in yrs), Variable
params; initial timestep (yrs), # timesteps,
scaling factor (initial guess)

q
boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0
boundary condition parameters for lower boundary;
[T] or [q] = f(time in yrs);
A+B(time)+C/sqrt(D*time)
0
boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100
parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ]
parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure
0.0
parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ]
filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
2 0.5 0
parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.
3
20000 2.e4
parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

1.e6 50 5 100 1.1
time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
q
boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0
boundary condition parameters for lower boundary;
[T] or [q] = f(time in yrs);
A+B(time)+C/sqrt(D*time)
0
boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100
parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ]
parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure
0.0
parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ]
filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
2 0.5 0
parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.
3
2000 1.e6
parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)
3.6 e 500 50 100 1.1 : time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)

q : boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 : boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C/sqrt(D*time)

0 : boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 : parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] : parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure

0.0 : parameter, production/sink term for additional nodes during this stress period in (W/m^2)

[ ] : filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

3 0.5 0 : parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.

200 : parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File {Flag to write must be set to [yes} for writing to Log file)

5.6 e 1000 500 1000 : time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)

q : boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))

1 0 0 0 : boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C/sqrt(D*time)

0 : boundary condition (upper), temperature in degrees C that boundary is held constant at.

0.000100 : parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr

[ ] [ ] : parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure

0.0 : parameter, production/sink term for additional nodes during this stress period in (W/m^2)

sinks-off_600.hflx : filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes

2 0.5 0 : parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.
20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

5.e6 5000 1000 100 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
1.1
q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0 :boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C/sqrt(D*time)
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure
0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
3 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 == -1, variable node addition depth scaled by param. 3
20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

5.e6 5000 5000 100 :time, length of this stress period (in yrs) followed by maximum time step (in yrs), Variable params; initial timestep (yrs), # timesteps, scaling factor (initial guess)
1.1
q :boundary condition (lower), ([T] for Temperature (degrees C), [q] for heat flow (W/m^2))
1 0 0 0 :boundary condition parameters for lower boundary; [T] or [q] = f(time in yrs); A+B(time)+C/sqrt(D*time)
0 :boundary condition (upper), temperature in degrees C that boundary is held constant at.
0.000100 :parameter, basement subsidence rate or sedimentation rate during this stress period in m/yr
[ ] [ ] :parameter, [s] seepage followed by value in m/yr or [p] lower boundary pressure followed by value in (kPa); (+) down/underpressure
0.0 :parameter, production/sink term for additional nodes during this stress period in (W/m^2)
[ ] :filename containing constants for calculating production/sink (Q=f(t)) values for selected nodes
3 0.5 0 :parameter, subsidence distance (m) for addition of a new node followed by tolerance (0-1). If param 1 ==-1, variable node addition depth scaled by param.

20 1.e6 :parameter, number of time steps to increment before storing data in Mat File followed by writing to Log File (Flag to write must be set to [yes] for writing to Log file)

************* node, number of nodes. Following are node depths (m), initial temps (deg C), radiogenic production/sink (W/m^2), [optional] conductivity (W/m-K)

<table>
<thead>
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<th>Depth</th>
<th>Initial Temp</th>
<th>Temp</th>
<th>Temp</th>
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</tbody>
</table>
The file `sinks-off_600.hf.x` is shown below. Setting parameters A and B to zero would turn the heat sinks off instantaneously.

```
% ----------- Begin Header ------------
% This file contains constants for calculating production/sink terms as a function of time
% The equation in use is:
% \[ Q = A + Bt + Ct^2 + Dt^3 + E\ln(t) + F\exp(Gt) + H^I \]
% where t is time in years, and A-->I are constants.
% The first value in the line is the node depth, followed by the constants
% For basement nodes (whos spacing is constant but subside during the model simulation), depths
% are referenced to the ORIGINAL starting depth in the input deck.
% Note: Do not apply to boundary nodes or Sediment-Basement-Interface node!
% ----------- End Header ------------

8    -0.00535117056856188  5.35117056856188e-10  0  0  0  0  0  0
10   -0.00535117056856188  5.35117056856188e-10  0  0  0  0  0  0
12   -0.00802675585284282  8.02675585284282e-10  0  0  0  0  0  0
15   -0.01337792642140470  1.33779264214047e-09  0  0  0  0  0  0
20   -0.01337792642140470  1.33779264214047e-09  0  0  0  0  0  0
25   -0.01337792642140470  1.33779264214047e-09  0  0  0  0  0  0
30   -0.02675585284280940  2.67558528428094e-08  0  0  0  0  0  0
40   -0.02675585284280940  2.67558528428094e-08  0  0  0  0  0  0
50   -0.0668963210702340  6.6896321070234e-09  0  0  0  0  0  0
75   -0.08294314381270900  8.29431438127090e-09  0  0  0  0  0  0
106  -0.0668963210702340  6.6896321070234e-09  0  0  0  0  0  0
131  -0.0668963210702340  6.6896321070234e-09  0  0  0  0  0  0
156  -0.1337792642140470  1.33779264214047e-08  0  0  0  0  0  0
206  -0.2675585284280940  2.67558528428094e-08  0  0  0  0  0  0
306  -0.2675585284280940  2.67558528428094e-08  0  0  0  0  0  0
406  -0.53511705685618800  5.35117056856188e-08  0  0  0  0  0  0
```
11. Figures

Figure 1.
Schematic representation of the effect of sedimentation on the geotherm, incorporating one sediment layer and three basalt layers, where each layer has a different thermal conductivity. Basal heat flux is constant. Solid line shows conductive profile, dotted curve shows heat flux elevation due to seepage through the sediment section, and dash-dot curve shows heat flux suppression due to sedimentation.
Figure 2.
Cartoons describing the physical and numerical models. **A:** Physical model layering scheme. Sediment accumulates on top of a permeable basement aquifer where heat is transported by advection and/or conduction. Heat is transported purely by conduction within the underlying basement layers. **B:** The numerical representation of the physical model uses Eulerian and Lagrangian reference frames for the sediment and basement sections, respectively. Node depths are represented by the horizontal dashed lines, whereas time steps are represented by the vertical solid lines. The solid circles on each vertical line denote the finite difference node points used at that time step. **C:** Node and block properties used in numerical calculations: \( z \) is depth, \( T \) is temperature, \( \lambda \) is thermal conductivity, \( Q \) is a production or sink term, \( V_w \) and \( V_s \) are the water and sediment velocities, respectively, \( \phi \) is porosity, and \( k \) is permeability. The thermal conductivity of adjacent blocks \( \lambda \) is calculated using the harmonic mean of the enclosing nodes.
Figure 3.
Relation between sediment accumulation rate ($V_b$) and deposition rate ($V_o$). Numeric labels indicate sediment flux in m/M.y. $V_b$ can be taken as the velocity of the node at the sediment-basement interface, and $V_o$ as the velocity of material entering the model at the seafloor. As the model steps through time, normal consolidation and compaction of the sediment section requires that the flux of sediment across the seafloor must increase as basement subsides at a constant rate. When the deposition rate is constant, the velocity of the sediment-basement interface node must decrease with time.
Figure 4
SlugSed function call flowchart.
Figure 5.
Comparison to analytical solutions. Linear flow of heat in the solid bounded by two parallel planes. Case 1: The region 0<x<L. Ends kept at zero temperature. Initial temperature f(x)=Vo, constant. A. Temperature throughout the slab as a function of time. B. Comparison of SlugSed and analytical calculations at five different times, as labeled. C. Absolute value of temperature residuals between numerical and analytical calculations at five different times, as labeled.
Figure 6.
Comparison to analytical solutions. Linear flow of heat in the solid bounded by two parallel planes. Case 2: The region \(-L<x<L\). Initial temperature = 0, ends at constant temperature. A. Temperature throughout the slab as a function of time. B. Comparison of SlugSed and analytical calculations at five different times, as labeled. C. Absolute value of temperature residuals between numerical and analytical calculations at five different times, as labeled.
Figure 7.
Case 3: The region \(-L<x<L\). Zero Initial temperature. Heat production constant. A. Temperature throughout the slab as a function of time. B. Comparison of SlugSed and analytical calculations at five different times, as labeled. C. Absolute value of temperature residuals between numerical and analytical calculations at five different times, as labeled.
Figure 8.
Comparison to Benfield (1949) analytical solution at accumulation rates of 50 and 550 m/M.y. Differences are <0.1%
Figure 9.
Comparison to analytical solution for seepage [Bredehoeft and Papadopulos, 1965]. Depth is positive downward. A. Comparison of SlugSed and analytical calculations at three seepage rates, as labeled. C. Temperature residuals between numerical and analytical calculations at three seepage rates, as labeled.
Figure 10.
Figure 11.
Figure 12.
Constant sediment accumulation, variable porosity, high Nu basement aquifer, variable conductivity lower basement, and heat sinks that shut down linearly, as discussed in the text. A. Temperatures within accumulating sediments as a function of time. B,C. Heat flux, basement depth, and sediment-basement interface temperature as a function of time. D. Heat flux as a function of sediment thickness.
12. References


