```
C     Last change:  3 April 2014 by M. Fernandez
C     Version adapted to sbr-ATTEN, TAST and ABAST
C     Sinthetic tomography and reference model
C     delete line 4 entry mater
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCC
C        *****************************************************
C        * PROGRAM   "LITMOD_v4.0"  for Lithospheric Modelling  *
C        *****************************************************
C
C                         Written by:
C
C          J.C. Afonso(1),  H. Zeyen(2)  &  M. Fernandez(3)
C
C          (1) Macquarie University, Sydney, Australia
C          (2) University Paris-Sud, Orsay, France
C          (3) ICTJA-CSIC, Barcelona, Spain
C
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C
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C                    Sydney, Australia.  All rights reserved.
C
C Main Reference: Afonso et al., 2008, G-3, 9, doi:10.1029/2007GC001834
C Based on program CAGES by Zeyen and Fernandez (1994)
C
C*********************************************************************
C
C  LitMod is a self-consistent geophysical-petrological approach in which
C  most of the rock physical properties are derived from EOS. These
C  properties are externally calculated by the 'GENERATOR' code which after
C  reading the main oxides composition (given by the user) calculates the
C  mineral assemblages according to P-T conditions and the physical
C  properties according to EOS via PERPLEX. GENERATOR provides a set of tables
C  with the relevant properties (Vp, Vs, density, thermal conduct., thermal
C  expansion, etc.) at different P-T. These tables are used by LitMod as inputs.
C
C  The use of GENERATOR is mandatory for mantle bodies whereas for crustal
C  bodies is optional (i.e., crustal properties may be introduced in LitMod.inp
C  independently on rock composition.
C
C  The model extends down to 400 km depth (d410) and bodies can be coupled or
C  decoupled in calculating isostatic elevation to take into account processes
C  like subduction, slab detachment, etc. These decoupled bodies do not have
C  effects on calculated topography but they do on gravity/geoid calculations.
C  The lowermost point of the 'lithosphere model' should be ALWAYS at < 400 km
C  since the level of compensation is taken at 400 km (~d410).
C
C  The program solves the (heat) flux equation in 2D using "simplex" finite
C  elements assuming steady state. Temperature is fixed at the base of the model
C  (400 km) with a default values of 1520 ºC. Temperature is also fixed at the
C  base of lithosphere at 1320 ºC and below the LAB temperature evolves with an
C  adiabatic gradient between 0.35 and 0.5 ºC/km. To avoid unrealistic
C  discontinuities in the thermal gradient at the base of the lithosphere, a
C  temperature buffer is applied between the lithospheric and sublithospheric
C  domains (Afonso et al., 2008). With the calculated temperature and apriori
C  pressure the code reads the properties of each material, particularly
C  density, from GENERATOR and then calculates elevation, gravity, geoid and
C  synthetic tomography.
C
C  For topography below sea level the gravity effect before Bouguer reduction
C  is calculated at sea level. No water body must be defined. Gravity
C  calculations include Bouguer, Free Air and a combination of both.
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C  The Bouguer anomaly is calculated with a reduction density of
C  2670 kg/m3 after having calculated the total 2D effect of the model
C  mass below every surface node. The reduction is a full topographical
C  one. A reference model which occupies the same space below sea level
C  is substracted from the calculated anomalies in order to reduce
C  border effects. The resulting anomaly is shifted so that the mean
C  difference with the measured data becomes zero.
C
C  The geoid is calculated in 2D based on a formula for 3D rectangular prisms
C  (the triangles of the FE grid are converted by pairs to best fitting
C  rectangles), developed by HZ in
C      Zeyen et al., 2005, TECTONICS, 24,doi:10.1029/2004TC001639.
C  A 1D geoid calculation is also added following the formulas given by
C  Turcotte & Schubert 1982 (Geodynamics), p. 225-226, i.e. taking all
C  distances from sea level and integrating rho(z)*z*dz from topo to
C  depth of compensation (Caution: in Turcotte & Schubert, topography
C  has a different sign than depth, which is not the case in LitMod).
C
C**********************List of main changes*******************************
C
c     Begining of LitMod generation: TO BE CHECKED (MF_15aug2012)
c
C
c 01.Jan.2007:  First thermodynamically self-consistent version of LitMod.
C              It works with self-consistent thermodynamic databases for mantle
C              domains and with petrological models of oceanic lithosphere.
C              Thermal conductivitites and seismic velocitites are calculated
C              with newer models of composites. The thermal conductivity of all
C              mantle bodies are explicitly modelled as a function of pressure
C              (strictly, depth) and temperature, but not as a function of
C              composition. The code works together with Perple_x, which is
C              used in a pre-modelling stage to obtain thermodynamic info
C              for different lithospheric bodies. (JCA)
c Dec 2010:     Now the code can be used to model crustal bodies with the
c              same thermodynamic formalisms as for the mantle. Although
c              not strictly necessary, these crustal bodies should be identified
c              with LITHO numbers 1 < LITHO < 10 in the Litmod.inp file. (JCA)
C June 2012:    Thermal conductivity is now calculated as function of composition,
c              temperature, and pressure following the newest models of Anne
c              Hofmeister (parameterised by Chirs Grose). This version is really
c              messy in the way it does it... to be improved. (JCA)
c May 2013:     Cleaning the code and subroutines. This new version does not
c              incorporate calculations in 2.5D, rheology (strength envelopes)
C              and some input and boundary conditions are fixed
c              The following variables have been deleted: MODGRA, XW, XE,
C              NCOLUMN,ICOLUMN, COMSTR,EXTSTR, SSSTR, TOTCOM, TOTEXT, TOTSS,
C              U0, XL0. The following subroutines have been deleted: GRAV25,
C              DENINP, NUDTOT, CALGEO2D (MF)
C              Input parameters in litmod.inp have been changed! (MF)
C Mar 2014:   Incorporation of perturbations within the sublithospheric mantle.
C              Perturbations can be introduced by:
C              1.- An external file 'tomo1level.dat' where seismic velocities
C                are given for up to 4 depth levels. Seismic data can be either
C                Vp(%), Vs(%), Vp-absolute or Vs absolute. See sbr-TAST.
C              2.- Anomalous sublithospheric bodies. In this case, bodies can
C                have anomalous composition (C), temperature (T) or seismic
C                velocity(V). In each body, a combination of C-T or C-V can be
C                given. Any combination of C-T-V is allowed for different bodies.
C                see sbr-ABAST
C            When sublithospheric mantle perturbations are given, the code
C            calculates both, coupled elevation (i.e. considering that density
C            anomalies beneath LAB are transmitted to surface elevation) and
C            decoupled elevation (i.e., when these anomalies are not
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C             transmittedto surface elevation but to potential fields and
C             seismic velocities). (MF)
C
C             Incorporation of attenuation through subroutine ATTENU (MF)
C             Calculation of sinthetic tomography relative to a thermodynamic
C             reference model (Pr-2). (MF)
C
C             New SUBROUTINES: TAST, ABAST, ATTENU (MF)
C
C
C***********************************************************************
C
C               PARAMETERS TO BE READ BY THE INPUT FILE (ALL MANDATORY)
C
C
C 0. INPUT AND OUTPUT FILE NAMES
C
C    If a file name is blank, this file is not used (read or written)
C
C    1. Input file elevation data (1st line is interpreted as header).
C           Ideally points must coincide with nodes.
C    2. Input file gravity data (1st line is interpreted as header)
C           Ideally points must coincide with nodes.
C    3. Input file free air data (1st line is interpreted as header)
C           Ideally points must coincide with nodes.
C    4. Input file geoid data (1st line is interpreted as header)
C           Ideally points must coincide with nodes.
C    5. Output file elevation result (1 header line)
C    6. Output file Bouguer gravity result (1 header line)
C    7. Output file free air (1 header line)
C    8. Output file free air offshore, Bouguer onshore (1 header line)
C    9. Output file geoid results in 2D and 1D (1 header line)
C   10. Output file temperatures (1 header line)
C   11. Output file surface and asthenospheric heat flow (1 header line)
C   12. Input file 'tomo1level.dat' with
C       line #1 NLEVELS (max. 4) and ISEIS (code for seismic data)
C       line #2 ZLEVEL. Depth in m (negative downwards) of the anomalous level
C       line #3-n Seismic perturbation in each node of ZLEVEL (10F6.3). NX data.
C       lines #2 and #3-n repeat NLEVELS times.
C       level at -400000 m is mandatory (including perturbations at that depth)
C   13. Output file FREE for future use
C   14. Output file FREE for future use
C   15. Output file with results of special material boundaries
C       (ok for "TMOHO") ADD PRESSURE AND AVERAGE DENSITY
C   16. Output file with body limits
C   17. Output file with element boundaries
C   18. Output file FREE for future use
C   19. Output file with P,T at every node (1 header line?)
C   20. Output file for densities
C   21. Output file which serves as input file for Transient-LitMod
c   22. Index of Thermodynamic database used (see Generator.exe)
C
C 1. TITLE              FORMAT 72A1          SUBROUTINE INPUT
C
C 2. MATER,NCORP,IEL_C,DSIZE,IOSPE,IPRINT
C                       FREE FORMAT           SUBROUTINE INPUT
C          MATER: Number of different materials (Last material must be
C                asthenospheric material!)
C          NCORP: Number of different bodies
C          IEL_C: Control on density variations within the sublithospheric
C                mantle due to thermal or compositional anomalies.
C                = 0: Sublithospheric mantle homogeneous and without thermal
C                     anomalies.
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C                 = 1: Sublithospheric mantle affected by anomalies of thermal
C                      and/or compositional origin. Anomalies can be prescribed
C                      in given nodes over given depth levels via external file
C                      (only seismic perturbations), or defining anomalous
C                      bodies within the sublithosphere, thus requiring either
C                      thermal or seismic perturbations to be prescribed.
C                      Both coupled (anomalous asthenosphere influences elevation)
C                      and decoupled (elevation is not affected by sublithospheric
C                      perturbations) elevations are calculated.
C          DSIZE: Mantle grain size (mm). Recommended value = 5.0 Range = 3. - 15.
C          IOSPE: Oscillation period. Chose among 50, 75 and 100 seconds.
C         IPRINT: Parameter for the print of entries and results:
C                 IPRINT = 0: Results are printed for all nodes,
C                             entries are not printed
C                        > 0: Results for all nodes and entries are
C                             printed
C                        < 0: Results are printed only for interfaces
C                             and special columns (surface and base
C                             in any case), not for all nodes. Entries
C                             are not printed.
C
C  3. 3xMATER lines (see 2.) with the description of the materials:
C     3.1 Identification:      NCAPA,LITHO
C     3.2 Thermal parameters:  HPA,HPB,C1,C2,AL2,TCT,TCD
C     3.3 Density parameters:  RHO,FACRHO,ITDEP,DILAT
C                                    FREE FORMAT     SUBROUTINE INPUT
C          NCAPA:     Identification number of the material
C                     The asthenospheric mantle has to be the last
C                     material entered.
C          LITHO      < 0: Sedimentary layer. Density is read in for
C                          every column (see below: 6.)
C                     = 0: General layer (no associated thermodynamic table)
C                     1 <= LITHO <= 10: Crustal layer with a thermodynamic table
C                     > 20: Lithospheric mantle bodies: a thermodynamic table
C                           must be associated with this body (same number).
C                     =99: Ashtenosphere (needs thermodynamic table)
C          HPA,HPB    HPA = Parameter A0 of the heat production (W/m3)
C                     HPB = Reference thickness B for the exponential
C                           term of heat production. [m]
C                     IF HPB = 0.: Constant production (= HPA)
C          C1,C2,AL2: Description of the conductivity tensor for the
C                     solution of the transport equation [W/m K]. Conductivity
C                                 for mantle materials comes from thermodynamic table and
C                                 values are not used but needed.
C          TCT:       Temperature dependence of the thermal conductivity
C                     If TCT=0: No temperature dependence
C                     ELSE: for the crust:
C                        C=C0/(1+TCT*T)
C                     For mantle bodies a thermodynamic table is used unless
C                                                    TCT=0 and then is constant.
C          TCD:       Depth dependence of thermal conductivity
C                     IF TCD=0., No depth (pressure) dependence
C                     For mantle bodies a thermodynamic table is used unless
C                                                    TCT=0 and then is constant. In this case TCD is irrelevant.
C                     Depth coordinates are metres
C              Recommended values:
C                     Sediments:   C0=1.3  TCT=0.      TCD=0.7D-4
C                     Upper crust:    3.0      1.55D-3     0.
C                     Lower crust:    2.5      0.80D-3     0.
C          RHO:       Reference density in kg/m**3. Requires (LITHO=0)
C                     Normally this number is the density at the
C                     surface (zero presure and zero temperature).
C                     Mantle materials read density from thermodynamic table.
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C         FACRHO:    Is thought for use in the upper crust, but can be
C                    used anywhere else (even for the sediments).
C                    Density is then: RHO*(1+FACRHO*P), being:
C                    P = Pressure at the node in Pa [Pa**-1]
C         ITDEP:     = 0: Density is independent of temperature
C                         (mainly for the crust)
C                     <>0: Density depends on temperature
C         DILAT:     Coefficient of thermal expansion (valid only for the crust)
C
C   FOR ANOMALOUS BODIES WITHIN THE ASTHENOSPHERE (IEL_C=1)
C
C         RHO < 0    Denotes that this body is anomalous in composition, or
C                    temperature, or seismic velocities
C         FACRHO: denotes DT in K or C-degree (needs ITDEO < 0)
C         ITDEP: Type of anomaly
C            > 0 denotes VTOMO code for v-anomaly
C                (1) Tomography referred to Vp(%)
C                (2) Tomography referred to Vs(%)
C                (3) Tomography referred to Vp(>6.5), Vs(<6.5)
C            = 0 denotes no T- or v- anomaly
C            < 0 denotes T-anomaly
C         DILAT: Average VTOMO values according to ITDEP
C
C  4. This group is given NCORP times, describing the different bodies
C
C    4.1 NMAT        FREE FORMAT              SUBROUTINE CUERPO
C              NMAT: Identification number of the material forming
C                    the body.
C
C    4.2 XC(I),ZC(I),I=1,4     FORMAT  8F8.0     SUBROUTINE CUERPO
C              Coordinates of the corners of the bodies (X,Z)
C              In every line 4 corners are defined. The last corner
C              given has to have the same coordinates as the first one.
C              Z is positive upwards.
C
C        In subroutine MATERI the bodies to which the elements belong
C        are calculated, taking as reference the mass center of the
C        element.
C
C  5. Boundary conditions and dimensions of the net
C
C    5.1 - 5.3: 3 lines with five numbers each, describing the default
C              boundary conditions. The order of these five values is:
C              1. General condiciones
C              2. Conditions at the upper limit
C              3. Conditions at the lower limit
C              4. Conditions at the left border
C              5. Conditions at the right border
C
C    5.1 ICOD               FREE FORMAT           SUBROUTINE NUDXZ
C           ICOD: Code for the fixed conditions:
C                 = 0: Fixed heat flux
C                 = 1: Fixed temperature
C                      usually (0,1,1,0,0) -> fixed T at surface and LAB
C
C    5.2 HEAT              FREE FORMAT           SUBROUTINE NUDXZ
C            HEAT:  Fixed heat flux (W/m) integrated over half of the
C                   contiguous element boundaries for border nodes
C                   where ICOD=0. For nodes at the four corners, this
C                   value is automatically reduced to one half.
C                   However, if the grid spacing is not regular, the
C                   heat flux has to be defined manually for every
C                   corresponding node (see 5.7). This is especially
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C                    the case if non-zero horizontal heat flow is
C                    defined at the vertical model boundaries.
C                              usually (0.,0.,0.,0.,0.) -> no heat flow is imposed at any
C                                                 boundary
C
C     5.3 TEMP               FREE FORMAT           SUBROUTINE NUDXZ
C            TEMP: Fixed temperature for border nodes where ICOD=1
C                              usually (0.,15.,1320.,0.,0.) -> only Tsup and Tlab are
C                                                 imposed
C
C     5.4 DIMENSIONS OF THE NET:
C         X0,DX,NX,NZ   FREE FORMAT          SUBROUTINE NUDXZ
C            X0:    Origin of the net (meters).
C            DX:    Distance between two horizontal nodes (meters)
C            NX:      Number of nodes in X direction
C            NZ:    Must be set to 96 ALWAYS.
C
C         ATENTION!! VERY IMPORTANT:
C                              NX > 96 (or > NZ) ALWAYS. Then, the nodes are numbered by
C                              columns, e.g.:
C                            1  4  7 10
C                            2  5  8 11
C                            3  6  9 12
C
C     5.5 Z(I), I=1,NZ    FORMAT 8F8.0     SUBROUTINE NUDXZ
C         Z-coordinates of the rows (from top to down)
C         Z(I) are not taken as fixed values, but the column between
C         Z(1) and Z(NZ) is fitted between the surface and base level of
C         every column (calculated from the body limits).
C
C  6. Mean sediment density for every column if LITHO<0 (FORMAT(10F6.0))
C                                        SUBROUTINE INPUT
C     The densities must be given for all columns, not only where they are
C     needed (i.e., bodies containing LITHO < 0). Densities in kg/m3.
C
C  7. Description of output of special material limits.
C
C     7.1 NLIMIT,ILIMIT(1,...,2*NLIMIT)   FREE FORMAT  SUBROUTINE INPUT
C         NLIMIT = Total number of material limits for which the
C                resulting temperature, horizontal and vertical heat
C                flow are outputted to print.
C         ILIMIT = Two numbers for every material limit indicating the
C                codes (= NCAPA, see 3.) of the materials which
C                contact at the desired limit.
C
C*********************************************************************
C
C  INPUT FILE WITH SEISMIC PERTURBATIONS (file='tomo1level.dat')
C       line #1 nlevels, nrem: number of levels (<5) and reference earth model
C       line #2 ZLEVEL(nlevels). Depth (negative downwards) of vtomo-level
C       line #3-n vtomo(nl,j): vtomo values for each level (j=1,nx) (10F6.3).
C       lines #2 and #3-n repeat NLEVELS times.
C       level at -400000 m is mandatory (including perturbations at that depth)
C       nrem:
C          case (1). Tomography referred to Vp(%)
C          case (2). Tomography referred to Vs(%)
C          case (3). Tomography referred to Vp(>6.5), Vs(<6.5)
C
C*********************************************************************
C
C  THERMODYNAMIC DATA
C
C  Thermodynamic calculations of material properties at different P-T
```

```
C  conditions are permorfed by GENERATOR.FOR
C  LITMOD requires to know with which thermodynamic database GENERATOR
C  calculated the thermodynamic tables for each body (composition).
C  The thermodynamic database is identified by an index (integer*2) in
C  line 22 of Input/output filenames.
C  The thermodynamic tables for each material (composition) are identified
C  by LITHO in each body. These tables contains the following parameters:
C  R1:T(K); R2:P(bar); R9:Vp(km/s); R10:Vs(km/s); R12:RHO(kg/m3);
C  R25:dVp/dT; R26:dVs/dT; R28:dVp/dP; R29:dVs/dP; R50: k(W/m K).
C
C  Presently GENERATOR generates thermodynamic phases within the T range
C  of 250 to 1800 C, which results in DT of +/-280 C or a DVp of +/- 1.3%
C  and DVs of +/- 2.5%. Larger DV need modification of GENERATOR.
C
C**********************************************************************
C
C  Logical units (LU ASSIGNED NUMBER):
C
C  INELE   (1): Input of measured topography data (read in subr. OUTPUT)
C  TEMOUT  (2): Output of calculated temperatures
C  FLUOUT  (3): Output of surface and LAB heat flow
C  ELEVUT  (4): Output of calculated topographic elevation
C  INP     (5): Input of program parameters
C  OUTP   (98): Control output (PRINT)
C  STCOUT  (7): Output file set FREE for future use
C  STEOUT  (8): Output file set FREE for future use
C  COLOUT  (9): Output file set FREE for future use
C  COROUT (10): Output of the corner coordinates of the bodies
C  GINP   (11): Input of Bouguer gravity data
C  GOUT   (12): Output of calculated gravity
C  MATOUT (13): Output of results along special material boundaries
C  ELEMUT (14): Output of element boundaries
C  STROUT (15): Output file set FREE for future use
C  POUT   (16): Output of Pressure and Temperature for every node for
C                                  VELPREP. To be set FREE
C  IOUT   (17): Output of material, body, node and element specifications
C         for RECAGES
C  DINP   (18): Input file set FREE for future use
C  DOUT   (19): Output of densities
C  FREOUT (20): Output of free air anomaly
C  FREINP (21): Input of free air data
C  FBOUT  (22): Output of combined free iar and Bouguer anomalies
C  GEOIN  (23): Input of geoid data
C  GEOUT  (24): Output of geoid data
C
C**********************************************************************
C
C  Minimum dimensions of the vectors and arrays used in the programs
C
C  If the net consists of NX*NZ nodes:
C  MAXNX  = NX
C  MAXNZ  = NZ
C  MAXNUD = NX * NZ
C  MAXELE = (NX-1) * (NZ-1) * 2
C  MAXBAN = MIN(NX+2,NZ+2)
C  MAXPAR = 4 * MAXNUD: Maximum number of non zero elements in the
C                    matrix to be inverted.
C  MAXMAT   Maximum number of materials
C  MAXCOR   Maximum number of bodies
C  MAXNC    Maximum number of corner points for any body
C
C  MEMTOT=277*MXNUD+8*MXBAN*MXNUD-152*MXNZ-116*MXNX+152+100*MXMAT+
C     (16*MXNC+8)*MXCOR+50K (for the rest of used variables)
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C
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CC
C