From tectonic reconstruction to upper mantle model: An application to the Alpine–Mediterranean region

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ABSTRACT


The seismic velocity structure of the upper mantle and lithosphere in the Mediterranean region is very complex: many areas with anomalous P-wave velocities can be recognized by means of seismic tomography. In view of the complicated tectonic evolution of the peri-Mediterranean orogens and basins this is not surprising. In this study we will show results of a modelling approach we have recently developed to predict this structure. In this approach we make a quantitative connection between the tectonic evolution on one hand and the present seismic velocity structure on the other. Our model predicts the evolution of temperature distributions in the lower lithosphere and upper mantle, by simulating the flow of material inferred from a kinematic description of lithosphere-scale processes. From the modelled present thermal state (the endpoint of an evolution) we calculate expected seismic velocity anomalies that can be compared with results obtained by seismic tomography. Thus, the method enables us to compare the implications of geological reconstructions, describing the past tectonic processes, with seismological results for the present structure. The predicted mantle models show a good correlation with the tomographic results obtained for the mantle. This means we can verify many features present in the tectonic scenarios with the seismologically determined deep structure.

The geological evolution of the Mediterranean region has been subject of many studies (e.g., by Biju-Duval et al., 1977; Dercourt et al., 1986, 1990; Dewey et al., 1989) that often arrive at different descriptions of the events that have led to the presently observed tectonic structure. These tectonic reconstructions are based on large amounts of geological and geophysical data. However, it appears that the data pertaining to the shallow (lithospheric) structure are simply not sufficient to decide between various possible hypotheses describing the tectonic evolution. We have developed a forward modelling approach that may be helpful in analysing the merits of various tectonic scenarios. With this modelling we can produce a detailed quantitative description of the present thermal and seismic velocity structure of the deeper lithosphere and upper mantle. Because the model is derived without making use of deep seismological data, the velocity structure we obtain can be tested against independent tomographic results which describe the P-wave velocity structure of the lithosphere and mantle (Spakman, 1988; Spakman et al., 1993). This procedure enables us to compare the kinematic implications of geological and geophysical field observations with results obtained by deep seismic imaging. In this study we will use our synthetic models as tools for the verification of hypotheses for the tectonic evolution. One could employ the same modelling method as a geodynamic process-oriented analysis of the tomographic images. The difference between these viewpoints is in the eye of the beholder: in the first case the objective is verification of a given tectonic hypothesis, in the
second case the objective is the understanding of the present mantle structure as a result of geodynamic processes. We will model features present in the tectonic reconstructions to a detail of typically a few tens of kilometres where we consider these important for the structure of the lithosphere and mantle. This limits the amount of detail that we can describe. However, the resolution of the tomographic results against which we compare our models is at best 40 to 80 km.

The modelling method

The approach we use to couple the tectonic evolution to the present seismic velocity structure of the Mediterranean lithosphere and upper mantle is schematically shown in Figure 1. We will briefly describe the various steps needed in our approach (for a more detailed description see De Jonge et al., 1993):

- Select a, sufficiently detailed, tectonic evolution that is to be tested (or on the basis of which the mantle structure is analyzed).
- From this description estimate initial properties of the modelling volume, like (thermal) age of oceanic regions, thickness of continental crust, etc.
- Determine the time-dependent kinematics of the various parts of the region, like extension of lithosphere and rate of relative convergence of lithospheric fragments.
- Use the above-mentioned parameters to numerically determine the thermal development of the lithosphere and mantle from its initial state towards the present.
- Use the temperature dependence of the seismic velocity to calculate the P-velocity structure from the predicted present temperature distribution.
- Compare modelled structure with seismic tomography results.

If a predicted velocity structure and the tomographic description do not show a good correlation, the discrepancies can result from three important modelling errors (see also the numbers in the flow chart of Fig. 1). For a given part of the models one or more of the following problems may play a role:

1. The tectonic reconstruction is not correct. This implies we (possibly correctly) model an evolution that has not occurred. If this were the only source of errors in our procedure we could quickly falsify incorrect tectonic hypotheses (we cannot verify correct ones because of the non-uniqueness of the thermal structure).

2. Our modelling approach is not correct. Errors of type 2 imply incorrect modelling of a possibly correct description of the tectonic evolution. This may be a result of simplifications or omissions in our modelling procedure.

3. The tomographic image is not correct. This may result from many causes (Spakman et al., 1993). All of these, however, are independent of our modelling. Identifying errors of this type can be useful for improving our understanding of the tomographic images. These errors can in some cases be hard to discern from the previous two, but in general it is possible to estimate the relative reliability of the tomographic results. In this
work we will not discuss type 3 errors in detail, but we will take the tomographic results at face value with some restraint on interpretation of possible misfit between predictions and structures in areas poorly resolved in tomography.

When we find a good correlation between tomography and modelling results, this supports the kinematic description and the implied processes given by the tectonic reconstruction. It also lends support to the reliability and usefulness of our modelling method, by implying that at least for some parts of the mantle we do not have type 2 or 3 errors.

Because our modelling approach produces the thermal evolution of the lithosphere and mantle, interesting secondary result of the model can be derived as a ‘by-product’ (see the grey path in Fig. 1). Two of the independent quantities that we will discuss are the evolution of basin subsidence and the evolution of heat-flow density, which are both strongly controlled by the thermal evolution.

**Kinematic model**

The kinematic model is a quantification of the geological evolution over a period of typically many tens of million years. Our approach implies that we make a fundamental assumption about the nature of mantle processes: we assume that tectonic processes cannot be considered separately from processes in the underlying mantle. In our modelling we link the principal processes, that we infer from tectonic reconstructions, to processes influencing the underlying mantle. Specifically, we assume that large amounts of convergence between lithospheric fragments are accommodated at subduction zones and that increase in surface area of lithosphere is diagnostic of extension (which we associate with upwelling...
of mantle material). As a result the mantle will show thermal perturbations that are related to processes observed at the surface.

Figure 2 shows the concepts of the translation of horizontal displacements as described in a tectonic reconstruction (which is restricted to the outer shell of the Earth) towards depth modelling. In this figure the top panels give a schematic sequence of stages of the geological evolution in the map view in which they are normally presented in a reconstruction. The bottom panels in this figure depict the processes that we infer from this evolution. The features shown in this figure that determine the thermal structure are (more or less in decreasing order of importance for the thermal model):
- position of subduction zones as a function of time;
- time of formation of oceanic lithosphere at spreading ridges (which determines the thermal age of the lithosphere);
- composition and initial thickness of continental lithosphere (which determine the initial temperature distribution);
- rate and direction of relative convergence as a function of time;
- timing and magnitude of extension processes.

The thermal effects of the inferred processes are calculated in two dimensions for small segments of the plate contact (in a cross-section perpendicular to the margin in question). This method is similar to the one described by for example Minear and Toksöz (1970) or de Jonge and Wortel (1990). The actual path followed by material descending into the mantle is based on the convergence velocity and on the angle of dip of subduction. We can estimate a dip angle on the basis of convergence velocity, age, and composition of the lithosphere nearby the subduction contact. For a discussion of the lithospheric age dependence of slab dip see Wortel and Vlaar (1978, 1988).

For intraplate extension processes the vertical component of motion is derived by modelling extension as a (time dependent) pure shear deformation. This is essentially a minor modification of the stretching model proposed by McKenzie (1978). The surface motion given in the used tectonic reconstruction dictates the amount of stretching required for each time step. In the model asthenospheric material flows in from below in order to maintain a mass balance.

**Thermal model**

We treat the determination of the development of the thermal structure of the mantle as an initial value (convection–diffusion) problem in which both the initial structure and the — explicitly given — material flow field are prescribed by the geological reconstruction. The initial structure may be different for various parts of the model; it depends on the type and age of the lithosphere present at a given position at the beginning of the time-span under consideration.

The kinematic model, derived from the investigated plate tectonic history, is used to displace these initial reference structures. Material flow is modelled by (discrete) translation of the initial structure in small time steps (0.1 to 0.5 My) for the entire period of the considered tectonic evolution. For every time step the thermal structure is determined by calculating the thermal diffusion with a two-dimensional finite-difference method. This calculation yields two-dimensional results, in the form of approximately 400 vertical sections for the entire Mediterranean, which are combined into a three-dimensional model only after the thermal diffusion is evaluated. The approach has the disadvantage that some possible lateral heat loss, out of the plane of the vertical section, is ignored. This means we may overestimate the magnitude of the anomalies in strongly curved subduction zones and small extensional basins. But, in most cases (small curvature and wide basins) the approximation will be reasonably accurate.

**From thermal model to seismic velocity structure and other geophysically observable quantities**

When the three-dimensional thermal structure is determined, this is the starting point to predict other geophysical quantities and observables like seismic velocity and heat flow density. For the velocity perturbations this conversion consists of
scaling the deviation from the average temperature at a given depth with a depth dependent P-velocity temperature derivative \( \frac{\partial V_p}{\partial T} \) (De Jonge et al., 1993).

The velocity perturbation is calculated by multiplying the difference between model and average temperature (for a certain depth) with this derivative. Note that this is only an approximation, as our \( \frac{\partial V_p}{\partial T} \) is a constant for a given depth, whereas in fact it depends on temperature and pressure.

Beside this synthetic \( V_p \) perturbation, we derive from the thermal model two other parameters: the thermal subsidence and the basement heat flow density. The subsidence is determined by (numerically) integrating the temperature and composition dependent density of a vertical column of material and requiring a constant pressure at a large (compensation) depth. This synthetic subsidence can be compared with backstripped stratigraphic data.

The basement heat flow density is calculated from the temperature gradient across the top layer of the thermal model and the average thermal conductivity of the crust at a given point. In both heat flow and subsidence calculations the contributions of a possible sedimentary cover or erosion have been ignored.

**Modelling the evolution of the Alpine–Mediterranean region**

We have selected three tectonic scenarios to which we apply our modelling approach. These are the reconstructions by Dercourt et al. (1986), Dewey et al. (1989), and Dercourt et al. (1990). The tectonic reconstructions describe the evolution of (parts of) the Mediterranean region in the form maps of major structural and geographic features for different stages of the development. In De Jonge et al. (1993) we focused our attention primarily on structures in the mantle formed during the Eocene to Recent development of the Mediterranean. In this study we will also discuss the implications of earlier stages of the evolution (from Middle Cretaceous onwards) which are especially relevant for the Alpine, Carpathian and Tauride–Pontide chains. For this reason we have also modelled the reconstruction given by Dercourt et al. (1990) of the evolution of the Northern Tethys margin (DRC-III model). Figure 3 shows the coverage in time of the used tectonic reconstructions. We will refer to the synthetic velocity structures based on these tectonic reconstructions as:

- DRC-I, which is derived from the Dercourt et al. (1986) work, with an additional assumption
about the Hellenic subduction zone (De Jonge et al., 1993).
- DRC-III, containing information from the Der-
court et al. (1990) and the Dercourt et al. (1986)
work.
- DRW, containing information from both the
Dewey et al. (1989) and the Dercourt et al. (1986)
work.

Because the surface area covered by the three
tectonic reconstructions is not the same – Der-
court et al. (1986) describe the entire western
Tethys, the other two only specific areas of inter-
est –, we have used results of the DRC-I model
to complete the untreated parts of the other two,
so that the model results can be compared more
easily. The ‘missing’ DRC-II model was designed
to test possible settings of the subduction process
in the Alboran Sea (Southern Spain), for the
region discussed in this paper it does not differ
from the DRC-I model.

For a proper comparison of the synthetic mant-
le structure and the results obtained by seismic
tomography (Spakman et al., 1993), we project
the structure onto a block model with the same
cell sizes as the tomographic results (see Fig. 4).

Results and discussion

In De Jonge et al. (1993) we found that the
overall correlation between synthetic mantle
structure based on recent tectonic reconstruc-
tions and seismic tomography results obtained by
Spakman et al. (1993) is quite good. The pre-
dicted structure below Calabria, the Tyrrhenian
Sea, the Sea of Crete and the Hellenide–Di-
naride chains seems to be determined almost
exclusively by the tectonic evolution from Eocene
towards the Present.

The following figures show horizontal sections
at different depths through the modelled mantle
structure. The top panel in every figure is the
image of the mantle obtained by seismic tomogra-
phy (EUR89B model of Spakman et al., 1993).
The other three panels show the various possibili-
ties that we model from different tectonic hy-
potheses. All panels show the seismic P-wave

Fig. 4. The tomographic model by Spakman et al. (1993) (EUR89B) with discrete cells (thin lines) and the area covered by our
predicted models (thick line). The dashed line indicates the line of section for Figs. 10 and 11.
velocity anomaly relative to ambient mantle velocities

The seismic velocity structure of the lower lithosphere and upper mantle

In Figure 5 we show the velocity structure at an average depth of 95 km (the layer thickness in the tomographic results is 50 km). In this figure the main features of the predicted structures do not always correlate well with the (EUR89B, top panel) tomographic image. The most important difference between the EUR89B image and the predicted models is the discrepancy below the Apennines and Calabria: our synthetic models all predict at least some high-velocity anomaly in this region, whereas the tomography shows a marked velocity minimum. For other parts of the Alpine–Mediterranean region we seem to predict the seismic velocity structure correctly. The low-velocity zone south of the Balearic Isles (lower left corner of the panels) is prominent in both tomographic and predicted structures; the high-velocity root below the western Alps, the Dinarides, and the Hellenic arc is also present in both approaches. It must be noted however, that the structure in the northeast corner of the DRW and DRC-I models (Carpathian region) seems to be poorly predicted. In this region we have problems in judging the importance of such a discrepancy because the tomographic results exhibit a poor resolution (Spakman et al., 1993), this could imply a type 3 error in the sense of Figure 1. If the tomographic results, showing a high-velocity zone running north–south below Rumania and a low-velocity region West of this, are significant we may conclude that the tectonic evolution of the Carpathian–Pannonian region used in the DRC-III model is the most reliable (smallest amount of possible type 1 errors).

At a depth of 195 km (Fig. 6), the correlation between predicted and tomographically determined structures improves remarkably. A high-velocity belt now also appears under the Apennines. The agreement between our thermally derived models and the tomographic image is good throughout the northern peri-Mediterranean chains including a good fit for complex regions such as the Alps and the Aegean Sea. The low-velocity region underlying the Pannonian basin inferred from seismic tomography is again more accurately predicted with the DRC-III model. Below Turkey, the synthetic structure of the mantle shows a system of two high-velocity regions

Fig. 5. Horizontal cross section through the tomographic model (EUR89B, top panel) and three predicted possible mantle structures at a depth of 95 km. Percentages denote the relative P-velocity perturbation.
that are the result of the modelling of two, asynchronous, parallel and oppositely dipping, subduction zones in this region, that is given in both the Dercourt et al. (1986) and the Dercourt et al. (1990) reconstructions. This feature correlates well with the seismic tomography results.

In Figures 7, 8 and 9, we show three deeper levels of the velocity structures; at these levels the correlation between the EUR89B image and the predicted velocity distributions remains good. In fact, for the deeper layers the high-velocity anomaly below the Carpathians, predicted in the DRC-III model is now also found in the tomographic image of EUR89B.

The cause for the discrepancies between synthetic and tomographic results, below the Apen-
Fig. 8. Section across the same models as shown in Fig. 5, at a depth of 425 km.

Minerals at 95 km and below the Western Carpathians at 95–195 km, may very well lie in the fact that we are representing subduction zones as continuous cold regions extending down from the surface. In this part of the Alpine–Mediterranean region we interpret from the tomographic results however, that the subducted lithosphere is detached and has sunk to a larger depth (see Spakman, 1990; and Wortel and Spakman, 1990, 1992, 1993). When this is really the case, we make a modelling error of type 2 by ignoring the thermal effects of the more rapidly sinking cold lithosphere. In how far this is the case in the Carpathian region, is at present not clear; we may be looking at either type 2 modelling errors or at type 3 errors.

Fig. 9. Section across the same models as shown in Fig. 5, at a depth of 565 km.
Fig. 10. Evolution of basin subsidence for a cross section of the Tyrrhenian Sea and Gulf of Lion (left-hand side: continental margin of southern France, right-hand side Calabria). The section crosses Sardinia. The left panels are based on the work of Dewey et al. (1989), the right panels on the work of Dercourt et al. (1986). The thick lines denote the predicted evolution of tectonic subsidence, the grey area in the final panels shows the present sea-floor topography at the same scale.
Evolution of heat flow density

Fig. 11. Evolution of heat flow density for the same section as Fig. 10. Thick lines denote the predicted evolution of heat flow density. The dashed line and the grey area in the final panel show the presently observed heat flow density (with uncertainty range) after Hutchinson et al. (1985).
Secondary results

The comparison of the P-velocities determined by forward modelling of the kinematics and those found by seismic tomography shows that we can predict the effects of the larger-scale processes in the region, but for the detailed analysis of smaller features the resolution of EUR89B is insufficient. We want to compare our thermal results to a different data set to see if the thermal modelling is reliable at this scale. For the top layer of the model we therefore calculate the heat flow and subsidence that accompanies the extension predicted by the tectonic reconstructions. These parameters are also important if the thermal models are used to constrain the internal evolution of sedimentary basins.

Figure 10 shows a section through the Tyrrenian Sea and the Gulf of Lion (for the section location see Fig. 4). The panels give the evolution of the predicted tectonic subsidence of these basins (thick line). The model bathymetry is based on thinning of continental crust with a constant initial thickness of 30 km. The timing and stretching factors were chosen to comply with the horizontal surface motion implied in the tectonic reconstruction. In the bottom panels the grey area denotes the observed present depths. The kinematics used for the DRC-I and the DRW model both predict a reasonable basin bathymetry. The difference between the synthetic results is not very large for this ‘time and depth integrated’ physical quantity.

Figure 11 shows the evolution of heat flow density (also without sediments) for the same section. The grey area in the bottom panel (final stage of the evolution) again denotes present observations, in this case based on work by Hutchinson et al. (1985). The difference between the two predicted final heat flow distributions is much larger in: the DRW model seems to predict actual present observations more accurately. Note that the main difference between the kinematics of the DRC-I and DRW models is not the total amount of extension, but rather the relative timing and position of the extensional phases. The larger detail in time that is given in the Dewey et al. (1989) reconstruction allows this improved modelling (see Fig. 3).

Conclusions

Our modelling approach allows us to compare the implications of a tectonic hypothesis on the evolution of a region with the results of seismic tomography and geophysical observations. The predictions of this forward modelling approach are quite accurate in cases of regional extension and subduction processes. We deliberately do not model slab detachment to avoid circular reference to the seismic tomography (which is at present the only source of information on this process). This is the most important cause of the discrepancies between our synthetic models and the tomographic results.

The tectonic reconstructions proposed by Dercourt et al. (1986), Dewey et al. (1989), and Dercourt et al. (1990) are all able to predict the mantle structure that can be observed by means of seismic tomography to considerable detail. But the different scenarios have their own specific advantages. The large area covered by Dercourt et al.’s (1986) work allows for the modelling of a large region, albeit at the cost of detail in the young extensional basins. The high resolution (in time and space) of the geographically more limited reconstruction of Dewey et al. (1989) enables us to predict the thermal structure of the Tyrrenian lithosphere and upper mantle to much more detail. The detailed early stages of evolution, given by Dercourt et al. (1990), allow a more accurate reconstruction of the deeper parts of the mantle below the Alpine, Carpathian, and Pontide–Tauride chains.

The fact, that the more detailed reconstructions (both for recent and for early stages of the development) produce a better fit to observations, suggests that the modelling approach we use is indeed valid for the region and thereby corroborates both the reconstructions and our assumptions on the nature and causes of the mantle and lithosphere structure.

We conclude that the combined palaeomagnetic, stratigraphic, sedimentary and structural
information underlying the reconstructions tested, is consistent with the distribution of seismic velocities imaged by tomography and other, thermally determined, parameters of this region.

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