

Genetic algorithm inversion of the average 1D crustal structure using local and regional earthquakes [☆]

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ABSTRACT

Knowing the best 1D model of the crustal and upper mantle structure is useful not only for routine hypocenter determination, but also for linearized joint inversions of hypocenters and 3D crustal structure, where a good choice of the initial model can be very important. Here, we tested the combination of a simple GA inversion with the widely used HYP071 program to find the best three-layer model (upper crust, lower crust, and upper mantle) by minimizing the overall P- and S-arrival residuals, using local and regional earthquakes in two areas of the Brazilian shield. Results from the Tocantins Province (Central Brazil) and the southern border of the São Francisco craton (SE Brazil) indicated an average crustal thickness of 38 and 43 km, respectively, consistent with previous estimates from receiver functions and seismic refraction lines. The GA+HYP071 inversion produced correct Vp/Vs ratios (1.73 and 1.71, respectively), as expected from Wadati diagrams. Tests with synthetic data showed that the method is robust for the crustal thickness, Pn velocity, and Vp/Vs ratio when using events with distance up to about 400 km, despite the small number of events available (7 and 22, respectively). The velocities of the upper and lower crusts, however, are less well constrained. Interestingly, in the Tocantins Province, the GA+HYP071 inversion showed a secondary solution (local minimum) for the average crustal thickness, besides the global minimum solution, which was caused by the existence of two distinct domains in the Central Brazil with very different crustal thicknesses.

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1. Introduction

Most problems in geophysics have a non-linear component. Hypocenter determination is a typically non-linear problem and can be resolved locally, with linearized techniques, or with grid search and artificial intelligence methods. Lee and Lahr (1975) used a preliminary hypocenter and local iterative analyses to find a solution that minimizes differences between observed and calculated P and S travel times in a group of regional seismographic stations. In another approach, Billings et al. (1994a, b) chose to explore the parameter/solution space with a genetic algorithm, which does not require an initial hypocenter and also allows the use of robust misfit functions such as the Least Power norm. Both approaches are important, but both possess advantages and disadvantages. The linear method employed by Lee and Lahr is very fast and efficient for local and regional hypocenter determinations, but the local linearized technique is not appropriate for working with a large number of seismic phases and/or 3D velocity

models. On the other hand, the method employed by Billings et al. is more useful for the teleseismic hypocenter determination.

Kissling et al. (1984) showed that the use of the linearized approach on a non-linear problem in 3D seismic tomography with local earthquakes makes the solution dependent on the initial reference model. Also, Kissling et al. (1994) used synthetic data to reinforce the importance of the reference model in the seismic tomography. In this way, although a 1D velocity model provides little information for tectonic studies, it is important for the first approximation in studies of local and regional seismic activities (Reasenber and Ellsworth, 1982; Groot-Hedlin and Vernon, 1998).

One of the most employed programs in 1D crustal model estimation (jointly with hypocenters) is VELEST (Kissling et al., 1994), which uses a ray tracing in a layered structure (Thurber, 1981). VELEST uses an iterative linearization of the problem, similar to that adopted by Lee and Lahr in the hypocenter determination. Generally, this is less stable for 1D model determination than for the hypocenter determination only, mainly because of the increase in the size of the search space and the number of local minimums. Thus, VELEST demands a large number of P and S readings as well as information about an initial mean crustal structure determined with an independent method (e.g., seismic refraction).

On the other hand, Groot-Hedlin and Vernon (1998) introduced an efficient method using evolutionary strategies to estimate a 1D model,

[☆] Code available from: <http://www.afonsovasconcelos.com/codes/ga-hypo.tar>.

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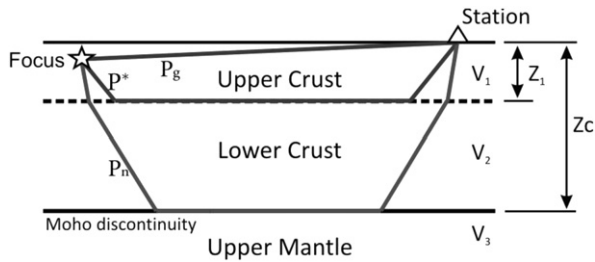


Fig. 1. Crustal structure model used in the hypocenter determination of regional earthquakes. This structure is represented by the vector $m_n=(V_1, V_2, V_3, Z_1, Z_c, V_p/V_s)_n$.

with lower risk of falling into a local minimum, because this method works with a stochastic process of evolutionary strategies observed in nature. This method is efficient for determining low-velocity zones, but it also needs a 1D reference model to compute projection operators. Only P-wave data is used.

Here, we propose a 1D crustal model determination with a genetic algorithm (GA) by searching for the best solution for a simple model composed of two layers and a half-space, representing the upper and lower crusts and the upper mantle, respectively (Fig. 1). Our 1D model is simpler than that proposed by Groot-Hedlin and Vernon (1998), but does not require any information about the crustal structure. Furthermore, our algorithm is useful for the characterization of a 1D reference model for use by Groot-Hedlin and Vernon's methodology, or as an initial model for VELEST, as it does not use any a-priori information.

The misfit function used in our algorithm is the root mean square (*rms*) of the P and S readings used in the hypocenter determination of regional earthquakes by HYPO71 (Lee and Lahr, 1975). The GA was used for determination of a 1D model in two tectonic regions of Brazil (southern region of the São Francisco craton and Tocantins Province). Tests with synthetic data showed good performance for crustal structure studies.

2. Genetic algorithm

Genetic algorithms (GA) are stochastic methods to search for near-optimum solutions, based on Darwin's natural evolution laws, and have been extensively used in geophysics for non-linear problems (e.g., Gallagher et al., 1991), including an inversion of surface wave dispersion curves (Yamanaka and Ishida, 1996), hypocenter location (Sambridge and Gallagher, 1993), focal mechanism determination (Kobayashi and Nakanishi, 1994), and stress tensor inversion with focal mechanism data (Loohuis and Eck, 1996).

A GA consists of a population of possible models and a set of operators inspired by biology (reproduction, selection, and mutation) to produce a new generation of better fitting models (i.e., a better "adapted" population) defining the values of all parameters. The initial population is chosen randomly, uniformly sampling the entire search space (large biodiversity), so that the evolution is likely to converge to all best models. Each individual in the population (each model) is evaluated with an objective function, or misfit criteria. In this work, each model is first used to determine all hypocenters, and the objective function is defined as the root mean square (*rms*) travel times residual from all hypocentral determinations. This means that better fitting models have lower values of the objective function.

Models are then chosen for the crossover (mating) operation, where the best-fitting models have higher probabilities of being selected as mates. The model with the best fit (lowest value of the objective function) is represented by the maximum pre-defined

number of copies (in our algorithm, 100 copies) and the worst model by only one copy, with the number of copies of the other models being linearly dependent on their fitness. This is called linear scaling (Goldberg, 1989). Once the individuals are selected, they go to the mating operation with a certain probability (for instance, 90%), where parts of the parent's genes are combined to produce an offspring. Besides mating, individuals can also suffer mutation with a small probability (say, 10%); this ensures that the model space is covered more uniformly, preventing the population evolution from converging to a local minimum.

The models resulting from the mating and mutation operations receive selection indexes according to the *rms*. The best model receives 100 selection indexes, the poorest model receives only 1 selection index, and other models receive an intermediate number of selection indexes determined by a linear relationship between *rms* and index number. The indexes are ordered and randomly chosen to pass to the next generation (this process is called "rank selection", Fig. 2), keeping the population number fixed (such as 100 individuals). Thus, the probability of a model being selected for the next generation also depends on its fitness.

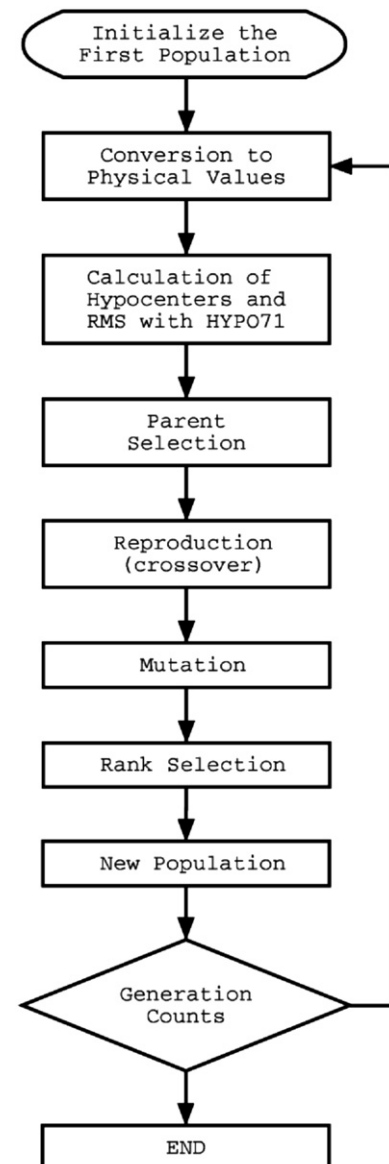


Fig. 2. Simplified flowchart of the genetic algorithm developed in this work.

The process is terminated after a certain number of generations. Fig. 2 summarizes the GA stages described above.

3. Genetic algorithm with HYPO71

We used GA to find the 1D model that best located the hypocenters with the program HYPO71 (Lee and Lahr, 1975). We searched for the model with the least *rms* travel time residual of all P and S readings. The objective function F_o to be minimized was

$$F_o(m_n) = \sqrt{\left[\sum_{i=1}^{nsis} rms_i^2 N_i \right] \left[\sum_{i=1}^{nsis} N_i \right]^{-1}} \quad (1)$$

where *nsis* is the total number of events; N_i is the number of P- and S-waves arrival times of the *i*-th event; and rms_i is the *rms* travel time residual of the *i*-th event. The parameters of the *n*-th crustal model, indicated by the vector m_n are the P-wave velocities of the upper crust (V_1), lower crust (V_2), and upper mantle (V_3), upper crust and total crustal thicknesses (Z_1 and Z_c , respectively), and the Vp/Vs ratio (Table 1 and Fig. 1). The HYPO71 code itself was not modified and was called by the GA code with a C-system function for each test model. To speed up convergence and reduce the computational cost, the initial solution used in the HYPO71 iteration process was the approximately known epicenter instead of the nearest station.

We used search ranges for the model parameters, shown in Table 1, that included most of the variation expected in the stable continental crust (Christensen and Mooney, 1995; Zandt and Ammon, 1995) and the previous knowledge of the regional crustal structure (Assumpção et al., 2004). Parameters V_2 (Vp in the lower crust) and Z_1 (thickness of the upper crust) are strongly dependent on P^* rays (P-wave refracted in the lower crust). Because of the small number P^* first arrivals, the parameters V_2 and Z_1 are strongly correlated. To avoid unrealistic models, the search space was limited to a range determined with data from the literature. In fact, one of the advantages of GA algorithms is the use of independent, a-priori information to define the search space.

The GA search was carried out with a population of 100 models for 75 generations (generation count = 75, Fig. 2). To ensure that the global minimum would be found, the GA process was run 20 times with different initial populations, testing a total of 150,000 models (0.06% of the total number of possible models from Table 1). This setting of GA parameters is a compromise among good coverage of the model space, speed of convergence, and an avoidance of local minima traps. For example, a small population makes convergence difficult, whereas a large population may require a large number of generations, which increases computational costs. Tests with synthetic data were carried out to help choose the appropriate settings. We used a crossover rate of 90% and a mutation rate of 10%.

In principle, the best crustal model (“optimum model”) should be the one with the minimum value of the objective function (rms_{min}). However, because of the non-linear nature of the hypocenter determination, the HYPO71 program (like many others) uses linearization approximations, as well as thresholds and

convergence criteria that cause the *rms* residual to depend on the crustal parameters in a function that is not perfectly smooth. For instance, a small change in one model parameter may cause the first arrival at one station to change from a direct wave to a refracted wave, causing an abrupt change in the event *rms* residual. More important than finding the best-fitting model, the range of all acceptable models can be used to assess the uncertainties of the crustal structure. For this reason, we used the χ^2 (qui-square) criteria, as suggested by Shearer (1999), to select all acceptable models within a 90% confidence interval in relation to the optimum (best-fitting) model. The acceptable models are all those tested during the GA evolution with *rms* errors less than rms_{max} , defined as

$$rms_{max} = rms_{min} \sqrt{\chi^2 / ndf} \quad (2)$$

with the number of degrees of freedom (*ndf*) given by

$$ndf = N_r - 4N_{sis} - 6 \quad (3)$$

where N_r is the total number of P- and S-arrival readings of all N_{sis} events. Each event is solved for four hypocentral parameters, and the number of parameters of the average 1D model is six (Table 1). The χ^2 values for 90% confidence were taken from the statistical tables of Bevington (1969).

The Vp/Vs ratio can also be obtained by a Wadati diagram, independently of the GA process. This can be used as a test to evaluate the quality of the GA inversion results, as seen below.

4. Inversion results

The GA inversion was applied to two regions of the Brazilian shield, as shown in Fig. 3a. The crustal thickness in the “Minas” area varies from 38 to 43 km and is relatively more uniform than the “Goiás” area, which is characterized by two separate blocks, one with a thinner (~33 km) and another with a thicker (~43 km) crust. The Wadati diagram for the events in each of the study areas indicated average values of Vp/Vs of 1.71 for the Minas area and 1.74 for the Goiás area (Fig. 3b). For each area, we also carried out inversion tests with synthetic data with the same event/station configuration.

4.1. “Minas” crustal structure: southern São Francisco craton and surrounding foldbelts

In SE Brazil, our “Minas” area (Fig. 4), mostly within the Minas Gerais state, includes the Archean block of the São Francisco craton (~3.0 Ga) and surrounding Neoproterozoic fold belts, such as the Brasília belt along the SW border of the craton (Almeida et al., 1981). In the western border of this study area, a thin layer of sediments and basalts (< 1 km thick) covers the Brasília belt crust. Small earthquakes, with magnitudes mostly in the range 2.7–3.5 m_R , are relatively common in the southern part of the craton and the Brasília belt (Table 2) and have been well recorded by several temporary stations deployed during the BLSP92 (Assumpção et al., 2002) and BLSP95 (Assumpção et al., 2006) experiments.

Receiver function studies in an SE Brazil (Assumpção et al., 2002; França and Assumpção, 2004) indicate crustal thickness mostly in the range 39–43 km. Assumpção et al. (2002) used first and second (wide-angle reflections) P-wave arrivals from 13 well recorded events in the São Francisco craton and the Brasília belt to estimate a 1D model. The results were a 43-km crustal thickness, upper and lower crust P-wave velocities of 6.2 and 6.85 km/s, respectively, and Pn velocity of 8.3 km/s. Their Vp/Vs ratio was 1.704 ± 0.003 , obtained from a Wadati diagram. No other uncertainties in the model of Assumpção et al. (2002) were provided.

Bouguer anomalies in the study area (Sá et al., 1993) are mainly in the range –140 to –80 mGal and are relatively smooth in our

Table 1

Search parameters used in the crustal velocity structure model (velocities in km/s and thickness in km).

| Parameter | Search space | Search step |
|----------------------------------|--------------|-------------|
| Vp in the upper crust (V_1) | 5.75–6.50 | 0.05 |
| Vp in the lower crust (V_2) | 6.55–7.48 | 0.03 |
| Vp in the upper mantle (V_3) | 7.88–8.50 | 0.02 |
| Upper crust thickness (Z_1) | 9.5–25.0 | 0.50 |
| Crust thickness (Z_c) | 28.3–50.0 | 0.70 |
| Vp/Vs | 1.65–1.80 | 0.01 |

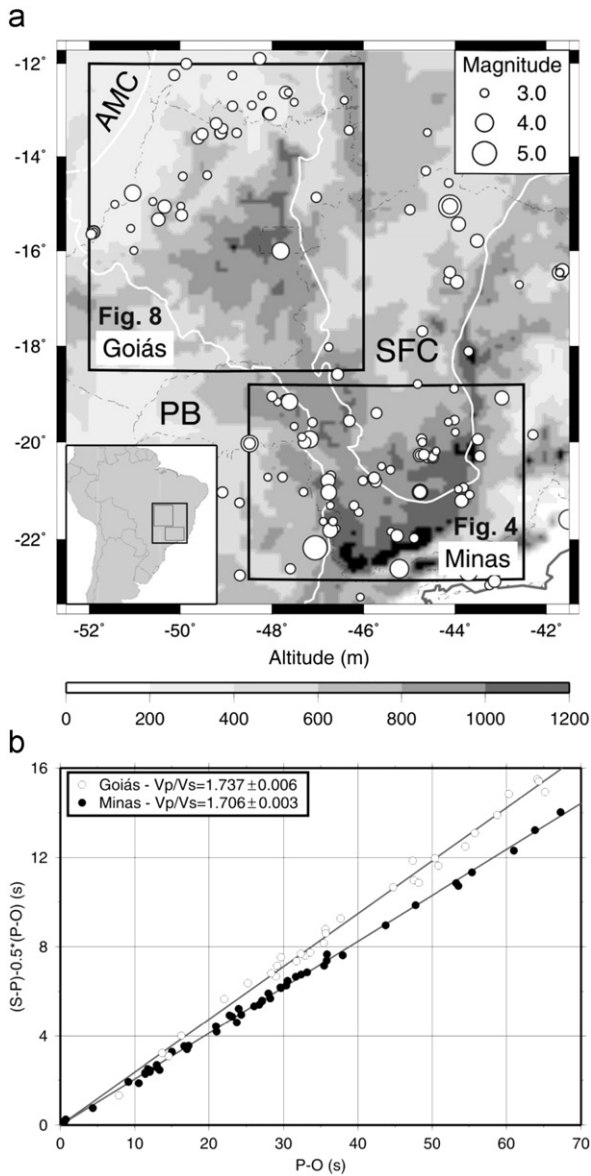


Fig. 3. (a) Seismicity map ($m_b \geq 3$) of the Central and SE Brazil. Grayscale represents the topography; circles are epicenters; dashed lines are state limits; and continuous white lines delimit the main geological features: Amazonas craton (AMC), São Francisco craton (SFC), and Paraná Basin (PB). The rectangles show the two study areas: “Minas” around the southern border of the São Francisco craton (Fig. 4) and “Goiás” in the Tocantins Province (fold belt between the São Francisco and Amazonas craton) (Fig. 8). (b) Wadati diagram (with reduced S–P), calculated for Goiás (white circles) and Minas (solid circles) areas.

study area (Fig. 4), except for a small gradient towards the coast in the SE corner (beginning of the crustal thinning) and a gradient in the SW corner that is interpreted as a suture zone. However, average crustal thicknesses on the two sides of this suture are not very different: ~ 42 km to the SW and ~ 40 km to the NE. Thus, the crustal structure in the central part of our study area is expected to be relatively uniform, with no major crustal variations.

The GA inversion was carried out with 22 earthquakes (66 P and 55 S readings and 27 S–P time differences), and 1536 acceptable models were selected, giving *rms* residuals within a 90% confidence interval ($rms_{min} = 0.123$ s, $ndf = 54$, $\chi^2 = 67.67$, $rms_{max} = 0.138$). Fig. 5a presents all acceptable models with a grayscale based on the misfit. The representative (average) model for the Minas area was taken as the misfit-weighted average of all acceptable models

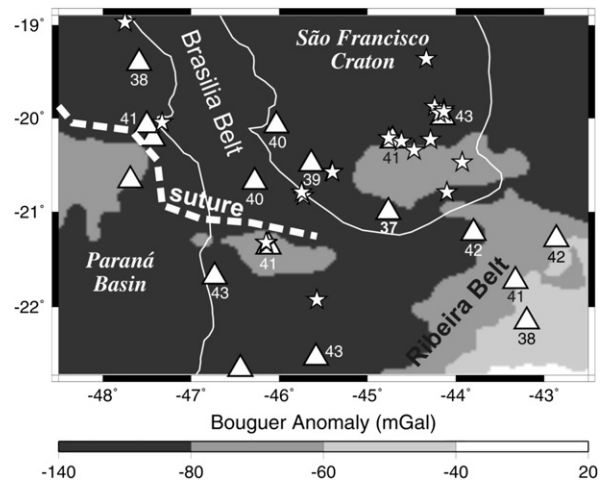


Fig. 4. Bouguer anomaly map of Minas area with earthquakes (stars) and seismographic stations (triangles) used in this study. Numbers close to stations represent crustal thickness calculated using the receiver functions (Assumpção et al., 2002; França and Assumpção, 2004; Juliá et al., 2008). A possible crustal suture is indicated by a dashed line; white solid lines delimit the main geological provinces (see Fig. 3). A summary of the earthquakes used in the GA inversion is given in Table 2.

Table 2

Upper crust and mantle structure models used in the synthetic data (velocities in km/s and thickness in km). The “Minas” column shows the model used for the São Francisco craton (crust with constant thickness), and the “Goiás” column shows the model used for the Tocantins Province. The Goiás synthetic travel times were calculated using a crustal thickness of 33 km when both the event and the station were in the Western crustal block, 43 km when both were in the Eastern block, and 38 km when they were in distinct crustal blocks.

| Parameter | Minas | Goiás |
|-------------------------------------|-------------------|-------------------|
| V_p in the upper crust (V_1) | 6.24 ± 0.05 | 6.20 |
| V_p in the lower crust (V_2) | 6.82 ± 0.20 | 6.91 |
| V_p in the upper mantle (V_3) | 8.22 ± 0.05 | 8.20 |
| Upper crust thickness (Z_1) | 21.9 ± 1.0 | 20.0 |
| Crust thickness (Z_c) | 42.5 ± 1.0 | 33, 38 e 43 |
| V_p/V_s | 1.710 ± 0.005 | 1.734 ± 0.010 |

($i = 1$ to mod), with each parameter p calculated as

$$p = \left[\sum_{i=1}^{mod} \frac{p_i}{rms_i} \right] \left[\sum_{i=1}^{mod} \frac{1}{rms_i} \right]^{-1} \quad (4)$$

Table 4 shows the representative model for the Minas area (average and standard deviation of each parameter), compared with the model of Assumpção et al. (2002). This average model is shown as the dashed line in Fig. 5a. Although our results represent the best 1D average model for an area somewhat larger than the one used by Assumpção et al. (2002), excellent agreement is found between the two models. In addition, by using the weighted average of all acceptable models, an estimate of model uncertainty can be obtained for our GA inversion.

Fig. 5b and c presents the misfit distributions for the crustal thickness (Z_c) and V_p/V_s ratio. The V_p/V_s ratio is well defined at 1.71, in agreement with the value obtained by the Wadati diagram, 1.706 ± 0.003 (Fig. 3b). V_p/V_s is well defined because it depends only on the P and S arrival times and does not depend on the other model parameters. The average crustal thickness is also reasonably well constrained at 42.5 ± 1.0 km, although values in the range 40–45 are possible.

To evaluate the performance of the GA inversion, we generated synthetic travel-time data with the same station/event configuration

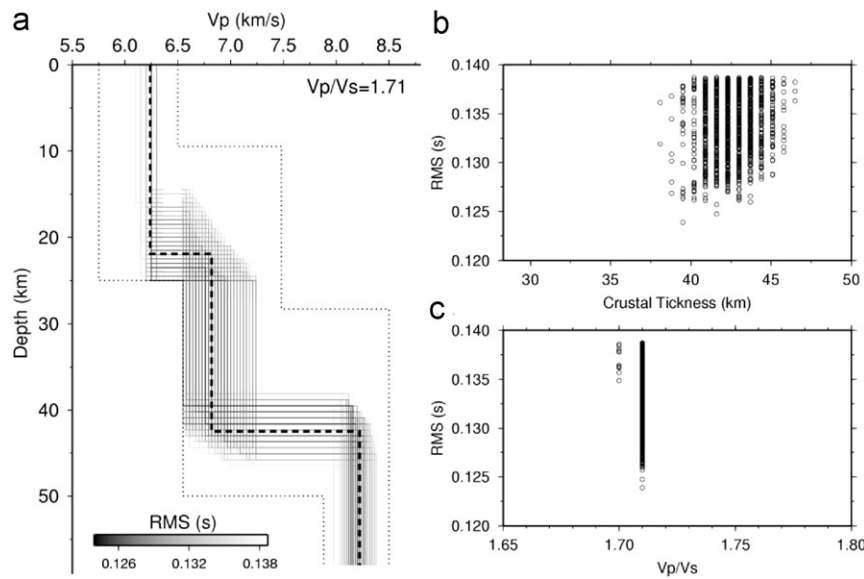


Fig. 5. GA inversion results for earthquakes and stations in the Minas area. (a) All models with *rms* inside a 90% confidence interval, with grayscale representing their *rms*. The dashed line represents the weight-average model. (b) and (c) The *rms* distributions based on the crustal thickness and Vp/Vs ratio, respectively.

Table 3
Seismic data used to estimate mean crustal structure in the Southern São Francisco craton (Minas area). Jday is Julian Day, and m_R is the Brazilian Regional magnitude (Assumpção, 1983).

| JDay/year | Origin time (UTC) | Latitude (°S) | Longitude, (°W) | Depth (km) | m_R | Range (km) | Locality |
|-----------|-------------------|---------------|-----------------|------------|-------|------------|-------------------|
| 068/1993 | 08:56:03 | 20.573 | 45.407 | 0 | 3.1 | 026–226 | Formiga, MG |
| 213/1993 | 07:56:15 | 19.876 | 44.241 | 4 | 2.3 | 064–327 | Betim, MG |
| 272/1993 | 04:06:27 | 20.579 | 45.396 | 0 | 2.4 | 027–184 | Formiga, MG |
| 281/1993 | 00:28:04 | 19.945 | 44.188 | 4 | 2.4 | 064–233 | Betim, MG |
| 338/1993 | 01:49:58 | 20.217 | 44.760 | 0 | 2.6 | 005–287 | C. do Cajuru, MG |
| 361/1993 | 22:48:11 | 20.340 | 44.472 | 6 | 3.6 | 028–278 | Itaguara, MG |
| 101/1994 | 18:03:20 | 19.902 | 44.137 | 3 | 2.6 | 002–240 | Betim, MG |
| 103/1994 | 00:07:41 | 19.928 | 44.139 | 0 | 2.3 | 002–169 | Betim, MG |
| 233/1994 | 05:12:22 | 21.320 | 46.155 | 0 | 2.4 | 072–197 | Areado, MG |
| 013/1997 | 03:42:27 | 20.237 | 44.297 | 0 | 2.7 | 190–241 | Rio Manso, MG |
| 321/1997 | 17:27:02 | 20.826 | 45.728 | 4 | 3.5 | 060–301 | Guapé, MG |
| 355/1997 | 01:37:06 | 20.466 | 43.929 | 0 | 2.4 | 106–246 | Jeceaba, MG |
| 016/1998 | 23:00:16 | 19.363 | 44.327 | 0 | 2.0 | 113–290 | Inhauma, MG |
| 106/1998 | 18:16:45 | 21.891 | 45.570 | 0 | 2.3 | 082–198 | S.G. Sapucaí, MG |
| 142/1998 | 17:33:01 | 18.966 | 47.750 | 0 | 4.1 | 026–482 | Nova Ponte, MG |
| 143/1998 | 12:48:36 | 20.789 | 44.100 | 0 | 2.1 | 057–220 | Lagoa Dourada, MG |
| 210/1998 | 01:46:44 | 20.766 | 45.753 | 1 | 2.3 | 056–274 | Guapé, MG |
| 236/1998 | 03:35:25 | 19.567 | 44.103 | 0 | 3.0 | 106–419 | P.Leopoldo, MG |
| 101/1999 | 20:26:49 | 20.026 | 47.258 | 0 | 2.9 | 028–280 | Jaguarinha, MG |
| 320/2002 | 01:28:24 | 20.262 | 44.614 | 0 | 3.4 | 150–327 | Itaguara, MG |
| 075/2003 | 21:29:41 | 21.331 | 46.136 | 8 | 3.2 | 074–381 | Areado, MG |
| 075/2003 | 21:35:07 | 21.332 | 46.144 | 8 | 2.7 | 144–381 | Areado, MG |

Table 4
Results obtained with GA inversion using real data (Minas-Real), and synthetic data (Minas-Synthetic). Parameter uncertainties are also presented, as well as results obtained by Assumpção et al. (2002) for the region. Uncertainties were estimated using a model distribution within a 90% confidence interval.

| Parameter | Minas-real | Minas-synthetic | Uncertainty | Assumpção et al. |
|----------------------|------------|-----------------|-------------|-------------------|
| V_1 | 6.24 | 6.25 | 0.05 | 6.0–6.3 |
| V_2 | 6.82 | 6.69 | 0.20 | 6.7–7.0 |
| V_3 | 8.22 | 8.19 | 0.05 | 8.2–8.3 |
| V_{average} | 6.52 | 6.46 | — | 6.53 |
| Z_1 | 21.9 | 22.5 | 1.0 | 22 |
| Z_c | 42.5 | 43.3 | 1.0 | 42–43 |
| Vp/Vs | 1.71 | 1.71 | 0.01 | 1.704 ± 0.003 |

and using the representative model obtained from the observed data (dashed line in Fig. 5a and Table 4). We added random Gaussian noise to the synthetic travel-time data with a standard deviation of 0.14 s. Fig. 6 and Table 4 show the results of the synthetic test. Note that the theoretical model is retrieved reasonably well, indicating that the parameters of our GA search are well tuned and that the method is robust. The only parameter that is not exactly recovered is the velocity of the lower crust (V_2). This is because very few refracted waves from the top of the lower crust are first arrivals in our data set, making the estimation of V_2 strongly dependent on the other crustal parameters. This can be seen in Fig. 7, where good coverage of the Pg and Pn phases constrains the V_1 and V_3 velocities. No P^* is observed as the first arrival.

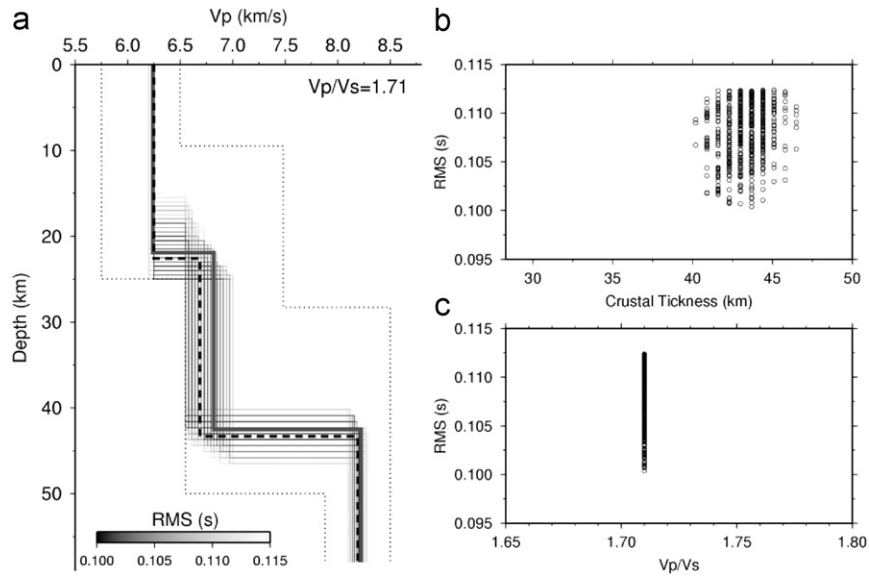


Fig. 6. GA inversion results for the synthetic data of the Minas model with Gaussian noise. (a) All models with *rms* inside a 90% confidence interval, with grayscale representing their *rms*. The weight-averaged model is shown by the dashed line, and synthetic model by a solid thick line. (b) and (c) The *rms* distributions based on the crustal thickness and Vp/Vs ratio, respectively. The absence of *P** arrivals prevents a good determination of the lower crust defined by Pn waves.

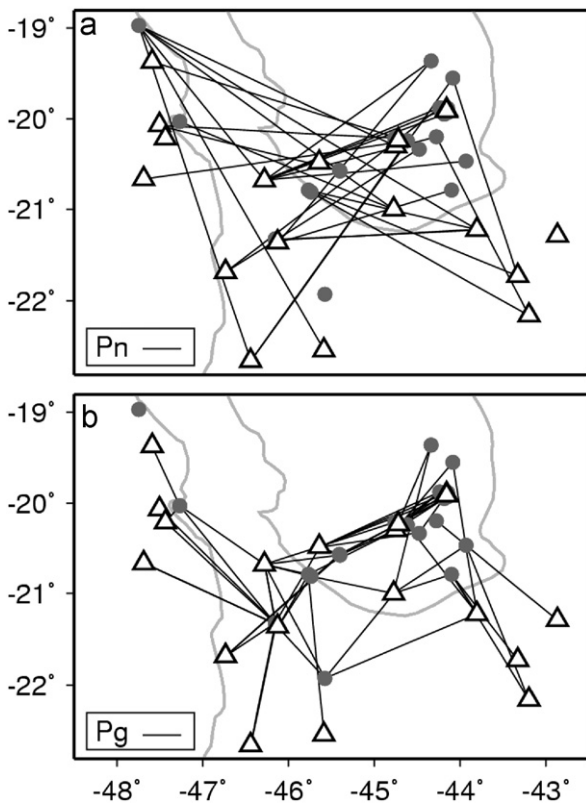


Fig. 7. Seismic rays (black lines) used in the GA inversion for the Minas area. Triangles are stations, and circles are epicenters. The gray lines delimit the main geological provinces (see Fig. 4). Maps show (a) P-wave refracted in the mantle, and (b) direct P-wave. There are no *P** first arrivals.

4.2. “Goiás” crustal structure: Tocantins Province

The “Goiás” study area, mainly within the Goiás state (Figs. 3a and 8), is in the Tocantins geological province (Fig. 8, Brito Neves et al., 1999; Pimentel et al., 1997, 1999), which comprises two

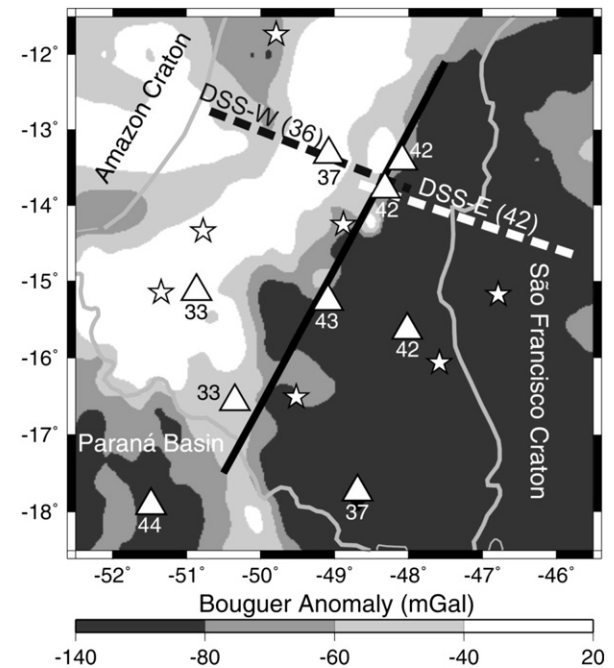


Fig. 8. Bouguer anomaly map of the Goiás area with epicenters (stars) and stations (triangles) used in the crustal model. Numbers close to stations are crustal thickness calculated using receiver functions (Assumpção et al., 2004; Juliá et al., 2008). The solid black line represents a simplified limit of a crustal discontinuity, used in the synthetic data, and gray lines delimit the main geological provinces (see Fig. 3). The dashed lines are two Deep Seismic Sounding (DSS) profiles studied by Soares et al. (2006). A summary of the earthquakes used in the GA inversion is given in Table 3.

Neoproterozoic mobile belts (the Araguaia fold belt bordering the Amazon craton and the Brasília fold belt bordering the São Francisco craton), a SW–NE trending magmatic arc roughly coincident with the high Bouguer anomalies, and a smaller Archean massif between the magmatic arc and the Brasília belt. A clear SW–NE trending seismic belt is observed in the Tocantins Province (Fig. 3a) and is known as the Goiás-Tocantins seismic zone (Berrocal et al., 1984). A strong gradient in the Bouguer anomaly

Table 5Seismic data used to estimate mean crustal structure in Goiás area. Jday is Julian Day, and m_R is the Brazilian Regional magnitude (Assumpção, 1983).

| JDay/year | Origin Time, UTC | Latitude, °S | Longitude, °W | Depth, km | m_R | Range, km | Locality |
|-----------|------------------|--------------|---------------|-----------|-------|-----------|---------------|
| 257/2000 | 07:39:48 | 11.727 | 49.788 | 1 | 3.7 | 189–670 | Gurupi, TO |
| 325/2000 | 09:36:32 | 16.062 | 47.599 | 2 | 3.7 | 053–362 | Brasília, DF |
| 075/2001 | 19:07:11 | 14.251 | 48.882 | 4 | 2.2 | 052–235 | Uruaçu, GO |
| 246/2001 | 20:22:16 | 16.512 | 49.516 | 4 | 2.2 | 086–207 | Goianésia, GO |
| 300/2001 | 18:42:08 | 15.147 | 51.345 | 4 | 2.8 | 047–402 | Aruanã, GO |
| 306/2001 | 07:27:31 | 14.336 | 50.782 | 1 | 2.3 | 088–437 | Cocalinho, GO |
| 238/2002 | 02:29:21 | 15.174 | 46.782 | 9 | 3.3 | 138–446 | Buritis, MG |

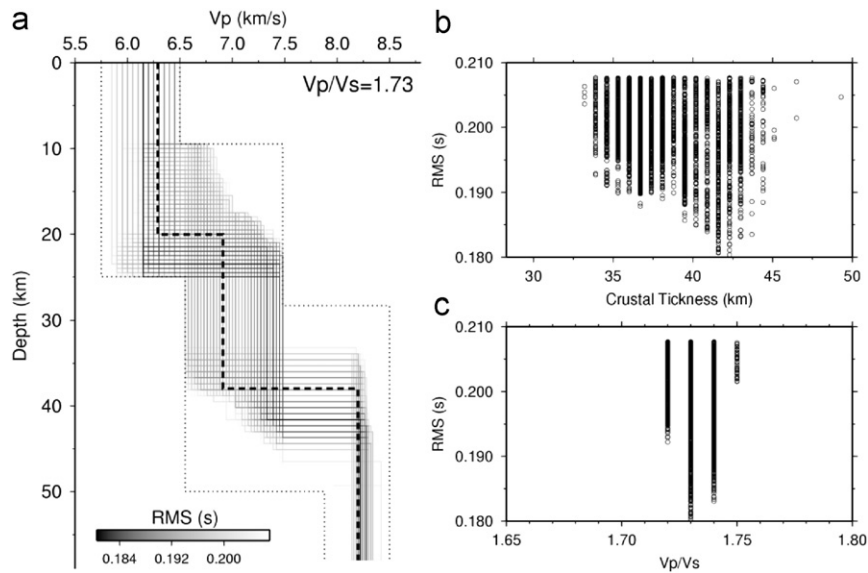


Fig. 9. GA inversion for epicenters of the Goiás area. (a) All models with rms inside a 90% confidence interval, with grayscale representing their rms . Note well-determined V_3 (many Pn paths) despite a poor Z_c characterization. (b) and (c) The rms distributions based on the crustal thickness and V_p/V_s ratio, respectively. The large scatter shown in (b) is interpreted as indicating a large lateral variation of the crustal thickness in the region (Assumpção et al., 2004). Note that there are two separate minima in the rms distribution.

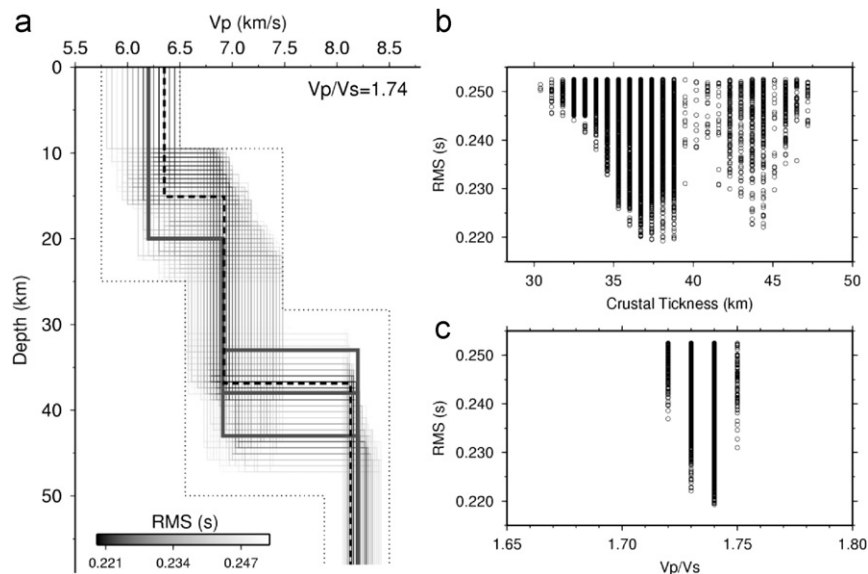


Fig. 10. GA inversion results using synthetic data with the same Goiás configuration. (a) All models with rms inside a 90% confidence interval, with grayscale representing their rms . The weight-averaged model is shown by the dashed line, and synthetic model by a solid thick gray line. The synthetic model is composed by two crustal blocks with a difference of 10 km in their thicknesses. The division between the two crustal blocks (black line in Fig. 8) was estimated using receiver functions (Assumpção et al., 2004), Deep Seismic Sounding (Soares et al., 2006) and gravimetric data (Marangoni, 1994). (b) and (c) The rms distributions based on the crustal thickness and V_p/V_s ratio, respectively. We did not add noise to the synthetic travel-time data, implying that the minimum rms residual of 0.22 sec observed in (b) and (c) is due to fitting a 1D model to data generated with a 2D model. Note in (b) that the resulting models show two minima near the thicknesses of the two crustal blocks.

is observed (Fig. 8) and has been interpreted as a suture zone (e.g., Marangoni, 1994; Ussami and Molina, 1999) with thicker crust to the SE and thinner crust to the NW (Assumpção et al., 2004).

Studies of crustal structure both with receiver functions and surface wave dispersion (Assumpção et al., 2004; França and Assumpção, 2004) and with a deep seismic refraction survey (Berrocal et al., 2004; Soares et al., 2006) indicate that the crustal thickness varies from as little as 33 km in the Goiás Magmatic Arc to as much as 43 km in the Brasília belt. Also, Bouguer anomalies in Goiás span a much wider range (from about -140 to $+20$ mGal) than in the Minas area (only -120 to -60 mGal). These previous results on crustal thickness, together with the contrasting Bouguer anomalies, indicate that the Goiás area is characterized by two domains of crustal thicknesses roughly separated by the thick solid line in Fig. 8: a thinner crust to the NW (average of ~ 35 km) along the magmatic arc, and a thicker crust (~ 43 km) to the SE beneath the Brasília belt. The deep seismic refraction line shot in the northern part of the study area measured Pn velocities in the range 8.0–8.3 km/s (Berrocal et al., 2004).

The GA inversion for the Goiás area was carried out with seven earthquakes (Table 5) recorded by up to eight stations (69 P and S readings). Most of the stations were temporary broadband deployments from the BLSP95 project. We used the same search parameters as for the Minas area. Fig. 9 shows the inversion results with all acceptable models defined by the 90% confidence misfit limit ($rms_{min}=0.180$ s, $ndf=35$, $\chi^2=46.06$; $rms_{max}=0.208$). Clearly, the small number of events and stations do not allow the crustal structure to be defined as well as in the Minas area.

Despite the large variability (Fig. 9c), the Vp/Vs ratio has a misfit-weighted average (1.734 ± 0.010) in agreement with the Wadati diagram (1.737 ± 0.006 , Fig. 3b), as well as with the Vp/Vs ratios calculated using the receiver function stacking (Assumpção et al., 2004), which gave values in the range 1.70–1.76.

Although the results for the crustal thickness have a large scatter (Fig. 9b), they show an interesting bi-modal distribution with two apparent peaks, one near 42 km and another near 36 km. This might reflect two misfit minima in the model space corresponding to the two crustal domains described above. To test this hypothesis, we carried out a synthetic test with the same station/event configuration. In the synthetic model, we assumed the area to be characterized by two domains of crustal thickness, separated by the thick solid line in Fig. 8, one with a thickness of 33 km to the NW and another with a thickness of 43 km to the SE. Synthetic travel times were calculated, taking into account the location of the station and the epicenter in relation to this dividing line. The P-wave velocities for the lower crust and upper mantle were taken as the misfit-weighted average result from the real data. The observed velocity of the upper crust (6.3 km/s), however, was thought to be larger than expected for this area, and we used 6.2 km/s in the synthetic test study.

The GA inversion for the 1D model using the synthetic data (Fig. 10) also shows a bi-modal distribution in the average crustal thickness, similar to that observed with the real data. This result confirms that the cause of the bi-modal distribution in the inversion of the Goiás data is the existence of two distinct crustal domains, and using a single average model for the whole area causes two minima in the model space, each minimum being more influenced by the paths contained in one of the crustal domains. This finding shows that it is important to analyze the distribution of all acceptable models to better assess the significance of the model parameterization. The synthetic test also shows that our inversion overestimates the upper crustal Pg velocity, which is probably an artifact caused by the variable crustal thickness and the few available Pg paths in our data (Fig. 11b). On the other hand, the Pn velocity, better controlled by a large number of Pn paths

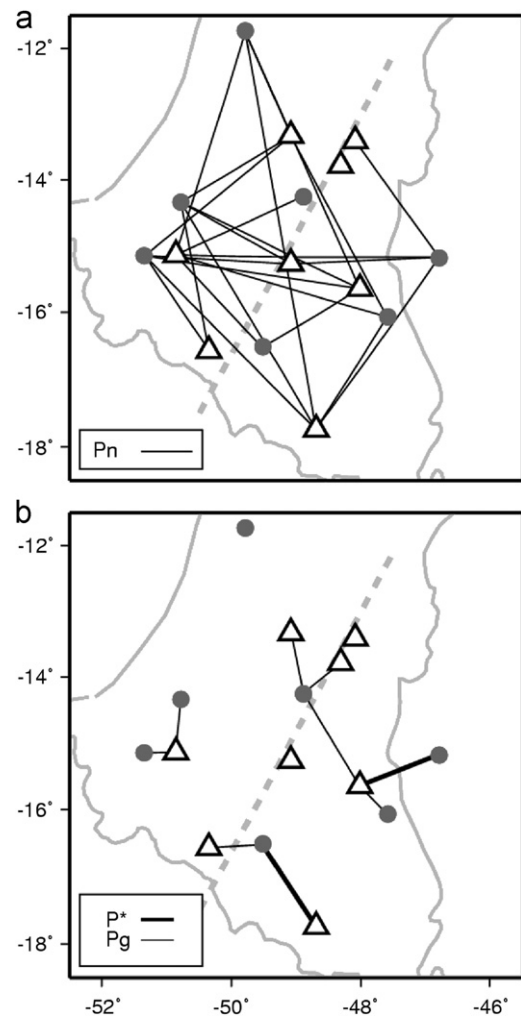


Fig. 11. Seismic paths (black lines) used in the GA inversion in the Goiás area. Triangles are stations, and circles are epicenters. The gray lines delimit the main geological provinces (see Fig. 8). Maps show (a) P-wave refracted in the mantle, (b) P-wave refracted in the middle crust interface (thick line), and direct P-wave (thin line).

(Fig. 11c), is well retrieved in the synthetic test. The same happens with the Vp/Vs ratios. Thus, synthetic tests are also necessary to better assess the significance and possible biases of the inversion results.

5. Conclusions

Obtaining the average crustal model using the genetic algorithm method proved to be very useful. The GA inversion is not straightforward to use, compared with the linearized methods, because several search parameters (such as population size, number of generations, cross-over, and mutation rates, etc.) need to be tuned for an efficient inversion. However, the advantages of the GA method are evident: (a) it is possible to use a-priori information from other geophysical methods to constrain the search of the model parameters and (b) an analysis of the range of acceptable models and the distribution of the model parameters provides an estimate of model uncertainties and reveals complexities in the actual crustal structure. Analysis of the distribution of the GA solutions can potentially reveal different local minima that may relate to important structural features.

In the Minas area of an SE Brazil (São Francisco craton and surrounding Brasília fold belt), the average crustal thickness is 42 ± 1 km, and the upper mantle Pn velocity is 8.2 ± 0.1 km/s.

While the average crustal thickness can be obtained from the receiver function studies, the upper mantle P-wave velocity is not so readily retrieved from the receiver function modeling. In the Tocantins Province (Goiás study area), the average crustal thickness is about 38 km. However, our GA inversion showed that this average thickness does not have much significance. The analysis of the distribution of the solutions confirmed the hypothesis that the Tocantins Province has two crustal thickness domains: a thinner crust in the magmatic arc and a thicker crust beneath the Brasília fold belt.

Source codes in C and FORTRAN format, the test data set and a short manual are available from the author's homepage at www.afonsovasconcelos.com/codes/ga-hypo.tar.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.cageo.2010.11.006](https://doi.org/10.1016/j.cageo.2010.11.006).

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