2005

The 2003 Boumerdes, Algeria Earthquake: Regional Moment Tensor Analysis

Jochen Braunmiller
Swiss Seismological Service, jbraunmiller@usf.edu

Fabrizio Bernardi
Swiss Seismological Service

Follow this and additional works at: https://scholarcommons.usf.edu/geo_facpub
Part of the Earth Sciences Commons

Scholar Commons Citation
School of Geosciences Faculty and Staff Publications. 810.
https://scholarcommons.usf.edu/geo_facpub/810

This Article is brought to you for free and open access by the School of Geosciences at Scholar Commons. It has been accepted for inclusion in School of Geosciences Faculty and Staff Publications by an authorized administrator of Scholar Commons. For more information, please contact scholarcommons@usf.edu.
The 2003 Boumerdes, Algeria earthquake: Regional moment tensor analysis

Jochen Braunmiller and Fabrizio Bernardi
Swiss Seismological Service, Institute of Geophysics, Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

Received 19 November 2004; revised 10 February 2005; accepted 18 February 2005; published 18 March 2005.

[1] We used regional broadband seismograms to determine seismic moment tensors for the destructive May 21, 2003 Boumerdes (Algeria) \( M_w = 7.0 \) earthquake and its larger aftershocks. Fully automatic inversions using near-real time data provided solutions for seven \( M_w \geq 4.7 \) events within 90 minutes after event occurrence. After adding off-line data, we manually obtained 30 solutions (\( M_w \geq 3.8 \)) from May 2003 to January 2004. All have shallow source depths (6–21 km). The median P-axis orientation (338°) of 24 thrust and four strike-slip events is consistent with Africa-Eurasia plate motion (330°). The main shock hypocenter at 8–10 km depth at the coastline and its shallow southward dip (\( 25° \pm 5° \)) puts the fault surface trace 15–20 km offshore, consistent with documented seafloor deformation at the base of the continental slope. A main shock rupture length of about 50 km is deduced from first day aftershocks and location of strike-slip events. The strike-slip events probably define the western rupture end and indicate a left-step of main convergence. Fault strike variability of thrust events suggests fault orientation changes and possibly fault segmentation. 


1. Introduction

[2] The \( M_w = 7.0 \) May 21, 2003 Boumerdes earthquake occurred about 50 km east of Algiers [Ayadi et al., 2003; Yelles-Chaouche et al., 2003]. A maximum intensity X (EMS 98) was assigned to heavily damaged coastal areas from Boumerdes to Delflys (Figure 1) where over 2000 people died due to building collapses. Along this 55 km long stretch, Meghraoui et al. [2004] found an average coastal uplift of 0.5 m. Minor cracks and landslides, but no surface faulting occurred [Ayadi et al., 2003; Yelles-Chaouche et al., 2003]. The relocated main shock hypocenter is at the coastline (36.83°N, 3.65°E) at 8–10 km depth [Bounif et al., 2004]. Modeling of GPS [Yelles et al., 2004], uplift [Meghraoui et al., 2004], geodetic and strong motion [Semmane et al., 2005], and teleseismic, GPS and uplift data [Delouis et al., 2004] and aftershock locations [Bounif et al., 2004] suggest rupture along a 50–55 km long south-dipping thrust fault. Slip modeling [Delouis et al., 2004; Semmane et al., 2005] shows a 12–18 s rupture duration and two major slip patches with displacements up to 2.5–3 m.

Copyright 2005 by the American Geophysical Union.
0094-8276/05/2004GL022038

2. Automatic Moment Tensor Analysis

[3] Destructive earthquakes in northern Algeria are due to Africa-Eurasia convergence. Most deformation occurs along a narrow strip of NE-SW trending right-stepping folds and faults of the Tell Atlas [Meghraoui et al., 1986]. Low convergence (~6 mm/yr, NUVEL-1A [DeMets et al., 1994]) causes infrequent, but destructive earthquakes. The largest 20th century event was the \( M_w = 7.3 \) 1980 El Asnam event 150 km southwest of Algiers. Near Boumerdes, seismicity before 2003 was considered low [Yelles-Chaouche et al., 2003].

[4] Installation of broadband seismic stations along the Mediterranean Sea (Figure 1) allows source mechanism retrieval of moderate earthquakes using regional waveforms. We present fully automatic near-real time moment tensor (MT) solutions to illustrate rapid source parameter estimation. Combining near-real time and later available data, we obtained 30 MTs for the Boumerdes sequence. We use the solutions and their relocations to develop a rupture model and to address the fault surface trace location.

3. Off-Line Moment Tensor Analysis

[5] Since 2000, we have been performing near-real time, fully automatic deviatoric MT inversions in the European-Mediterranean area [Bernardi et al., 2004]. We invert complete long-period three-component regional seismograms and find the depth by grid-search. The 50–100 s waveforms, insensitive to crustal heterogeneities, can be fitted with PREM synthetics even for slightly inaccurate locations and long paths. After automatic quality control, solutions are available 90 minutes after an event at http://emsc-csem.org and http://www.seismo.ethz.ch/mt.

[6] We obtained solutions for seven \( M_w \geq 4.7 \) events of the Boumerdes sequence (Table 1). Their source parameters (MT, \( M_w \), depth) were later confirmed by solutions from Harvard, the USGS and our manual analysis. Our automatic main shock MT (#1 Table 1) provided the first, unsaturated size estimate (\( M_w = 6.8 \)). Submarine slides had cut several underwater phone cables to Algeria [Hébert and Allasset, 2003] severing communication. Rapid, remotely derived size estimates, indicating destruction near the epicenter, helped initiate disaster relief efforts.

3. Off-Line Moment Tensor Analysis

[7] For off-line analysis, we used all broadband waveforms available within months after event occurrence. The larger three-component dataset improves azimuthal coverage and contains more close-in stations (Figure 1) than for the automatic analysis. This results in better-constrained mechanisms and permits analysis of smaller events. We filtered the data to periods with good signal-to-noise ratio.
For small events, we used near-stations and inverted in the
25–40 s, 30–50 s and 33–50 s bands; for large events, we
used stations up to 20° distance and inverted from 40 s to
60–100 s, the long period cut-off depending on event size.
We inverted complete waveforms using PREM synthetics
calculated for USGS's PDE locations. Depth was found by
grid search with 3-km steps. The method is described in
Nabélek and Xia [1995] and European applications are
shown in Braunmiller et al. [2002].

[8] We analyzed all 49 M ≥ 4.0 events of the sequence
from May 2003 to January 2004 and obtained 30 Mw ≥
3.8 MT solutions (Table 1 and auxiliary material1). Thrust
mechanisms dominate, though we also found four strike-
slip and two normal faulting events. Most events we could
not obtain solutions for were immediate main shock after-
shocks. Events #2–19 (Table 1) occurred within the first
two days. Their mechanisms could only be obtained with
regional waveforms since a temporary network to record
aftershocks had not yet been installed [Bouinif et al., 2004].

[9] Azimuthal amplitude variations constrain the well-
resolved and stable source mechanisms. Figure 2 shows the
main shock waveform fit. Thrust fault strike variability
and occurrence of strike-slip events are constrained by
waveforms at several stations that look distinctly different
(Figure 3). Fault rotation from NNE-SSW to E-W follows
from amplitude variations of vertical data (e.g., EMV). The
vertical-to-transverse amplitude ratio and a 90° periodicity
of near nodal vertical data (DIX, WDD and PAB) constrain
strike-slip events. Lack of data from stations south of
the epicenter, which precludes constrained first motion
solutions, does not cause a resolution problem when three-component waveforms are modeled.

[10] For each event, we estimated strike, dip, and rake
bounds for a 5% variance increase relative to the best
solution by varying one parameter. Main shock bounds
for strike, dip and rake are ±6°, ±5°, and ±6°, respectively; averages for all events are ±13°, ±9°, and ±14°. Larger
events with better coverage and more data have smaller
bounds. For dip-slip events, dip is best resolved, and for
strike-slip, strike is best resolved. We performed a double-
couple (DC) grid-search for the main shock and strike-slip
event #11 (Table 1) with the smallest DC contribution of all
events. The main shock MT is almost a pure DC and the
best pure DC is thus nearly identical (64% ± 9°, 23° ± 3°, 83° ±
11°). For event #11, differences (17° ± 8°, 68° ± 14°,
−22° ± 20° for moment-tensor DC vs. 11° ± 9°, 61° ± 16°,
−24° ± 22° for best pure DC) are small considering its large
non-DC source component. The DC part is well resolved.

[11] Centroid depths (Table 1) are not well constrained
because event-station distances are large (>300 km) and
paths cross complex tectonic structures through the Medi-
terranean Sea before reaching Europe. We thus had to
invert at long periods insensitive to small depth variations.
Resolved depths are between 6 and 21 km, but including
5%-bounds, most could have occurred from the surface

![Figure 1. Map of the epicenter region (star) and broad-
band seismic stations used (squares: off-line, circles:
automatic analysis). Stations north of 49.5°N are not
shown. Not all stations were available for each event.
Inset is a close-up; star marks main shock location from
Bouinif et al. [2004], A: Algiers, B: Boumerdes, D: Dellys.](image)

| Table 1. Regional Moment-Tensor Solutions* |
|---|---|---|---|---|---|---|---|---|---|
| # | Date | Lat (°N) | Lon (°E) | S/D/R | P | CD (%) | DC (%) | CO |
| 1 | 20030521 1844 | 36.832° | 36.832° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 2 | 20030521 1851 | 36.832° | 36.832° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 3 | 20030521 2204 | 36.916° | 36.916° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 4 | 20030521 2318 | 36.907° | 36.907° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 5 | 20030521 2323 | 36.812° | 36.812° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 6 | 20030522 0139 | 36.651° | 36.651° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 7 | 20030522 0155 | 36.629° | 36.629° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 8 | 20030522 0314 | 36.822° | 36.822° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 9 | 20030522 0429 | 36.891° | 36.891° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 10 | 20030522 0445 | 36.919° | 36.919° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 11 | 20030522 0627 | 36.794° | 36.794° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 12 | 20030522 0933 | 36.907° | 36.907° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 13 | 20030522 1137 | 36.833° | 36.833° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 14 | 20030523 0008 | 36.822° | 36.822° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 15 | 20030523 0304 | 36.812° | 36.812° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 16 | 20030523 1251 | 36.738° | 36.738° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 17 | 20030523 1537 | 36.833° | 36.833° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |
| 18 | 20030524 1921 | 36.816° | 36.816° | 6.52 | 28.52 | 338.7 | 18 | 76 | 95 |

down to 20–25 km depth. Our main shock centroid (18 ± 5 km) is slightly deeper than its hypocenter estimate of 8–10 km [Bounif et al., 2004]. Generally, our depths are compatible with aftershock depths from 4 to 16 km [Bounif et al., 2004] but are not precise enough to resolve spatial depth variations within the shallow sequence.

4. Teleseismic Relocation

[12] Deriving a simple rupture model requires accurate relative locations. We thus relocated all earthquakes with a moment tensor solution relative to the main shock epicenter [Bounif et al., 2004]. We applied the joint epicenter determination technique [Douglas, 1967] to teleseismic P-wave arrival times. All depths were constrained to 10 km due to limited resolution of teleseismic data. We consider 25 events with longitudinal uncertainties of less than ±6 km at the 95%-confidence limit well relocated. Five events were shifted from their PDE location by 0.134° in latitude and 0.016° in longitude, the difference between the PDE and Bounif et al. [2004] main shock locations. Relocations are marked ‘R’ and shifts ‘X’ in Table 1. The east-west epicenter extent is well constrained by the station distribution mainly towards north; latitudinal uncertainties are almost a factor 2 larger. Figure 4 shows fault plane solutions on their relocated, respectively, shifted epicenters.

5. Discussion and Conclusion

[13] The main shock thrust event generated a vigorous aftershock sequence with diverse focal mechanisms (Figure 4) indicating activity along several faults and fault segments. For the first three days, all events (#1–19) except strike-slip event #11 were thrusts. After the large aftershock #20, mechanisms were more diverse and we found thrust, strike-slip and even normal faulting. Activity west of 3.45°E (#21, 22, 23, 25, 30) started only then. The largest aftershocks (#2, 8, 20) occurred very close to and had very similar mechanisms as the main shock. This ‘main shock cluster’ (including #5, 12, 13) has a median 338° P-axes orientation. Thrust events east of about 3.8°E (#3, 4, 14, 16, 18, also 26) have a slightly more northerly 352° median, which could indicate a 10°–15° fault bend that coincides with a coastline bend near 3.9°E. The more northerly oriented thrusts (#6, 9, 10, 15, 17, 19) occurred also close to the main shock. Their latitudinal uncertainties allow that all could have occurred near 36.8°N and 3.5°–3.7°E where Bounif et al. [2004] found a tight aftershock cluster. We assume these events occurred in the hanging wall where the normal events #24, 28, the southern thrusts #7, 29, 27 and strike-slip event #11 probably also occurred.

[14] The strike-slip events #22, 23, and 30 probably define a north-south trending left-lateral transform fault that stopped main shock rupture from propagating further west.

Figure 2. Observed (solid) and synthetic (dashed) main shock waveforms for selected stations in the 40–100 s band. Numbers beneath stations are azimuth and distance. Amplitudes are normalized for cylindrical geometrical spreading. Z, R, and T are vertical, radial and transverse components. The best solution fault plane solution (lower hemisphere) is shaded; triangles are azimuths (dark for stations shown, light for additional 22 stations used). Dotted lines are fault planes and synthetics for a 45°-dipping source (instead of 25°, with strike = 62° and rake = 82° fixed).

Figure 3. Observed (solid) and synthetic (dashed) waveforms for thrust and strike-slip events for selected stations. Seismograms are 300 s long. Shown are, top to bottom, events #15, 14, 23 (Table 1). WDD (Malta), PAB and EBR (both Spain) are shown for all events; WDD horizontals for #15 were noisy. EMV and DIX in Switzerland have nearly identical distance and azimuth. For details see Figure 2.
The location of the postulated transform coincides with the western aftershock end [Bounif et al., 2004], rupture termination from horizontal GPS data [Yelles et al., 2004], and lack of coastal uplift west of 3.4°E [Meghraoui et al., 2004]. The transform forms a step-over of main thrust faulting, which further west might be accommodated along the Blida thrust system at the southern border of Mitidja basin [Bounif et al., 2004; Meghraoui et al., 2004].

Fault dip is the best-constrained parameter for thrust events. The south dipping plane of the main shock and of all thrust events dips with less than 30°. Regional waveforms are incompatible with steeper dips (Figure 2) found by teleseismic body wave inversions, Delouis et al. [2004] obtain 40°, Harvard and USGS have 44° and 47°. A shallow main thrust dip agrees with an aftershock cross-section in Bounif et al. [2004] dipping shallowly to the SSE. Though Bounif et al. [2004] suggest the main thrust plane cuts steeply through the aftershocks it seems more likely that the aftershocks cluster either around or just above the main thrust. Combining our fault dip (25° ± 5°) with location (36.83°N, 3.65°E) and depth (8–10 km) from Bounif et al. [2004] results in a fault surface emergence 15–20 km offshore (assuming ~2 km deep water). A morpho-tectonic map that shows active scarps at the bottom and mid-slope of the continental shelf parallel to the coast ~17 km offshore [Déverchère et al., 2003] agrees with our model.

We estimate a main shock rupture length of about 50 km based on the intersection of the proposed transform with the main thrust and the first day aftershocks, which extend to about 3.9°E (#14). The estimate agrees with modeling of coastal uplift [Meghraoui et al., 2004] and of seismic and GPS data [Delouis et al., 2004; Semmane et al., 2005; Yelles et al., 2004]. Assuming rupture initiated at 10 km depth and propagated to the sea bottom along a 25°-dipping 50 km-long fault gives an average fault displacement of about 1 m (rigidity 3 × 10¹⁰ N/m²) consistent with slip-models [Delouis et al., 2004; Semmane et al., 2005].

[17] The Boumerdes earthquake sequence was caused by Africa-Eurasia convergence. The local 330° relative motion direction [DeMets et al., 1994] agrees with the 338° median P-axis orientation of thrust and strike-slip events. The region experienced few earthquakes prior to 2003 and seismic hazard was considered relatively low [Yelles-Chaouche et al., 2003]. However, plate motions are essentially the same along entire northern Africa and destructive earthquakes could occur anywhere along the margin (like the Mw = 6.4 event near El Hoceima, Morocco in February 2004).

[18] Acknowledgments. We thank the Geofon, Geoscope, IRIS, MedNet, Nice University, ORFEUS, ReNass, Swiss SDS-Net, SZGRF, and ZAMG data centers for high-quality waveform data, A. Douglas for the JED code, and the USGS and ISC for phase data.

References
Ayadi, A., et al. (2003), Strong Algerian earthquake strikes near capital city, 
Eos Trans. AGU, 84(50), 561–568.
F. Bernardi and J. Braunmiller, Swiss Seismological Service, Institute of Geophysics, Eidgenössische Technische Hochschule Zürich, CH-8093 Zurich, Switzerland. (jochen@sed.ethz.ch)