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Earthquake focal mechanism and oceanic thrust in Easter microplate analogy with Oman ophiolite

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Abstract. Previous work has suggested compression and thrust faulting along the northern boundary of the Easter microplate due to its motion relative to the Nazca plate. Inversion of the P and SH seismic waves related to a recent M_S=7.1 earthquake located along the northern boundary of the Easter microplate indicates a thin sliver of crust thrusting at a shallow angle towards the South, giving support to this interpretation. The Oman ophiolite where similar thrusts have been mapped has been recently interpreted as being derived from similar microplate environment [*Boudier et al.*, 1997]. This interpretation 1) provides possible tests to document the existence of oceanic thrusts near microplates, and 2) suggests a new solution to the problem of how many ophiolites could have obtained oceanic detachment faults which will favour obduction.

Introduction

Oceanic microplates, such as Easter or Juan Fernandez in the southern part of the East Pacific Rise (EPR) or the Manus microplate in the eastern Bismarck Sea back-arc [*Martinez and Taylor*, 1996], form when active spreading segments propagate in opposite direction and capture in between them a domain which starts growing and rotating [*Hey et al.*, 1985; *Larson et al.*, 1992; *Schouten et al.*, 1993; *Searle et al.*, 1993]. Kinematic models describing the evolution of the Easter microplate [*Naar and Hey*, 1989; 1991] have favoured a rigid plate interpretation for recent plate motions. The plate tectonic reconstruction and relative plate motions predict, however, ~100 km shortening during the last 2Ma along the northern transverse boundary of the growing microplate [*Naar and Hey*, 1989; 1991] (Fig. 1). In contrast, the southern boundary has a transtension motion, as deduced from earthquake focal mechanisms [*Engeln and Stein*, 1984; *Naar and Hey*, 1989; 1991; *Rusby and Searle*, 1995]. Indication that thrusting is taking place along the northern boundary of the Easter microplate has been deduced by *Rusby and Searle* [1993] from a combination of fault plane solutions [*Engeln and Stein*, 1984], relative plate motions [*Naar and Hey*, 1989], bathymetry [*Naar and Hey*] and a GLORIA sidescan survey revealing asymmetric topographic features which have been ascribed to north-dipping oceanic thrusts [*Rusby and Searle*, 1993]. Near the Manus microplate, some thrusting is envisioned to accommodate the rotation-related compression but most of this rotation is explained by reverse strike-slip faulting ["bookshelf" deformation, *Kleinrock and Hey*, 1989] inside the microplate itself, a mechanism which is supported by earthquake focus analysis [*Martinez and Taylor*, 1996].

The 1996 Easter Microplate M_S=7.1 Event

A M_S=7.1 thrust earthquake (09/05/96 08:14) occurred along the northern boundary of the Easter microplate, following a similar event of M_S=5.8 in 1974 [*Engeln and Stein*, 1984]. The NEIC epicenter is 100 km east of the EPR axis (22.26°S, 113.41°W), within the E-W zone of north-dipping oceanic thrusts previously recognised by *Rusby and Searle* [1993] (Fig. 1). The P and SH broad band seismograms at teleseismic distances (30°-90°) recorded by the IRIS and GEOSCOPE networks were inverted using the *Nabelek* [1984] procedure in order to obtain the source parameters of the earthquake (Fig. 2a). For an offshore earthquake a good estimation of the water depth is required. The main depth of the oceanic floor in the epicentral region is 3200 to 3500 m but relieves associated with the E-W thrusts rise to a depth of 2500 to 2200 m in some places. The best values for the thickness of the water layer and for the depth of the rupture nucleation were obtained conducting a series of inversions with different fixed values for these two parameters (Fig. 2b). In each inversion the source time function and the focal mechanism are solved. Best fit values are 2.5 km ±0.5 km for the water layer and 3.5 km ±0.5 km for the source depth, which correspond to a source nucleation about 1 km ±1.0 km below the sea bottom. A similar exploration procedure was conducted in order to find the rupture azimuth and rupture velocity, solving for the seismic moment rate along a line-source and for the average focal mechanism. The best fit was obtained for a rupture azimuth of N60°E (down-dip oblique) and for a rupture velocity of 2.6 km/s. The average focal mechanism indicates a low angle (15°) NNE-dipping thrust (Fig. 2a). The total seismic moment, 4.0×10^{26} dyne-cm, corresponds to a moment magnitude M_W=7.0 similar to M_S. We found a much

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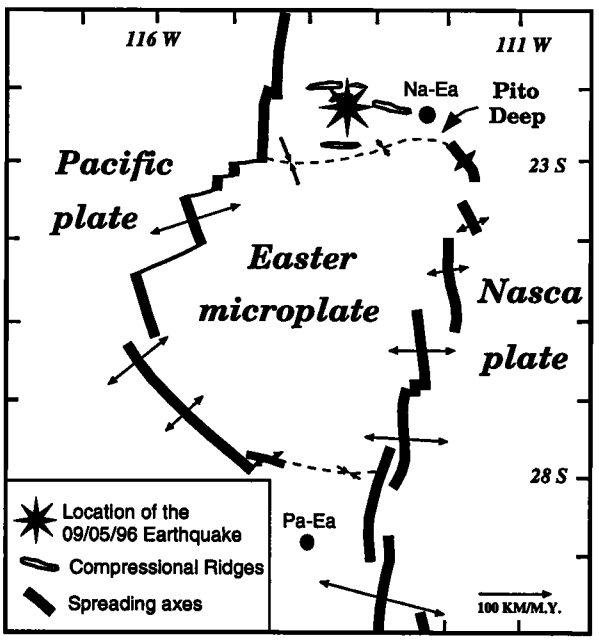

Figure 1. Simplified map of the Easter microplate with the location of the 09/05/96 M_S=7.1 earthquake in the northern compressive microplate boundary. Plate boundaries, relative motion vectors (arrows), and the Pacific-Easter (Pa-Ea) and Nazca-Easter (Na-Ea) Euler poles (black dots) are from Naar and Hey (1991). Compressional ridges at the northern boundary of the Easter microplate are from Rusby and Searle (1993).

shallower source depth and a much flatter fault plane than the Harvard Centroid Moment Tensor solution (HCMT depth =15km and HCMT dip=60° for the NNE-dipping thrust nodal plane). Source parameters of shallow earthquakes obtained by the long period HCMT inversion are generally less constrained than source parameters of deeper earthquakes. We gained precision by modelling higher frequency waveforms and taking into account more precisely the water layer and the spatio-temporal characteristics of the source. A very shallow rupture nucleation depth (around 1 km below the ground surface) would be very unusual for a continental thrust event. However, this shallow nucleation depth may reflect a strong difference in frictional behaviour between continental and young oceanic plates. The relatively low rupture velocity might indicate that the propagation was not entirely unilateral but it might also be due to the specific rheology of the young oceanic lithosphere. The dimension of a magnitude 7 earthquake is expected to be sufficient to break to the surface.

This rupture occurred in a 1-2 Ma old lithosphere whose thickness should not exceed 10-12 km [*Cormier et al.*, 1995]. It should be composed of strong lower crust and uppermost mantle, below a lid, layer 2, which corresponds to the extrusives and the underlying sheeted dikes. At superfast ridges the thickness of this lid is approximately 1.2 km [*Kent et al*, 1994]. The inversion of the 1996 earthquake indicates that the seismic rupture may have initiated near the base of the lid. Then, it should have propagated upward, toward the surface into increasingly fractured basalts; downward, the rupture should have penetrated into the stronger lithosphere, as indicated by the 15° dip of the fault plane found in the inversion.

The M_S=7.1 earthquake of September 5, 1996 is one order of magnitude larger than the previous known earthquakes in the area. This event alone accounts for most of the seismic defor-

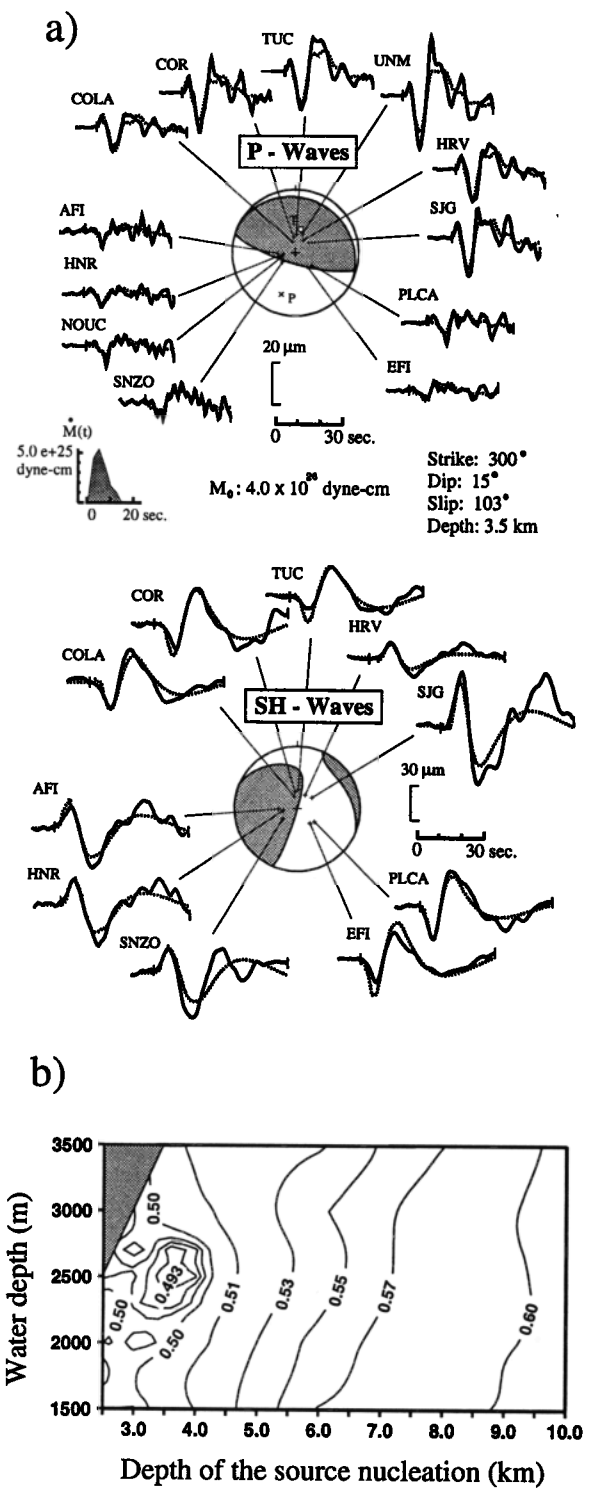

Figure 2. a) Result of the waveform inversion for a single propagating line source. Broad band seismograms were deconvolved from the instrumental response, integrated to displacement, bandpass filtered (0.01-0.8 Hz for P waves and 0.01-0.4 Hz for S waves), and equalised to a common instrumental magnification and epicentral distance. Focal mechanisms for the P and SH waves are shown, as well as the moment rate distribution (source time function). b) Isolines of RMS error as a function of water depth and source depth. Optimal values are 2.5 km and 3.5 km respectively. RMS error is the weighted mean squared difference between the observed and synthetic seismograms divided by the weighted mean squared observed signals. In the grey shaded area the source would be in the water layer.

mation taking place at the northern boundary of the Easter microplate since the beginning of the 1960's when earthquakes were first detected and located with sufficient confidence in this region (NEIC catalogue). For this reason, and because of high-quality broad band recordings of the IRIS and GEOSCOPE networks used here, the results obtained through the modelling of this single earthquake are considered to be representative of the active deformation in the region immediately north of the Easter microplate.

Analogy with Oman Ophiolite

The inversion study of this earthquake was prompted by results obtained in the Oman ophiolite suggesting that this ophiolite was derived from an EPR-type microplate with thrusting associated to the microplate activity [*Nicolas et al.*, 1994; *Boudier et al.*, 1997].

The Oman ophiolite also is underlined by a flat-lying thrust plane with mylonitic peridotites which are deformed at 900-1000°C and which overlay a metamorphic sole of oceanic crust-derived amphibolites (Fig. 3). The 1 Ma age difference [*Hacker*, 1994] between accretion and thrusting indicates that this thrust originated very close to the ridge of origin. The detachment occurred along the shallow and flat-lying lithosphere-asthenosphere boundary, thus explaining the initial 1000°C temperature of deformation recorded in basal peridotites during the early thrusting [*Boudier et al.*, 1988]. In the northern parts of the ophiolite belt, such thrusts and related shear zones cut through the entire ophiolite. They are invaded by gabbro-norite dikes, indicating that a more silicic magmatism was active during the thrusting [*Boudier et al.*, 1988]. We relate these and other more differentiated intrusions (amphibolite isotropic gabbro-norites, plagiogranites) to the "Lasail/Alley-V2" volcanism. "Lasail -V2" lavas are separated from the lavas on top of the ophiolite ("Geotimes-V1") by only a few meters of siliceous and metalliferous sediments. This confirms that this secondary magmatism occurred very close to the ridge of origin. For these reasons the secondary magmatism cannot be related to the later obduction and emplacement of the ophiolite. It has a Mg-rich and low incompatible elements geochemical signature interpreted by *Lippard et al.* [1986] as resulting from mantle hydrous melting in a supra-subduction environment. Alternatively, the hydrous signature can result from a water contamination during the thrusting evoked here [*Ernewein et al.*, 1988 ; *Boudier et al.*, 1988]. *Casey and Dewey* [1984] also suggested that high-Mg volcanics could be generated at present spreading axes in relation with shallow thrusting. In Oman, the assumption relating the thrusts and secondary volcanism is supported by the coincidence in time (1-5 Ma after accretion) and in space as the hydrous magmatism is mainly restricted to the northern parts of the ophiolite, where thrusts are observed. A 40° rotation documented in Oman by paleomagnetic data [*Thomas et al.*, 1988 ; *Perrin et al.*, 1994] occurs between the extrusion of the ophiolite ("Geotimes-V1") basaltic lavas related the oceanic accretion and the "Lasail/Alley-V2" lavas extruded 1 to 5 Ma later. Comparable rotation rates (10-30°/Ma) have been reported within EPR microplates [*Engeln and Stein*, 1984; *Naar and Hey*, 1989; *Larson et al.*, 1992 ; *Schouten et al.*, 1993 ; *Cogné et al.*, 1995].

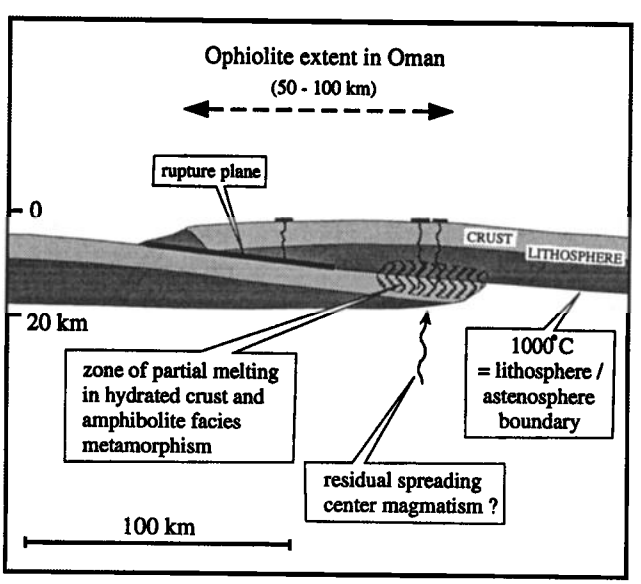

Figure 3. Model of detachment thrusts near an oceanic ridge inferred from the Oman ophiolite. The Earthquake documented here in Easter microplate may relate to a comparable thrust (see Fig. 2, in Boudier et al., 1997). Notice the secondary volcanism with a contribution of crustal hydrous melting induced by the heating effect of the overriding lithosphere (modified from Boudier et al., 1988).

Implications

In the light of the microplate analogy for the Oman ophiolite belt, we interpret thrusting in the northern massifs in a similar way as the thrust responsible for the 09/05/96 earthquake along the northern boundary of the Easter microplate. Important predictions and tests can be derived from this comparison.

1) Flat-lying thrusts should exist along the compressive or transpressive boundaries of EPR microplates. High-resolution mapping and seismic studies can test this. The apparently similar high temperature thrusts mapped in the Oman ophiolite could help to model and understand discovered oceanic thrusts,

2) The late " Lasail/Alley-V2" magmatism [*Lippard et al.*, 1986; *Ernewein et al.*, 1988], thought to be genetically related to thrusting in Oman, could be searched for near present-day oceanic thrusts associated with microplates using high-resolution mapping techniques and dragging.

3) The microplate analogy for the Oman ophiolite helps to answer how a large ophiolite such as Oman could be detached close to a ridge and rapidly rotated 45° within 1-5 Ma. with a total rotation angle of 145° [*Perrin et al.*, 1994]. A microplate with a similar size and shape as the Oman ophiolites nappe, is an obvious candidate in terms of size and mobility. This analogue might be applicable to other ophiolites [*Nicolas*,1989] which have also young basal thrusts with high temperature metamorphic aureoles indicating that detachment also occurred close to a ridge.

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References

Boudier, F., G. Ceuleneer, and A. Nicolas, Shear zones, thrusts and related magmatism in the Oman ophiolite : initiation of thrusting on an oceanic ridge, *Tectonophysics, 151*, 275-296, 1988.

Boudier, F., A. Nicolas, B. Ildefonse, and D. Jousselin, Shear zones, thrusts and related magmatism in the Oman ophiolite : initiation of thrusting on an oceanic ridge, *Terra Nova, 9*, 79-82, 1997.

Casey, J. F., and J. F. Dewey, Initiation of subduction zones along transforms and accreting plate boundaries, triple junction evolution, and forearc spreading centres-implications for ophiolitic geology and obduction. in *Ophiolites and oceanic lithosphere*, edited by Gass, I. G., Lippard, S. J. & Shelton, A. W., pp. 269-290, 1984.

Cogné, J. P., J. Francheteau, V. Courtillot, R. Armijo, M. Constantin, J. Girardeau, R. Hékinian, R. Hey, D. F. Naar, and R. Searle, Large rotation of the Easter microplate as evidenced by oriented paleomagnetic samples from the ocean floor, *Earth Planet. Sci. Lett., 136*, 213-222, 1995.

Cormier, M. H., K. C. MacDonald, and D. S. Wilson, A three dimensional Gravity Analysis of the East Pacific Rise, 18° to 21°30'S, *J. Geophys. Res., 100*, 8063-8082, 1995.

Engeln, J. F., and S. Stein, Tectonics of the Easter plate, *Earth Planet. Sci. Lett., 68*, 259-270, 1984.

Ernewein, M., C. Pflumio, and H. Whitechurch, The death of an accretion zone as evidenced by the magmatic history of the Sumail ophiolite, *Tectonophysics, 151*, 247-274, 1988.

Hacker, B. R., Rapid emplacement of young oceanic lithosphere: argon geochronology of the Oman ophiolite, *Science, 265*, 1563-1565, 1994.

Hey, R.N., D.F. Naar, M. C. Kleinrock, W.J. Phipps Morgan, E. Morales, and J.-G. Schilling, Microplate tectonics along a superfast seafloor spreading system near Easter Island, *Nature, 317*, 320-325, 1985.

Kent, G., R. Detrick, and J. Mutter, Uniform accretion of oceanic crust south of the Garrett transform at 14°15'S on the east Pacific Rise, *J. Geophys. Res., 99*, 9097-9116, 1994.

Kleinrock, M. C., and R. N. Hey, Migrating transform zone and lithosphere transfer at the Galapagos 95.5°W propagator, *J. Geophys. Res., 94*, 13,859-13,878, 1989.

Larson, R. L., R. C. Searle, M. C. Kleinrock, H. Schouten, R. T. Bird, D. F. Naar, R. I. Rusby, E. E. Hooft, and H. Lasthiotakis, Roller-bearing tectonic evolution of the Juan Fernandez microplate, *Nature, 356*, 571-576, 1992.

Lippard, S. J., A. W. Shelton, and I. G. Gass, The ophiolite of northern Oman, *Geol. Soc. Mem., 11*, 1986.

Martinez, F., and B. Taylor, Backarc spreading, rifting, and microplate rotation, between transform faults in the Manus basin, *Mar. Geophys. Res., 18*, 203-224, 1996.

Nabelek, J., Determination of earthquake fault parameters from inversion of body waves, PhD thesis, MIT, Cambridge, 1984.

Naar, D. F., and R. N. Hey, Recent Pacific-Easter-Nazca plate motions, in Evolution of Mid Ocean Ridges, *Geophys. Monogr. Ser., vol. 57*, edited by J.M. Sinton, pp. 9-30, AGU, Washington, D.C., 1989.

Naar, D. F., and R. N. Hey, Tectonic evolution of the Easter Microplate, *J. Geophys. Res., 96*, 7961-7993, 1991.

Nicolas, A., *Structures in ophiolites and dynamics of oceanic lithosphere*, Kluwer, Dordrecht, 1989.

Nicolas, A., F. Boudier, and B. Ildefonse, Evidence from the Oman ophiolite for active mantle upwelling beneath a fast-spreading ridge, *Nature, 370*, 51-53 1994.

Perrin, M., M. Prevot, and F. Bruere, Rotation of the Oman ophiolite and initial location of the Ridge in the hostpot reference frame, *Tectonophysics, 229*, 31-42 , 1994.

Rusby, R. I., and R. C. Searle, Intraplate thrusting near the Easter microplate, *Geology, 21*, 311-314, 1993.

Rusby, R. I., and R. C. Searle, A history of the Easter microplate, 5.25 Ma to present, *J. Geophys. Res., 100*, 12617-12640, 1995.

Schouten, H., K. D. Klitgord, and D. G. Gallo, Edge-driven microplate kinematics, *J. Geophys. Res., 98*, 6689-6701, 1993.

Searle, R. C., R. T. Bird, R. I. Rusby, and D. F. Naar, The development of two oceanic microplates : Easter and Juan Fernandez microplates, East Pacific Rise, *J. Geol. Soc. London, 150*, 965-976, 1993.

Thomas, V., J. P. Pozzi, and A. Nicolas, Paleomagnetic results from Oman ophiolites related to their emplacement, *Tectonophysics, 151*, 297-321, 1988.

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