# Energy-to-moment ratios for damaging intraslab earthquakes: Preliminary results on a few case studies

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## ABSTRACT

*We use the energy-to-moment ratio, as introduced by Newman and Okal [1998] to examine the source characteristics of normal-faulting intraslab earthquakes, compared to nearby interplate thrust events, based on recent case studies in central Chile and southeastern Mexico. In Chile, we find that the 1997 intraslab event had an exceptionally large $E/M_0$ ratio, 30 times greater than the nearby interplate shock. This suggests a very fast strain release at the source as the origin of the particularly destructive character of intraslab events. While the difference is less sharp in Mexico, we find a similar trend, which is in agreement with the observation that the locally most damaging earthquakes are indeed the intraslab events. We also document on the 1939 Chilean earthquake the feasibility of extending this approach to historical earthquakes for which high-quality analog records have been archived.*

### Introduction

Records of instrumental seismicity over the last century show that maximum earthquake size, measured in terms of seismic moment $M_0$, is achieved by interplate thrust earthquakes at subduction zones, as exemplified by the two largest seismic moments ever measured, the 1960 Chilean and 1964 Alaskan earthquakes (two to five times $10^{30}$ dyn-cm and $8.2 \times 10^{29}$ dyn-cm, respectively) [*Kanamori*, 1970; *Kanamori and Cipar*, 1974; *Cifuentes and Silver*, 1989]. In this context, and for the purpose of evaluating seismic risk in a given subduction zone, the largest interplate thrust event expected in the region has generally been used as a benchmark to define greatest possible hazard. For example, in the Pacific Northwest region of the United States, this reference event has been taken as a so-called "mega-thrust" interplate shock [*Heaton and Kanamori*, 1984; *Rogers*, 1988], rupturing the entire plate boundary from Cape Mendocino to the Juan de Fuca Strait, as proposed by *Satake et al.* [1996] for the source of the transpacific tsunami of January 26, 1700.

However, in a recent contribution, *Kirby* [1999] has pointed out that a number of intraplate earthquakes, occurring within the down-going slab, can result in significantly more damage than expected from their reported magnitudes. Examples include the Olympia, Washington event of April 13, 1949 ($M_{PAS}$=7), which resulted in eight deaths and more than 150 million 1949-dollars of damage and the Chilean earthquake of January 25, 1939 ($M_{PAS}$=8.3), which killed upwards of 25,000 people, i.e., at least five times as many as the 1960 event, in spite of an estimated moment 200 times smaller. A similar case is that of the Peruvian earthquake of May 31, 1970 which, in addition to casualties directly due to strong motion damage, also triggered a landslide burying the Yangay Valley and resulted in a total of 66,000 deaths. It was determined to be an intraplate event occurring within the descending slab, in a region featuring no great interplate thrust earthquakes [*Plafker et al.*, 1971; *Abe*, 1972]. Such intraslab earthquakes are usually deeper than 40 km, and displaced laterally away from the trench, often beneath populated regions. They frequently, but not always, feature normal faulting.

In comparing the hazards associated with a gigantic interplate thrust earthquake and a smaller intraslab event in the same region, one must bear in mind that the latter may have greater recurrence rate by virtue of its smaller size (expressed either as magnitude or moment). The combination of being closer geographically to populated areas, having a potential for greater damage and a greater probability of occurrence may outweigh the intrinsically smaller nature of the intraplate event and make it, rather than the interplate "megathrust", a potentially greater contributor to seismic risk in the region. This scenario would be particularly relevant in the Pacific Northwest, where the period of recurrence of a 1700-type megathrust event may range from 600 to 1600 years, based on the analysis of sand deposits in the intertidal zone [*Atwater*, 1992], while at least three destructive intraslab earthquakes took place in the past 52 years (Satsop, Washington, 1999; Puget Sound, 1965 [*Langston and Blum*, 1977]; and Olympia, 1949 mentioned above).

There can be *a priori* two explanations for the enhanced damage (in physical terms, higher accelerations) observed during intraslab earthquakes. One is intrinsic—the strain release at the source would be faster than usual, resulting in a source spectrum richer in higher frequencies. Another model would involve a receiver effect, namely that the areas most affected by the rupture, which are located directly above the source and hence displaced inland with respect to an interplate event sited at the trench, could be set in a geological environment particularly conducive to the local amplification of ground motion. This could be the case, for example, in the sediment-filled Central Valley of Chile, under which the 1939 earthquake took place.

By studying the teleseismic characteristics of damaging intraslab earthquakes, one can hope to eliminate local site effects and discriminate between the two models. We report here on a preliminary analysis of a few case studies in two subduction provinces: the Oaxaca region of southern Mexico and central Chile. We reject site effects as the source of enhanced damage and conclude that the three intraslab earthquakes studied did indeed exhibit a faster than usual seismic source.

## Data analysis

In each of the two regions studied, we selected a pair of earthquakes, one underthrusting interplate shock and one intraslab event, of comparable sizes and locations. In particular, the latter constraint ensures that site effects at teleseismic receivers will be comparable for both events in each pair, since seismic rays under the receiver will travel along essentially identical paths.

In Chile, we consider the interplate earthquake of July 6, 1997 (30.06°S, 71.87°W; $h$=19 km; $M_0$=1.9 x $10^{26}$ dyn-cm) and the intraslab event of October 15, 1997 (30.93°S, 71.22°W; $h$=58 km; $M_0$=4.9 x $10^{26}$ dyn-cm). In Mexico, we study the large 1978 Oaxaca interplate event (16.01°N, 96.60°W; $h$=18 km; $M_0$=5.3 x $10^{27}$ dyn-cm) and the more recent normal faulting earthquake of September 30, 1999 (16.06°N, 96.93°W; $h$=60 km; $M_0$=1.7 x $10^{27}$ dyn-cm; [*Singh et al.*, 2000]). Our analysis of these events parallels that by G.L. Choy [pers. comm.] using a generally similar methodology. The source locations listed above are hypocentral parameters given by the USGS. Centroid depths inverted at Harvard are 16 km (interplate) and 47 km (intraslab) in Mexico; in Chile, the intraslab event is given at 70 km, but the depth of the interplate one is unresolved and was constrained at 15 km in the inversion. The distances separating the epicenters in each pair are only 114 km in Chile and 36 km in Mexico (Figures 1 and 2).

We then use the energy-to-moment ratio to characterize the events through their "slowness" parameter

$$\Theta = \log_{10} E/M_0,$$

as introduced by *Newman and Okal* [1998] following the work of *Boatwright and Choy* [1986]. General scal-

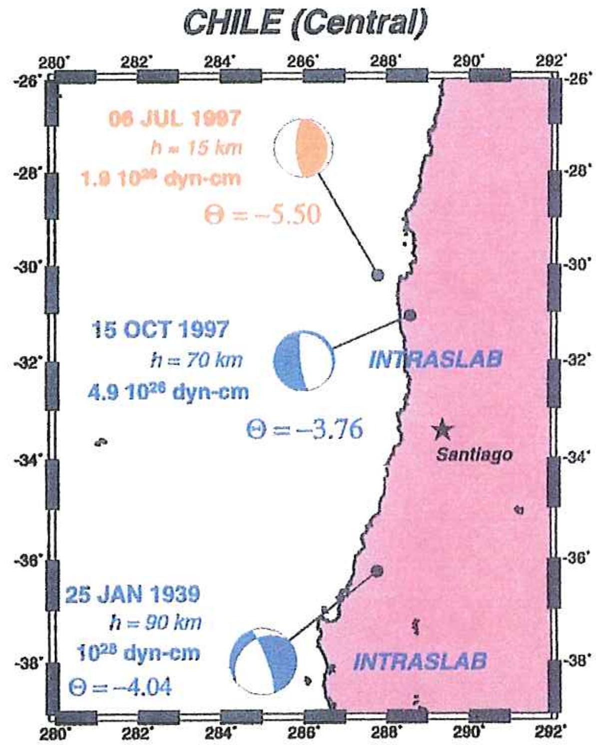


**FIGURE 1: Map of central Chile, showing the events analyzed in the present study. Depths plotted are for centroid solutions, either from the Harvard centroid moment tensor (CMT) catalog or as estimated by *Beck et al.* [1998] for the 1939 event. The focal mechanisms are color-keyed to the value of Θ (see Figure 3).**

ing laws predict Θ=-4.90, in excellent agreement with large worldwide datasets, such as *Newman and Okal's* [1998] and *Choy and Boatwright's* [1995]. Anomalously slow rupture, such as observed during so-called "tsunami earthquakes", leads to values of Θ deficient by as much as 1.5 to 2 units. Our results are summarized on Figure 3. We use energy estimates corrected for available focal mechanisms. For the recent (1997 and 1999) earthquakes, we analyzed between five and six broadband IRIS records at stations providing good azimuthal coverage. For the 1978 Mexican earthquake, we were able to find four short-period vertical records at SRO stations.

In Chile, we find Θ=-5.50 for the interplate event, which characterizes it as mildly slow. The intraplate earthquake, on the other hand, has Θ=-3.76, making its source one of the fastest analyzed by our technique. We also tested the possibility of using historical earthquakes, by processing the Pasadena–Benioff 1–100 record of the 1939 Chilean event (see Figure 4). This instrument can be regarded as the ultimate prototype of the modern broadband seismometer. We obtain a radiated energy of 8 x $10^{23}$ ergs (corrected for the focal mechanism given by *Beck et al.* [1998]), leading to Θ=-4.04, for a prob-

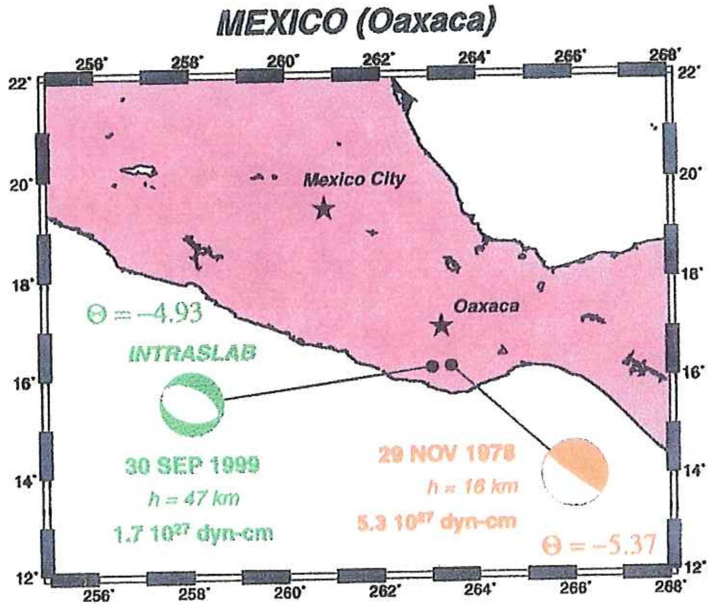


**FIGURE 2:** Map of southcentral Mexico, showing the events analyzed in the present study. Depths plotted are for centroid solutions, compiled from the CMT catalog. The focal mechanisms are color-keyed to the value of Θ (see Figure 3).

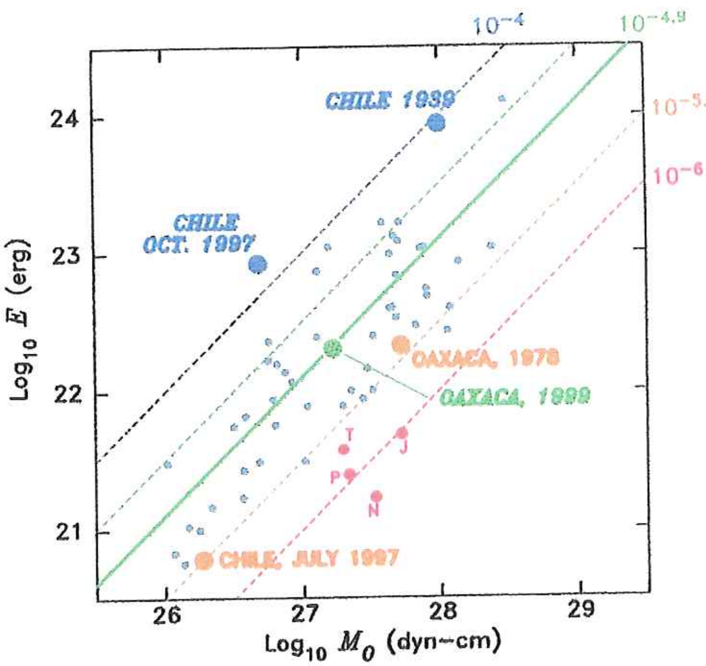


**FIGURE 3:** Summary of results obtained in this study. This figure plots radiated seismic energy against seismic moment, in logarithmic units (after *Newman and Okal* [1998]). The dashed diagonals are lines of constant Θ, with the thick line (Θ=−4.9) showing the relation predicted by scaling laws; they are color-keyed from fast (blue) to slow (red) sources. The smaller gray symbols are the dataset examined in *Newman and Okal* [1998] with bull's eye symbols referring to the four recent tsunami earthquakes (T: Tonga, 1982; N: Nicaragua, 1992; J: Java, 1994; P: Peru, 1996). The larger symbols show the events studied here. Interplate thrust earthquakes are labeled in roman type, intraslab ones in italics. Note the large disparity in Θ values in Chile and the smaller one in Mexico.

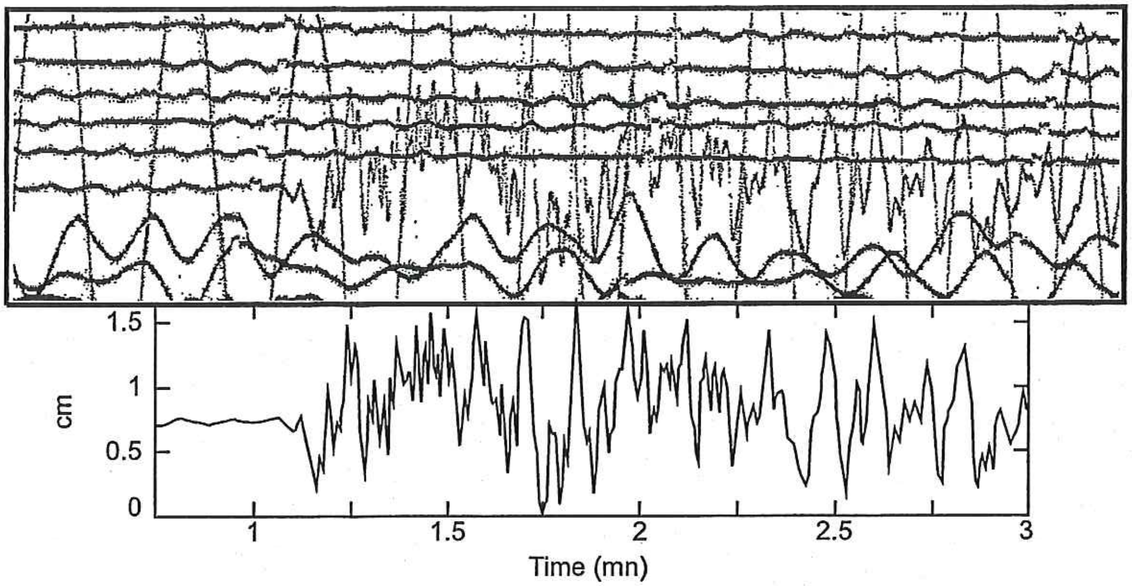


**FIGURE 4: Top: Close-up of the *P*-wave arrival of the 1939 Chilean intraslab earthquake, as recorded on the Pasadena–Benioff 1–100 north-south instrument (tick marks are minutes). Bottom: After optical magnification, such records can be successfully digitized at a rate of 10 samples per second and processed through *Newman and Okal's* [1998] algorithm.**

able moment of $1 \times 10^{28}$ dyn-cm, as suggested by the $G_2$ waves recorded on the Pasadena strainmeter. This indicates that the event is definitely fast.

In Mexico, the situation is not as clear-cut, with the deeper event only slightly faster than the interplate shock. The 1999 event has $\Theta$=-4.93, which is essentially the value predicted theoretically on the basis of scaling laws for shallow earthquakes. For the 1978 event, we find $\Theta$=-5.37, giving it a weak trend towards slowness. It is possible that the average character of the 1999 event is due to its relatively shallow centroid depth, as compared to its Chilean counterpart. While the difference in $\Theta$ between the two Mexican events is smaller than in Chile and the results are not as conclusive, the trend upholds the observation that the 1999 earthquake was more destructive (with 31 people killed locally) than the 1978 event (one local fatality). Similarly, the great normal-faulting intraslab earthquake of January 15, 1931 was by far the most destructive in Oaxaca province this century [*Ordoñez*, 1931; *Singh et al.*, 1985]. Higher energy-to-moment ratios for shallow normal faulting events (in various configurations including intraslab) were also found by *Choy and Boatwright* [1995] and *G.L. Choy* [pers. comm. to Steve Kirby, 2000].

## Conclusion

This very preliminary study, in which we have documented resolvable differences in source slowness between interplate and intraslab earthquakes, suggests the systematic use of the parameter $\Theta$, as introduced by *Newman and Okal* [1998], in the evaluation of the source characteristics of intraslab earthquakes worldwide. It further demonstrates on the case of the 1939 Chilean earthquake the feasibility of extending the technique to historical earthquakes through the use of high-quality analog data. Our work also confirms trends involving these types of earthquakes reported by *Choy and Boatwright* [1995] and *G.L. Choy* [pers. comm. 2000].

In the case of Chile, the comparative analysis of *P* waves from nearby earthquake pairs (one interplate and one intraslab) at teleseismic distances proves that the large accelerations responsible for the destruction during the intraslab event were an inherent characteristic of its source, rather than a local effect due to the structure of the Central Valley of Chile. This is in agreement with similar results reported by *Singh et al.* [this volume] in Mexico.

## Postscript

Since this research was presented at the Intraslab Workshop and this report written up, three major intraslab earthquakes took place: on January 13, 2001 in El Salvador; February 28, 2001 in Washington (the "Nisqually" event); and March 24, 2001 near Hiroshima, Japan, all three featuring higher values of $\Theta$ [*Okal and Kirby*, 2001].

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