

## Earthquake Seismology and IRIS

Göran Ekström • *Harvard University*

Earthquake seismology is a broad and diverse field, encompassing both abstract and theoretical work, as well as directly-applied investigations related to earthquake hazards. In between this range lies the broad spectrum of observational earthquake seismology that is focused on the characterization of seismic sources and their interpretation in terms of tectonic and other geophysical processes. IRIS facilities were designed and developed by the academic community that represents this latter field of intellectual inquiry. The impact of IRIS has also been, and will continue to be, significant for the broader scientific field represented by physicists, mathematicians, engineers, and social scientists.

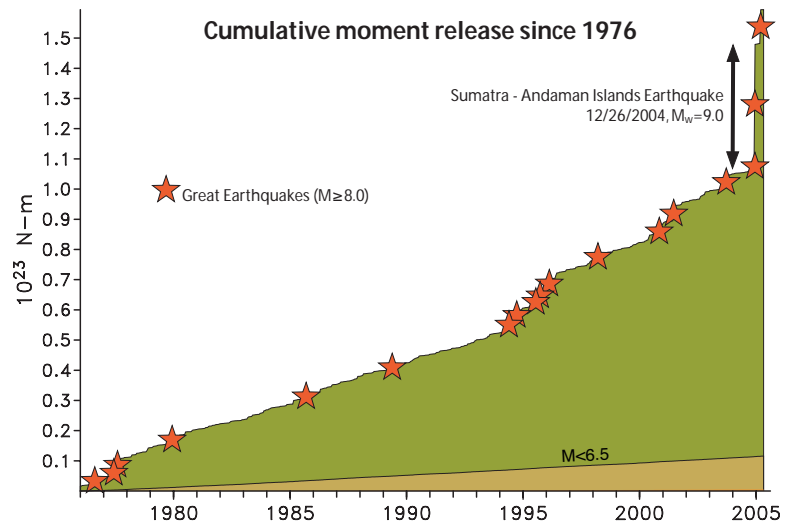
To a large extent, the broader impact that data and observations from IRIS facilities have made stems from the high level of our ignorance. We are still far from reaching a comprehensive understanding of earthquakes based on first principles, and have little opportunity to perform controlled experiments that can isolate the specific physical conditions that control their occurrence. Observations from individual earthquakes are therefore essential for constraining theoretical models, both of the earthquake phenomenon and of the relationships to geophysical processes such as tectonism and volcanism. Similarly, experiences learned from individual earthquakes are still essential for understanding and mitigating their societal effects.

The importance of individual events for furthering our understanding is characteristic for our science, and this is one context in which the value of IRIS facilities can be evaluated. The unpredictability of the events that we wish to study makes targeted hypothesis testing difficult. For example, while many important earthquake-science results come from PASSCAL deployments, motivated by specific scientific questions, other discoveries and unique observations obtained with IRIS instrumentation come as the indirect result of the existing observational infrastructure. The last several years have provided several examples of unanticipated observations that provide added justification for the significant investments in IRIS facilities.

The quality and value of IRIS facilities and the data they produce were demonstrated by the recording of the  $M_w$  9.0 Sumatra-Andaman earthquake of December 26, 2004, and the earthquake sequence that followed. The ability to record an earthquake of this size on-scale and with high fidelity was one of the goals specified when the GSN was designed 20 years ago. This was achieved for the Sumatra-Andaman earthquake, even at stations closest to the earthquake. In addition, data from most GSN stations were available in near-real time via the internet, and were used immediately by operational agencies and academic researchers to provide an initial assessment of this major event.

With nearly all of the seismological data available immediately, scientific investigations started quickly, and research results have arrived nearly continuously since the earthquake occurred. Many reported characteristics of the earthquake have now reached the point of being the consensus view: the earthquake initiated in the south, rupture spread essentially unilaterally to the north for nearly 1300 km, most of the slip occurred in the area near the hypocenter, and the moment magnitude of the event is in the range of 9.0-9.3. Also, the slip direction in the earthquake is consistent with slip partitioning and a very large amount of strike-slip and extensional deformation occurring in the upper plate.

Beyond these basic observations, much still needs to be learned about this earthquake. It is clear that while the tools and techniques that exist today are adequate for getting zeroth- and first-order information about this earthquake, new methods need to be developed to analyze fully an event of this size. This is not surprising, given that the seismic moment of the Sumatra-Andaman earthquake is likely to be 10 to 30 times larger than any event that has occurred since the deployment of the first digital seismograph network in the 1970s (see the Figure). Many seismologists were simply not prepared or equipped



The Sumatra-Andaman earthquake was 10-30 times larger than any other event in the past 30 years, and accounts for roughly a third of the total moment release during this time.

with the appropriate analysis tools to investigate an earthquake of this size, which had a duration of nearly 10 minutes. Newly-developed techniques, some applied for the first time, have already produced important results such as the imaging of the moving rupture area using regional and global short-period recordings and array-processing algorithms.

A key question regarding the Sumatra-Andaman earthquake is the nature of the slip in the northern half of the rupture, where much of the tsunami was generated. Was the character of the rupture different from elsewhere on the fault? Was there a slow component to the slip and the deformation? Is there a connection between some special characteristic of the earthquake and the large tsunami, especially in light of the lack of a large tsunami following the  $M_w$  8.6 aftershock on March 28, 2005? These questions will find answers over the next few years as the result of more-detailed seismological studies. Many of these questions will also be addressed most productively in joint analyses of seismological, geodetic, and geologic data.

In addition to providing a wealth of seismological data directly relevant to the source process of the Sumatra-Andaman earthquake, this earthquake generated a number of observations of related but poorly-understood phenomena. A dramatic example is the intense and geographically-focused earthquake swarm that occurred near the Nicobar Islands one month after the mainshock. A second example is the seismic activity in volcanic areas as much as 10,000 km away that was triggered by the passage of surface waves from the mainshock. It is likely that additional phenomena will be discovered as seismologists examine the data from the earthquake in greater detail. Given that we are still seeing effects of the  $M = 9.5$  1960 Chile earthquake in the distribution of current earthquakes off the coast of southern Chile and in the geodetic deformation measured on land, we should expect the effects of the 2004 earthquake to be seen for decades to come.

Over the last few years we have also seen several discoveries in seismic-source seismology that have resulted from analysis and reanalysis of massive datasets that originally were collected for other purposes. In many cases these investigations have involved the characterization and analysis of noise. The low-frequency ‘hum’ of the Earth was discovered in the late 1990s and is still awaiting a convincing explanation, though it seems likely to involve land-ocean interaction. High-frequency ‘chatter’ has now been observed in several subduction zones, and in the Pacific northwest subduction zone is associated with periodic slip transients that were first observed a few years ago. Array analysis of intermediate-period surface waves has led to the discovery of  $M = 5$  slow seismic slip events associated with outlet glaciers in Greenland, and other glaciers in Antarctica and Alaska. Of these three newly-observed phenomena, the subduction-zone chatter is the one that now seems most directly relevant to the traditional field of earthquake seismology and, specifically, to the question of seismic and aseismic slip in subduction zones. The other two illustrate the range of geophysical phenomena that can be observed and investigated with IRIS instrumentation. Equally important are the facts that they demonstrate how discovery is possible with the tools we have developed, and that discovery frequently is unpredictable.

Related to the discoveries to be made in the massive volumes of high-quality data IRIS has collected is the growing trend among seismologists to reuse and reprocess data stored at the IRIS DMC with new algorithms and increasingly capable computers. This is necessary when the goal is to find signals and sources in the noise, and also when the objective is to determine better source parameters and refine images of seismicity. Very impressive relocation results are currently resulting from massive cross-correlations of broad-band waveforms. One can expect that this type of processing, involving computations that would have been impossible a few years ago, will be the normal way to deal automatically with the enormous volume of data now being generated by IRIS facilities and networks all over the world.

In conclusion, it is likely that over several years significant advances of our understanding of both the tectonic processes which result in seismicity and of the earthquake rupture process will result from the analysis of the unprecedented volume of high-quality data generated and distributed by IRIS facilities. Some of this progress will be incremental and will come as the simple result of the accelerating accumulation of seismological observations. However, judging by recent developments, it seems probable that dramatic improvements will also occur in the estimation of earthquake parameters, the imaging of the earthquake source process, and the interpretation of seismic “noise” as the result of new and innovative approaches to the processing of broad-band data.