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UNIVERSITY OF CALIFORNIA, SAN DIEGO

New events from the Apollo lunar seismic data and an investigation of the
relationship between tidal stress and deep moonquake occurrence

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Earth Sciences

by

Renee Bulow

Committee in charge:

Catherine Johnson, Chair

Peter Shearer, Co-chair

Bruce Bills

Donna Blackman

Steve Cande

Mark Thiemens

2007

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2007

To Mom

TABLE OF CONTENTS

Signature Page	iii
Dedication	iv
Table of Contents	v
List of Figures	viii
List of Tables	x
Acknowledgments	xi
Vita and Publications	xiv
Abstract	xv
1 Overview	1
References	5
2 New events discovered in the Apollo lunar seismic data	6
1. Abstract	6
2. Introduction	7
3. Data preparation	11
4. Analysis of previously identified deep moonquakes	15
1. Qualitative event characteristics: All events	17
2. Quantitative event characteristics: Deep cluster A1	18
5. Search for new A1 events in the continuous data	30
6. Discussion: Analyses of complete A1 cluster	34
1. Generation of optimized stacks	36
2. Travel time picks	37
3. Location estimates	40
4. Temporal Distribution	41
7. Conclusions	42
8. Acknowledgments	43
References	45
3 Temporal and spatial properties of some deep moonquake clusters	47
1. Abstract	47
2. Introduction	48
1. Tidal periodicities present in deep moonquake occurrence times	50
2. Locations of deep moonquake source regions	51

3.	New event report	52
4.	Spectral analyses of deep moonquake occurrence times	54
1.	Multitaper method	58
2.	Spike-train method	60
5.	Moonquake locations	62
1.	Method	63
2.	Results	67
6.	Discussion	68
1.	Temporal characteristics	68
2.	Spatial characteristics	70
7.	Conclusions	71
8.	Acknowledgments	72
	References	74
4	The influence of Earth-Moon geometry on deep moonquake occurrence	76
1.	Introduction	76
2.	The lunar orbit	80
3.	Position of the Earth at the times of moonquakes	81
4.	Interpretation of histogram results	85
5.	Conclusions	101
A.	Appendix: Model of orbital motion	103
B.	Appendix: Demodulating time series	109
	References	114
5	The influence of tidal stress on deep moonquake occurrence	116
1.	Introduction	116
2.	Building the stress tensor	119
1.	Tidal stress and strain from the solution vector	124
2.	Propagating the solution vector through a layered model	125
3.	Stress tensor exploration	126
4.	Shear and normal stresses and rates	131
5.	Grid search	138
6.	Results and discussion	151
	References	157
6	Summary	159
1.	New events: Implications for locations, velocity models, and lunar seismicity	161
1.	Cluster locations and velocity models	161
2.	Lunar seismicity	162

2. Geometry and stress analyses: implications for mechanisms	163
3. The future of lunar seismology	167
References	169

LIST OF FIGURES

Figure 2.1:	Station location map	10
Figure 2.2:	Benefits of filtering and despiking	14
Figure 2.3:	Noise spikes	16
Figure 2.4:	Grade examples	17
Figure 2.5:	Histograms of event visibility	19
Figure 2.6:	Amplitude estimation method	21
Figure 2.7:	Amplitude comparison	22
Figure 2.8:	Correlation histograms	24
Figure 2.9:	Variability in time shifts	25
Figure 2.10:	Example traces and stack	27
Figure 2.11:	A1 peak mode stacks	28
Figure 2.12:	A1 flat mode stacks	29
Figure 2.13:	Correlation coefficient versus time	31
Figure 2.14:	Number of events versus cutoff	33
Figure 2.15:	New event stacks for deep event group A1	35
Figure 2.16:	A1 optimized stacks	38
Figure 2.17:	A1 arrival time picks	39
Figure 2.18:	A1 anomalistic phase	42
Figure 3.1:	Cluster location map	48
Figure 3.2:	Multitaper spectrum	60
Figure 3.3:	Spike-train spectra	61
Figure 3.4:	Phase plots	64
Figure 3.5:	Relocation map	68
Figure 3.6:	Spectrum of event subset	69
Figure 4.1:	Deep moonquake cluster location map	79
Figure 4.2:	Geometrical parameters versus time	82
Figure 4.3:	Histograms of (r, θ, ϕ)	84
Figure 4.4:	Demodulation example	85
Figure 4.5:	Example of large-skewness distribution	86
Figure 4.6:	Example of large-kurtosis distribution	87
Figure 4.7:	Example cluster with no favored geometry	88
Figure 4.8:	Example distribution with linear trend	89
Figure 4.9:	Normalized histograms of r for 9 clusters in quadrant 1	96
Figure 4.10:	Normalized histograms of θ for 9 clusters in quadrant 1	97
Figure 4.11:	Normalized histograms of ϕ for 9 clusters in quadrant 1	98
Figure 4.12:	Similarity of cluster pairs with $\Delta \leq 20^\circ$	100
Figure 4.13:	Fourier amplitude spectra of (r, θ, ϕ)	104
Figure 4.14:	Example signal envelopes	110
Figure 4.15:	Demodulation example	111

Figure 4.16:	Envelopes for (r, θ, ϕ)	111
Figure 4.17:	Histogram of sine function	112
Figure 4.18:	Histogram of demodulated parameters	112
Figure 5.1:	Principal stress directions	128
Figure 5.2:	Principal stress directions at various locations	129
Figure 5.3:	A1 principal stress directions	130
Figure 5.4:	A1 sub-Earth point geometry	131
Figure 5.5:	A22 principal stress directions	132
Figure 5.6:	Shear and normal stress at test locations	134
Figure 5.7:	A1 shear and normal stresses	136
Figure 5.8:	A1 shear and normal stress rates	137
Figure 5.9:	A1 variance	140
Figure 5.10:	A1 linear combination of normal and shear stress	141
Figure 5.11:	A1 linear combination of normal and shear stress rates	142
Figure 5.12:	A1 linear combination of normal and shear stresses and rates	143
Figure 5.13:	Minimum variance ratio comparison	148
Figure 5.14:	A16 linear combinations, methods 1 and 2	149
Figure 5.15:	A16 linear combinations, method 3	150
Figure 5.16:	Significance based on f-test	152
Figure 5.17:	Additional low variance ratio examples	153
Figure 5.18:	Variance ratio for A28	155

LIST OF TABLES

Table 2.1:	Number of catalogued A1 events stacked	26
Table 2.2:	Newly identified A1 events	34
Table 2.3:	New A1 events detected per channel	36
Table 2.4:	Number of A1 events in optimized stacks	37
Table 2.5:	Travel-time picks for cluster A1	40
Table 2.6:	A1 location estimates	41
Table 3.1:	New events	55
Table 3.1:	(continued)	56
Table 3.1:	(continued)	57
Table 3.1:	(continued)	58
Table 3.2:	Number of original and new events by cluster	59
Table 3.3:	Dominant periods of moonquake occurrence by cluster . . .	63
Table 3.4:	Seismic phase arrival picks	65
Table 3.5:	Relocation estimates	66
Table 3.6:	Location errors	70
Table 4.1:	Moments of distributions, r	90
Table 4.2:	Moments of distributions, θ	91
Table 4.3:	Moments of distributions, ϕ	92
Table 4.4:	Moments of distributions, dr/dt	93
Table 4.5:	Moments of distributions, $d\theta/dt$	94
Table 4.6:	Moments of distributions, $d\phi/dt$	95
Table 4.7:	K-S probabilities	99
Table 4.8:	Highly similar pairs	101
Table 4.9:	Number of functions by parameter	106
Table 4.10:	Fundamental periods of the lunar orbit	107
Table 4.11:	Fit to parameters (r, θ, ϕ)	108
Table 4.12:	Residual standard deviation	109
Table 5.1:	Grid search results, normal and shear stress	145
Table 5.2:	Grid search results, normal and shear stress rates	146
Table 5.3:	Grid search results, normal and shear stresses and rates . .	147
Table 5.4:	Clusters for which the minimum variance ratio is ≤ 0.1 . .	154

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ABSTRACT OF THE DISSERTATION

New events from the Apollo lunar seismic data and an investigation of the
relationship between tidal stress and deep moonquake occurrence

by

Renee Bulow

Doctor of Philosophy in Earth Sciences

University of California, San Diego, 2007

Professor Catherine Johnson, Chair

Professor Peter Shearer, Co-chair

A network of seismometers emplaced on the Moon during the Apollo missions recorded many types of seismic signals during the lifetime of the experiment (1969 – 1977). The research presented in this thesis focuses on understanding a subset of those signals: deep moonquakes – natural lunar seismic events that appear to be related to tides, and occur at great depths (800 – 1000 km) in the Moon. We investigate when, where, and why deep moonquakes occur by: (1) establishing an extended catalog of deep moonquakes using a cross-correlation technique to identify events missed in earlier visual examination of printed seismograms, (2) investigating the tidal periodicities present in moonquake occurrence times through spectral analysis, (3) estimating the uncertainties in deep moonquake source locations using revised seismic phase arrival picks from stacks which include our new events, (4) developing an orbital model which describes the position of the Earth with respect to the Moon, and examining these parameters at the times of moonquakes, and (5) using our orbital model to compute the gravitational tidal potential within the Moon (due to the Earth) and determining how the Moon deforms, and what stresses are generated within the Moon, in response to this potential.

We observe tidal (~ 27 -day, 206-day, and 6-year) periods in moonquake occurrence times, suggesting a relationship between deep event occurrence and tidal forcing. Investigation of the relationship between the position of the Earth and the times of moonquakes from 51 source regions reveals that while individual moonquake clusters sometimes produce events at specific values of Earth position, relatively few groups of nearby clusters respond similarly. This indicates that local structure is possibly important to failure at individual clusters. To investigate, we compute tidal shear and normal stresses on a range of failure plane orientations at the same 51 locations. While linear combinations of stresses can fit moonquake occurrence at many clusters quite well, for some clusters, the fit is not heavily dependent on plane orientation. This suggests that the process responsible for generating moonquakes has two components: one which is dependent on plane orientation, and another which is independent of orientation.

1

Overview

The Apollo Passive Seismic Experiment (PSE) consisted of four seismometers deployed on the lunar surface between 1969 and 1972. Data from these instruments were recorded continuously until late 1977. Several types of seismic signals were recorded by the lunar seismic network, including natural impacts (meteoroids), artificial impacts (booster rockets from the Apollo spacecraft, and the landers themselves), shallow moonquakes (natural events occurring in the upper 50 to 220 km of the Moon), and deep moonquakes (natural events occurring between 700 and 1000 km depth).

Of these event types, deep moonquakes comprise approximately half of the over 12,000 catalogued seismic events (Nakamura et al., 1981). These deep events are known to originate from distinct source regions within the Moon (often referred to as ‘clusters’), and each source emits its own characteristic waveform. In addition, deep moonquakes occur periodically, with events from each source occurring approximately every 27 days. This periodicity is consistent with tidal forcing, and suggests a relationship between tidal stress and moonquake occurrence (Toksöz et al., 1977; Lammlein, 1977; Cheng and Toksöz, 1978; Nakamura, 1978; Goult, 1979; Minshull and Goult, 1988).

Seismic data from the PSE were digitized and telemetered to Earth, where

they were stored on reels of magnetic tape. By the end of the experiment, over 10,000 tapes had been recorded. Due to the large volume of data and limitations of computers at the time, only small portions of the seismograms were ever analyzed. Initial identification of events was performed visually, using translucent plotting paper and a light table. Later computerized classification of events was performed using this subset of the continuous data.

Modern computers allow us to easily store and manipulate this once-formidable data set. In Chapter 2 of this dissertation, we discuss our method of searching for new events in the continuous lunar seismic data. In this search, we make use of the repeatability of deep moonquake seismograms, by using a cross-correlation technique to perform a systematic search through the continuous data for new events. Using this technique, we were able to recover 123 new events from the A1 deep moonquake cluster.

Application of this search method to 8 additional moonquake clusters allowed us to recover a further 503 new events from the continuous data. In Chapter 3, we discuss how the expanded catalog of events resulting from our new event search can be used to further our understanding of the temporal and spatial properties of some deep moonquake clusters. First, a larger number of events contributes to better temporal resolution of the catalog, since we can fill gaps in the catalog where no events were previously detected. Through investigation of occurrence-time spectra, we observe that moonquake occurrence at individual clusters can be fairly sensitive to different tidal periods.

Second, since seismic phase arrivals are selected from stacked seismograms, we can examine the sensitivity of arrival picks to the addition of our new event seismograms to the stacks. We use our revised arrival picks along with two seismic velocity models (Nakamura, 1983; Lognonné et al., 2003), to relocate the nine deep moonquake clusters for which we perform event searches. We observe a variety of behaviors in terms of agreement among cluster locations. Some cluster locations are less well-constrained than others, due to the difficulty in identifying

reliable body wave arrival times at one or more seismic stations.

We next turn to the investigation of the relationship between moonquake occurrence times and tidal forcing. Deformations in the lunar interior, which are related to tidal stress, are controlled by the imposed potential of the Earth, which varies with the position of the Earth as seen from the Moon. In Chapter 4, we present an analysis of the geometry of the Earth-Moon system at the times of moonquakes, as an intermediate step in the process of computing tidal stress. By considering the geometry we can explore any relationships between moonquake occurrence times and tidal forcing without having to make assumptions regarding the rheological response of the Moon.

We analyze six parameters describing the position and rate of change of position of the Earth with respect to the Moon at the times of moonquakes from 51 deep event clusters, to determine whether there are coherent geographical patterns in lunar seismicity. We find that while individual moonquake clusters sometimes produce events at specific values of Earth position or rate of change of Earth position, relatively few groups of nearby clusters respond similarly to the same distributions. One possible interpretation, which we explore further in Chapter 5, is that local structure is likely important to failure at individual clusters.

As the quality of the lunar seismic data and the limited source/receiver geometries of the seismic network make the determination of fault mechanisms difficult, we must search for a failure criterion. Based on the large S- to P-wave arrival amplitudes observed on deep event seismograms (Lammlein et al., 1974), most previous studies searched for conditions under which deep moonquake occurrence at the A1 source could be linked to shear failure. However, no such correlation was found to be consistent throughout the entire period of operation of the seismic network. In addition, relatively few clusters apart from A1 have been investigated.

In Chapter 5, we investigate the relationship between moonquake occurrence and tidal stresses more generally. First, we examine the sensitivity of moonquake occurrence times to both normal and shear stress, and the rates of

change of normal and shear stress. Rather than impose a specific failure plane and/or failure criterion, we perform a grid search over all possible plane orientations to identify the plane that produces a linear combination of normal stress, shear stress, normal stress rate, and shear stress rate resulting in the most nearly constant values at the times of moonquakes from 51 clusters. This allows us to determine which of these four stress criteria are most important, on an individual basis, to seismic event occurrence at each cluster.

We find that linear combinations of stresses and stress rates can fit moonquake occurrence at many clusters quite well, and observe that there is no obvious correlation between the proximity of clusters and the orientation of the best-fitting failure plane. This suggests that moonquake failure geometry is a dominantly local phenomenon, consistent with our result from Chapter 4. For some clusters, the fit is not heavily dependent on plane orientation, suggesting that the process responsible for generating moonquakes has two distinct components: one which is dependent on plane orientation, and another which is independent of orientation.

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2

New events discovered in the Apollo lunar seismic data

2.1 Abstract

We use modern seismological data processing tools to revisit the Apollo lunar seismic data set with the goal of extending and further characterizing the existing catalog of deep moonquakes. Our studies focus on the long-period data and include filtering and despiking noisy data, event classification, cluster identification, and robust methods for amplitude estimation. We perform cross-correlation analyses for known groups of deep events, confirming earlier visual classifications. By combining the cross-correlation approach with a robust median despiking algorithm, we produce improved differential times and amplitudes, enabling us to construct cleaner stacks. Each event group, represented by a single waveform stack of its constituent members, is cross-correlated with the continuous time series. We focus on the A1 cluster because it has more catalogued events than any other cluster and is generally well-characterized. Using this approach, we identify additional events that can be associated with previously-defined deep clusters. For the deep event group A1, we have found 123 new events, which show phase behavior similar

to the 323 previously catalogued events. Our new event search allows us to create optimized event stacks with improved signal-to-noise from which revised travel time picks (and thus location estimates) can be made. Application of our methods to other deep clusters should form a more complete event catalog and improve our understanding of the spatial and temporal distribution of deep lunar events.

2.2 Introduction

The Apollo Passive Seismic Experiment (PSE) consisted of four seismometers placed on the lunar surface between 1969 and 1972 as part of the Apollo Lunar Surface Experiment Package. The seismometers were deployed by astronauts on the Apollo 11, 12, 14, 15, and 16 missions. Each station included three long-period instruments (one vertical and two horizontal components, sample rate 6.625 Hz) and one short-period instrument (vertical component, sample rate 53.00 Hz). Continuous data from stations 12, 14, 15, and 16 (the Apollo 11 instrument failed after one lunar day) were telemetered to Earth and recorded until 1977.

Analysts visually inspected the records in order to identify seismic events. Early studies classified events into four main types: artificial impacts (such as the booster rockets ejected from the command module), natural impacts (meteoroids), shallow moonquakes occurring at depths of 50 - 220 km (Khan et al., 2000; Lognonné et al., 2003), and deep moonquakes (natural events with focal depths between 700 and 1000 km). Events were classified using a variety of criteria, including waveform matching, rise time, spectral characteristics, shear-wave identification, and time of occurrence (Lammlein et al., 1974). Over 12,000 events have been identified, more than half of which (6549) are deep moonquakes (Nakamura et al., 2004). Most studies performed on the lunar seismic data have concentrated on these previously identified events, which contain data starting ten minutes before the detected signal onset and lasting until that signal attenuates below the noise

level, often an hour or more later.

Early analyses of the lunar event data included the generation of seismic velocity models with different types of events used to infer information about different regions in the lunar interior. For example, because artificial impacts create seismic events of known location and origin time at relatively small distances from the stations (median distance 172 km), energy recorded from these impacts provides information on crustal structure – thickness and seismic velocities to approximately 100 km depth (Toksöz et al., 1972, 1974). In contrast, accurately locating meteoroid impacts and moonquakes is challenging because of the small number of stations, the poor signal-to-noise ratio of many of the records, the often emergent P-wave arrivals, and the strong P-wave coda that hampers identification of S-wave arrivals. Nonetheless, subsets of these events have been used to estimate lunar seismic velocity profiles down to about 1000 km, the depth of the deepest moonquakes (Nakamura et al., 1976; Dainty et al., 1976; Goins et al., 1981; Nakamura et al., 1982; Nakamura, 1983; Khan et al., 2000; Lognonné et al., 2003). Seismic velocity structure at depths greater than 1000 km is not known due to the lack of deeper events and definitively identified far side events.

Deep moonquakes are the most numerous type of event recorded by the PSE. These events appear to originate from specific source regions, each of which produces repeatable waveforms (Lammlein, 1977). Early classifications were made by visual inspection and matching of waveforms. Seismograms printed on translucent paper were compared by placing one atop another on an illuminated table. The most current event catalog still lists events selected from the continuous data in this manner. A combination of waveform cross-correlation and single-link cluster analysis performed on this catalog (Nakamura, 2003) has identified clusters of associated deep events from more than 300 distinct source regions. However, as the catalogued events were originally detected by eye, it is possible that many low signal-to-noise events may have been overlooked. Modern computing capabilities provide motivation to analyze the continuous data. Waveform correlations can be

performed systematically, enabling the quantification of similarities among deep moonquakes and the objective detection of such events in the continuous time series.

Two characteristics of deep moonquakes are especially notable: seismograms from each deep event source region are highly repeatable, and correlate in time with lunar tides (Lammlein et al., 1974). The waveform repeatability allows us to use stacking and cross-correlation methods to search for previously undetected events in the continuous data. Newly-identified events can be added to the existing catalog (Nakamura et al., 2004). The application of cross-correlation techniques to all events in our expanded catalog enables robust identification of events associated with a specific deep cluster, including our new events, and previously unclassified or incorrectly-classified events. This can yield event stacks with increased signal-to-noise and better seismic phase identification, from which we can pick travel times and estimate cluster hypocenters.

Previous studies have suggested that the periodicity of deep moonquake occurrence times results from the buildup and release of tidal stresses (Lammlein et al., 1974; Lammlein, 1977; Toksöz et al., 1977). This further motivates our interest in obtaining a more complete catalog of deep moonquakes, as improved temporal information for each event cluster will allow for more accurate analyses of tidal periodicities.

In this paper, we demonstrate how the existing lunar deep event database can be improved through the analysis of the A1 cluster (Figure 2.1). We focus on A1 as it is the cluster with the most catalogued events (323 as identified by Nakamura et al. (2004)) and has been the subject of many previous studies (Lammlein et al., 1974; Lammlein, 1977; Nakamura, 1978; Toksöz et al., 1977). However, our approach is general and can be extended to other deep clusters. We document the techniques and data processing steps required in some detail since our analysis begins with the lunar seismic data in its original format. Although much of this information is available in previous papers and technical reports, our analy-

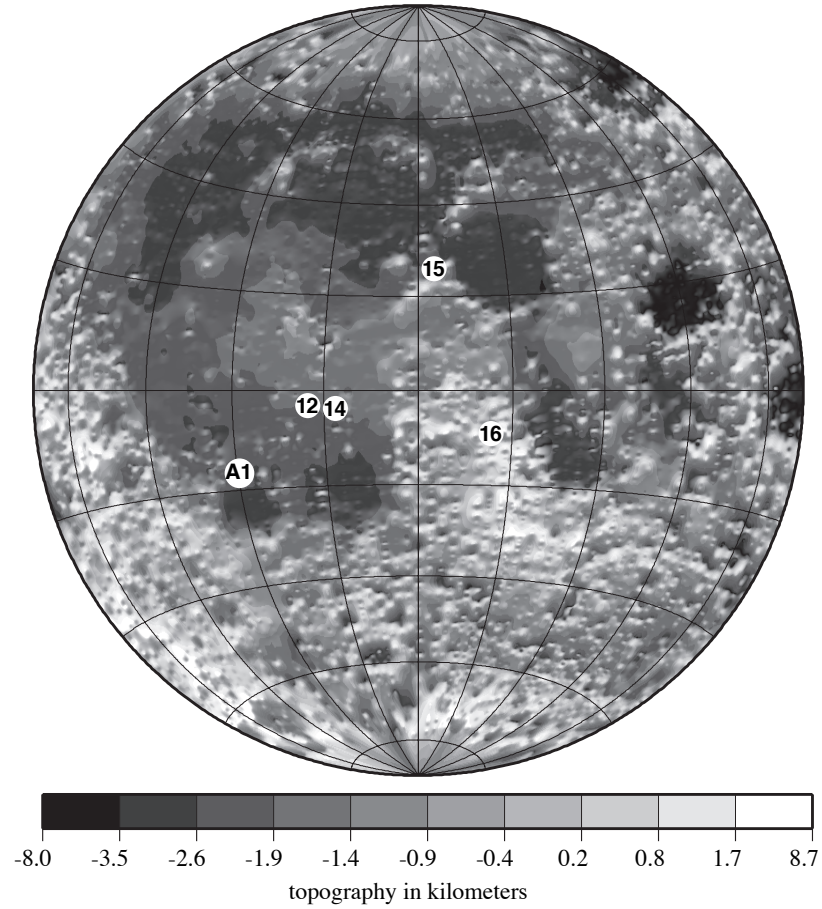


Figure 2.1 Station location map. Topographic map (Zuber et al., 1994) of the near side of the moon showing station locations and the epicenter of the A1 deep event group.

ses have been greatly helped by additional information provided through personal communication with investigators who originally worked with the PSE data. We hope that the synthesis provided here will prove useful to those wishing to use this challenging data set in the future.

We first describe initial processing steps applied to both the event and continuous time series to remove potentially erroneous records, filter, and despoke the seismograms (Section 2.2). We conduct a qualitative assessment of the seismograms for previously-catalogued events: a visual inspection of records to provide familiarity with the data set and to obtain an estimate of the percentages of data

that are of a specified quality.

Our new event search has so far focused on the A1 cluster. We begin with the preparation of a *target trace* for cross-correlation: a representative A1 event stack used to identify all potential A1 events from the continuous data (Section 2.3). We perform cross-correlations between the stack and the continuous data, noting the times of peaks in the correlation function for comparison to catalogued event times. Correlation peak occurrence times not coinciding with catalogued event times (Nakamura et al., 2004) may represent new events. New event records are distinguished from noise by requiring the absolute value of the cross-correlation function to be greater than a threshold value (Section 2.4). We validate these new events (Section 2.5) by stacking them to enhance their signal levels and by comparing their occurrence times to tidal periodicities recognized previously for the A1 cluster (Lammlein et al., 1974; Toksöz et al., 1977; Lammlein, 1977). The methods used to discover new events can also be applied to identify all events associated uniquely with A1 and to optimize event stacks. These stacks produce improved signal-to-noise records for measuring P and S arrival times. Our methodology should be applicable to other deep event clusters, where the discovery of additional events will assist in location and tidal periodicity studies, particularly for the smaller, less well-identified clusters.

2.3 Data preparation

The lunar seismic data are currently available from the IRIS Data Management Center (www.iris.edu) either via exabyte tape request or by ftp. Both event data and continuous data are available. The event tapes contain events reported in the catalog of Nakamura et al. (2004). The continuous data tapes are available as two separate groups: the PSE (Passive Seismic Experiment) tapes archiving the seismic data up until 1976 Julian day 60, and the Normal Bit-Rate Work tapes which archive the data from that time until the end of the experiment

on Julian day 273, 1977. These two types of continuous lunar seismic data have minor differences in format; both are available from IRIS.

Each tape consists of a series of records. Read errors from the original magnetic tapes occasionally resulted in the fragmentation of a record. Other problems were introduced by instrument sensitivity to temperature fluctuations between lunar day and night, telemetry errors, and the limited dynamic range of the instruments (10 bit sampling). In general, the quality of lunar seismograms is low compared to typical terrestrial seismograms. In addition, strong scattering and low attenuation result in emergent arrivals and extended codas for both P and S waves.

Each long-period instrument could be operated in one of two modes: ‘peak’ or ‘flat’ (broader band) response (Lammlein et al., 1974). Operating the instruments in flat mode sometimes made them unstable, so for the most part the stations were operated in peak mode. This latter mode had a higher gain, which was fortunate owing to the low dynamic range of the instruments and the small magnitude of natural seismic signals. Additionally, the resonant period of the instruments in peak mode is 2.2 seconds, coincident with the frequency range of deep moonquakes. Nonetheless, from Julian day 180, 1975 (1975/180), to day 86, 1977 (1977/086), stations 12, 15, and 16 were operated in ‘flat’ mode, in which the instrument response was extended to lower frequencies. (Station 12 was also operated in the flat mode from 1974/289 to 1975/99.) In this mode, the long-period seismometers have a level response from 1 to 15 seconds (Lammlein et al., 1974).

The analog seismometer output was digitized and telemetered directly to Earth. Various digitization irregularities were common as the digitization of seismic traces was still in its infancy when the lunar data were gathered. Error checks and filtering performed on the event and continuous data are described below. Our processing began with the conversion of files from their original format to a format used in analyses of terrestrial seismic data and adapted for the lunar

data. During this conversion procedure we conducted the following checks:

1. Software time flag check: This flag indicates that one of the receiving stations had difficulty reading the standard time signal, and a computer-generated time was substituted. Such times may be off by as much as several seconds from the standard time.

2. Sync pattern check: This bit string in the data represents the Barker code and its complement. Barker codes are commonly used for frame synchronization in digital communication systems. If the bit string in the data does not match the code, the data are out of sync.

3. Timing mismatch check: The timing mismatch is computed as $(t_c - t_p) - \Delta t$ where t_c and t_p are the times of the current and previous records respectively and Δt is the predicted time difference assuming evenly sampled data. We considered records more than 0.5 seconds off from the previous record unusable.

In this study, we discard records containing any of the above errors since the precise time correction required for reliable timing information is unknown. To remove long-period fluctuations and secular trends from the data, we band-pass filter the traces from 0.25 Hz to the Nyquist frequency (3.3127 Hz). However, some large-amplitude anomalies characterized by sharp onsets and exponential amplitude decay pass through the filter and emerge as spikes (Figures 2.2a and 2.2b). These spikes are observed on all stations and are most intense near lunar sunrise and sunset; they are likely caused by the thermal expansion and contraction of the insulating shroud protecting each instrument (Lammlein et al., 1974).

The association of noise spikes with lunar sunrise and sunset is illustrated in Figure 2.3, in which we show the maximum peak-to-peak amplitudes in 1-hour time windows as a function of time since the last new moon (the phase relative to the 29.53 day period of the synodic month, or the time between two consecutive new moons) for continuous data from station 12. The noisiest parts of the records occur near the times of lunar sunrise and sunset, and in general the records are noisier during the daytime. Figure 2.3 also illustrates gaps in the data as recovered

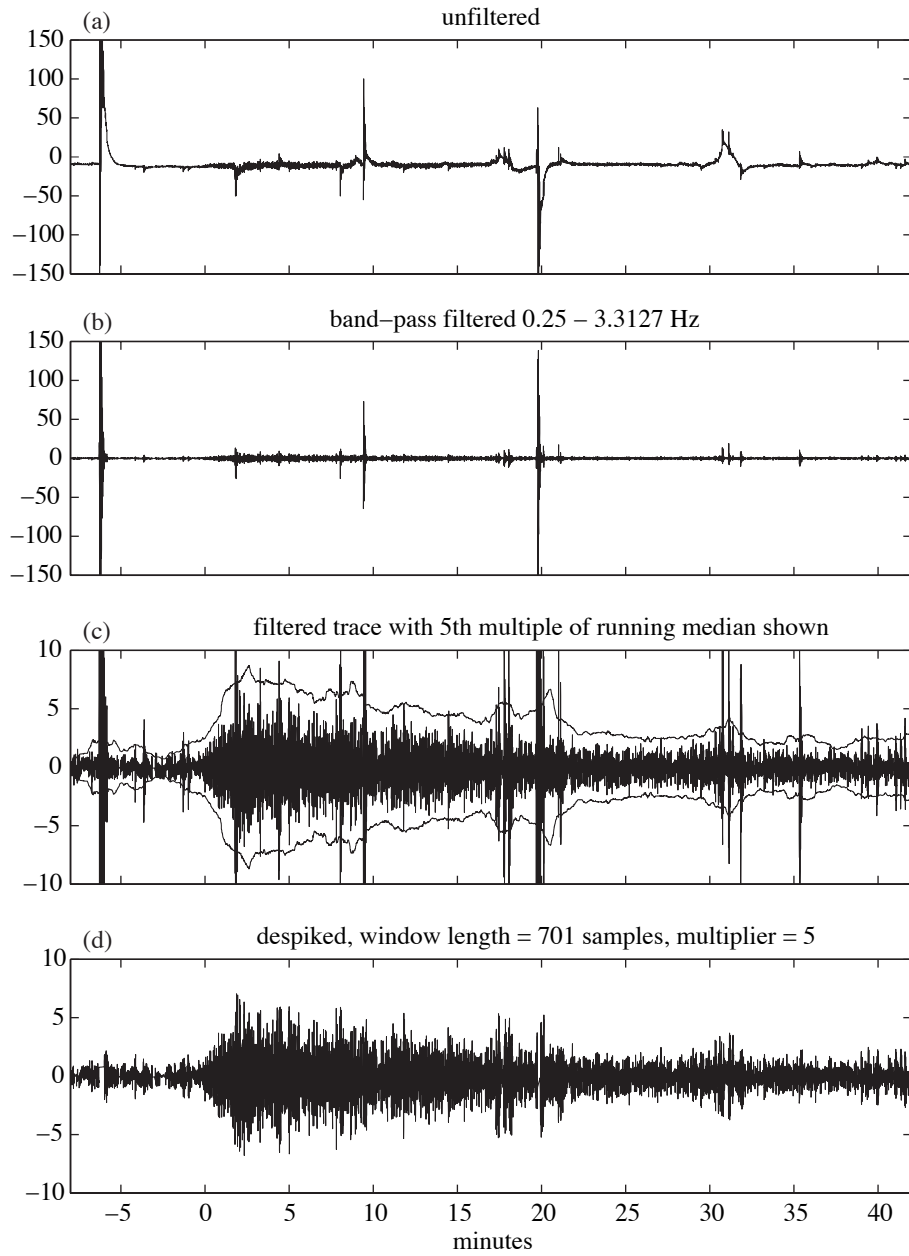


Figure 2.2 Benefits of filtering and despiking. (a) Unfiltered A1 trace from deep event occurring on 1977/149 at 1136 UT. The record shown is component lpx at station 14. Note that the dynamic range in the record is dominated by high-amplitude thermal spikes such as those near -7, 2, 10, and 20 minutes. (b) The same trace after application of band-pass filter (0.25 - 3.3127 Hz). (c) The same trace with 5 times the running median value outlined. (d) The same trace after application of running median despiker (window length 701 samples, median multiplier 5).

from the tape archives; these gaps amount to only about 1% of the total time period.

We remove noise spikes and thermal anomalies from our filtered records using a robust median despiking algorithm (Evans, 1982) to avoid bias in event amplitude estimation and other calculations. We compute the median value of the time series in a running window of length m samples. Points within the window that lie above a user-specified multiple of the median are removed and replaced with a linear interpolation of the data across the spikes. A trace that has been despiked using a window length of 701 samples (approximately 2 minutes) and a median multiplier of 5 is shown in Figures 2.2c and 2.2d. Experimentation showed that these parameter values result in a relatively conservative despiking method that removes the largest anomalies associated with the spikes with minimal clipping of actual data. Despiking also improves phase/time plots, emphasizing the correlation between noise spikes and lunar sunrise and sunset (Figure 2.3b).

2.4 Analysis of previously identified deep moonquakes

To familiarize ourselves with the lunar data, we analyze previously detected deep moonquakes for which event seismograms are available. We visually inspect this entire data set to evaluate event quality and distribution. Next, we assess A1, the largest of the deep clusters, examining event amplitudes and correlations among waveforms. The results are used to establish selection criteria for A1 events that can be stacked to create target traces. These traces are then used to find previously undetected events in the continuous time series.

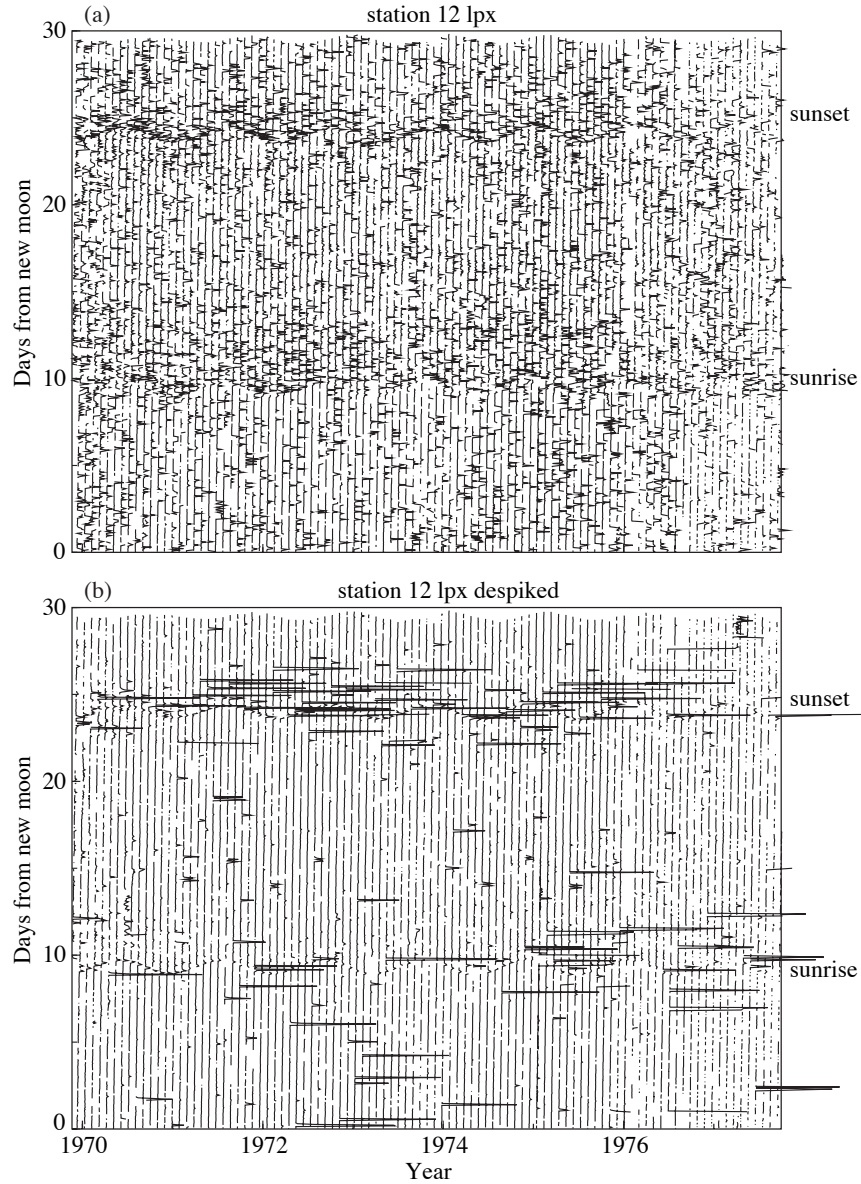


Figure 2.3 Noise spikes. (a) Continuous data synodic phase versus occurrence time for station 12. The maximum peak-to-peak amplitude in 1-hour time intervals determines the magnitude of the horizontal deviations from the slightly angled continuous lines defined by the synodic phase (days) versus the absolute time (years). Sunrise and sunset times are noted. The maximum amplitudes exhibit a sinusoidal behavior consistent with the varying length of the lunar synodic month. (b) the same plots after despiking the data. Note daytime noise has been greatly reduced. In this case, amplitudes are enlarged by a factor of 10 compared to (a).

2.4.1 Qualitative event characteristics: All events

We apply a manual “grading” technique in which all catalogued events (Nakamura et al., 2004) are inspected visually and assigned a grade of A, B, or C based on the quality of their traces. In the grading process we consider several factors, including signal-to-noise, initial impulse coherence, the shape of the envelope function, and the appearance of the event on one or more of the long-period channels. This grading allows for easy selection of subsets of high, medium, or low quality traces for later analyses (Figure 2.4).

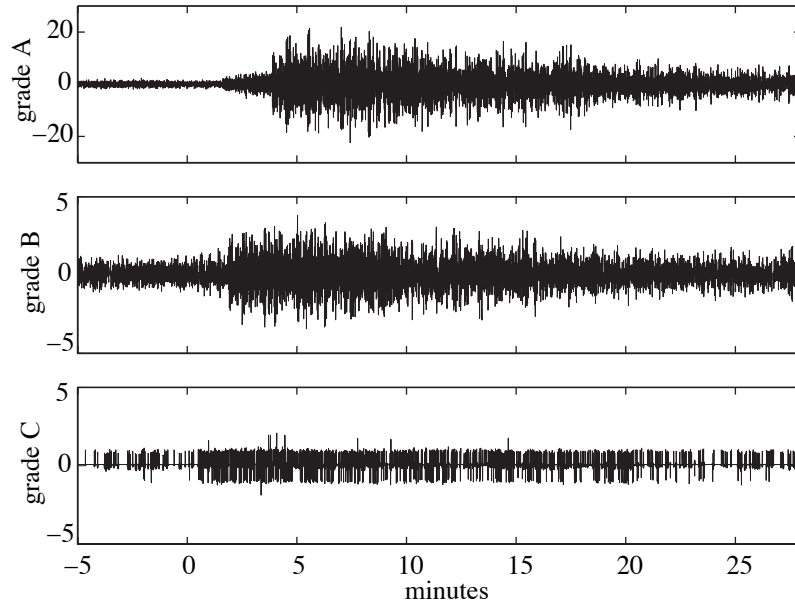


Figure 2.4 Grade examples. Examples of assigned grades for three events from the A1 cluster. Grade A shows event at station 16 lpy component occurring on 1975/304 at 0634 UT. Grade B shows event at station 16 lpy component on 1975/333 at 0815 UT. Grade C shows event at station 12 lpx component on 1970/189 at 1809 UT.

A trace receiving the grade “A” generally has high signal-to-noise and an impulsive onset, and seismic phases may be visible. A grade “B” trace has somewhat lower signal-to-noise and a more gradual emergence, but a distinct envelope is still evident. A grade “C” trace has inferior signal-to-noise and the entire event trace is often dominated by amplitudes of a single digital unit, with the event

seen as a region in the trace with a greater frequency of 1-bit fluctuations between high and low. While events may (optimistically) be detected from such traces, any estimation of event amplitude or timing is problematic. The percentages of events receiving grades A, B, and C are 2%, 8%, and 57% respectively, with 33% remaining ungraded (i.e. of poorer quality than grade ‘C’), representing 263, 1019, 7127, and 4149 of the 12,558 events in the Nakamura et al. (2004) catalog.

We consider a previously-catalogued event “visible” if it received a grade during this process. Events not receiving a grade were not readily distinguishable from background noise (and in fact were originally detected only after processing with an unconventional filter). Significant variability in the total number of “visible” events is seen among different stations and for a given station among the x, y, and z channels. Histograms of event visibility by station and channel are shown in Figure 2.5a for all events and Figure 2.5b for the deep event group A1 alone.

Similar patterns in the relative number of visible events are seen for all events and for the A1 group. However, the A1 cluster has higher relative visibility on station 12 compared to stations 14 and 16 (Figure 2.5b) than that of all events (Figure 2.5a). This is likely due to the proximity of the A1 source to station 12 (Figure 2.1). Two additional station characteristics are apparent in Figure 2.5. First note that the long-period z-component of station 14 was inoperative for most of the deployment and did not record many seismograms. Second, the A1 events (and deep moonquakes in general) tend not to appear in the short-period seismograms. (Note that there is no data for the station 12 short-period instrument, which failed shortly after deployment). Because of this, we restrict our analyses of deep events to the long-period data.

2.4.2 Quantitative event characteristics: Deep cluster A1

The deep event cluster A1 has the most catalogued events and is the focus of further quantitative studies, including amplitude estimation and waveform

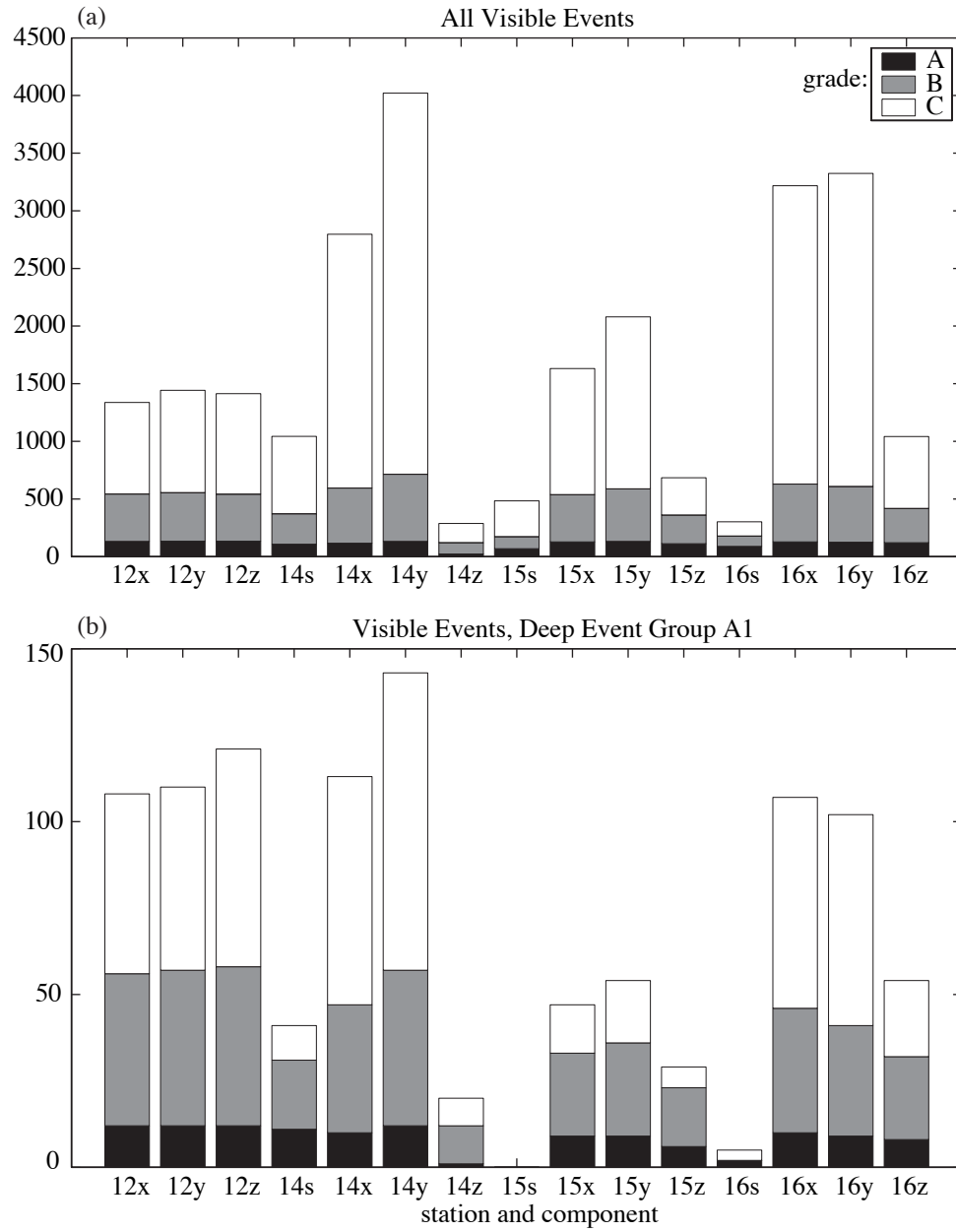


Figure 2.5 Histograms of event visibility. Histograms of visible events per station and component for (a) all events and (b) deep event group A1. The station 12 short-period component is not shown as that channel was inoperative for a majority of the experiment.

cross-correlation.

Event amplitude estimation

We investigated several methods for estimating event amplitudes in order to identify a consistent amplitude measure despite the poor signal-to-noise ratio exhibited by a majority of the traces. These included relative amplitudes calculated through cross-correlation and several different estimates of absolute amplitude.

Among these estimation methods, the most consistent amplitudes were obtained using the 75th percentile of the absolute deviation of the data from the median (Figure 2.6). We consider amplitudes consistent if they exhibit similar values on the horizontal channels, corresponding to a 1:1 relationship on x-component versus y-component amplitude plots. Amplitude consistency between the long-period horizontal channels is shown for deep event cluster A1 in Figure 2.7. We have found that amplitude characteristics vary depending on the mode in which the instruments were operated. As a result, the flat and peaked modes are shown separately for stations 12, 15, and 16 (station 14 was not operated in the flat mode). Events recorded during the flat mode exhibit a clear 1:1 relationship between x- and y- amplitudes. In contrast, x- and y- component amplitude estimates for events recorded during the peak mode are less consistent. This is probably due to the fact that flat mode events tend to have better signal-to-noise than peak mode events. This is manifest in our grade results, which show that 23% of graded flat mode events received an ‘A’ grade, while only 6% of peak mode event did so. Consequently, in further analyses we treat flat mode and peak mode recordings separately. Overall, stations 12 and 16 show the most consistent amplitudes on the horizontal channels.

Robust identification of A1 events

Due to variations in deep event classification methods and the low signal-to-noise ratio of many records, waveforms from one deep event source may be

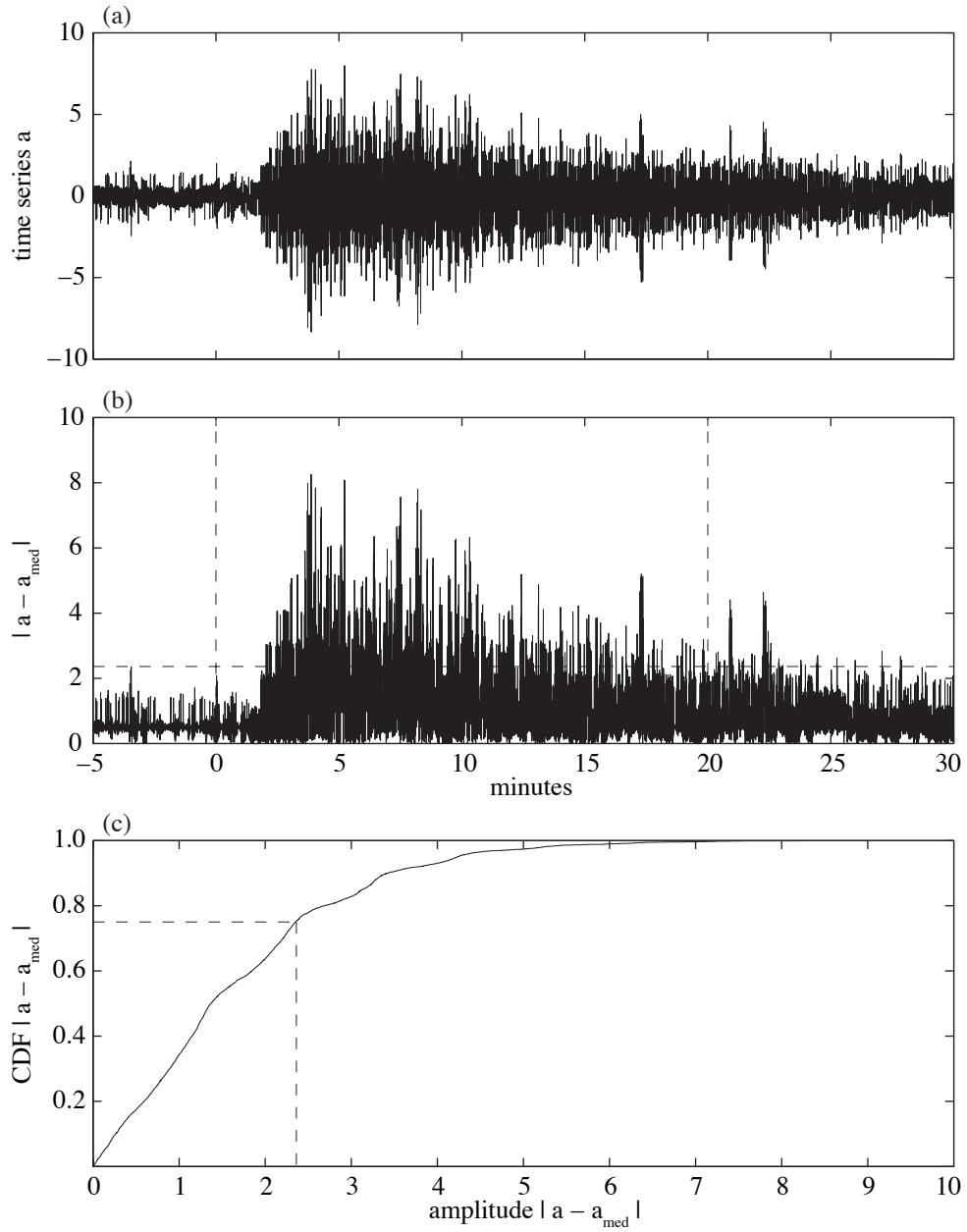


Figure 2.6 Amplitude estimation method. Example of our amplitude estimation method. (a) Time series a , an event occurring at station 14 lpx component on 1971/187, at 1652 UT. (b) Absolute deviation of time series about the median value (a_{med}). (c) Cumulative distribution function of $|a - a_{med}|$. Dashed line shows location of 75th percentile. In Figure 2.6b vertical dashed lines show time window used in Figure 2.6c, and horizontal dashed line shows amplitude as determined in Figure 2.6c.

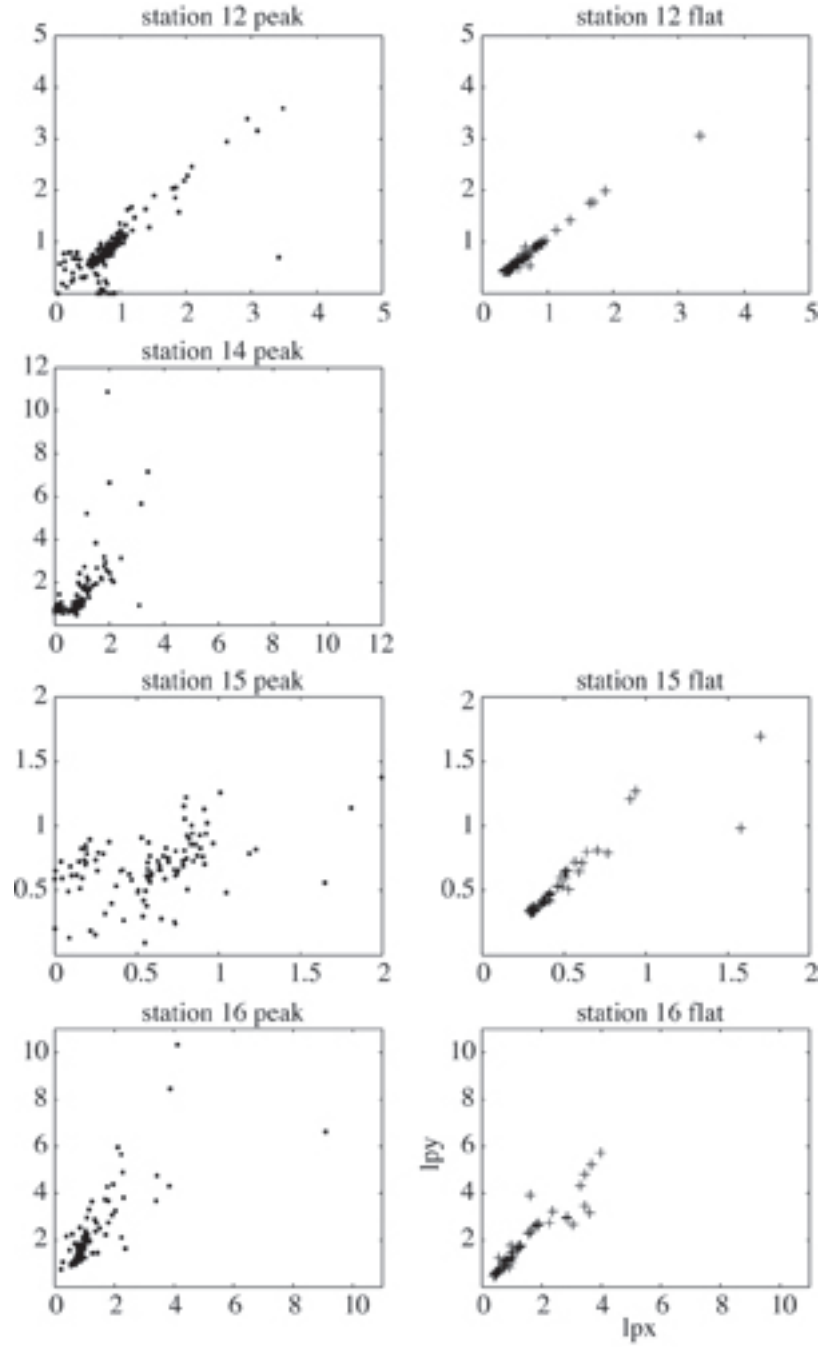


Figure 2.7 Amplitude comparison. Amplitudes of all A1 events per station, x-component versus y-component. Crosses (circles) indicate events during time when stations were operated in “flat” (“peak”) mode (note station 14 only operated in peak mode). Amplitudes generally agree with the expected 1:1 correlation on the horizontal channels. For the flat mode events the scatter is greatly reduced.

similar to those from other sources. To more accurately identify deep event group members, every event from a previously-classified group is cross-correlated with every other event in that group. This quantifies the level of association among members of a deep event group, identifying the best-matched events. Before cross-correlation, the data are filtered and despiked. A 20-minute window is used in each calculation; the beginning of the window is aligned with the catalog event start time. The time shifts and relative amplitudes of the traces are recorded for the peak positive and negative correlations of two given traces. The largest absolute value of the correlation coefficient determines the event polarity. For each event pair, correlations for the three long-period channels at each station are performed separately.

Histograms of correlation coefficient values for calculations performed among all A1 deep events are shown in Figure 2.8. Note the malfunction of the lpz component at station 14, reflected in the overall low correlation of its traces. The few high correlations (0.9 to 1.0) for 14 lpz are artifacts generated by correlations between two ‘flatline’ traces on that channel. Another station characteristic is the low number of events with absolute values of correlation coefficient higher than 0.2 on any of the channels on station 15. This could possibly be a result of the overall low amplitude of events recorded on that station (Figure 2.7). Whether this reflects instrument or site characteristics is unknown, although it has been suggested that station 15 is situated in such a manner that waveforms from the A1 source vary with tidally-induced changes in slip behavior (Y. Nakamura personal communication, 2005). The overall number of correlations decreases from station 12 to 16 since stations deployed earlier recorded more events. Application of the despiking algorithm to the data before performing the cross-correlations produces overall larger correlation coefficient values and improved estimates of differential times and amplitudes.

“Good” correlations are identified by examining the agreement in time shifts (the time offset required to align a pair of traces for maximum cross correla-

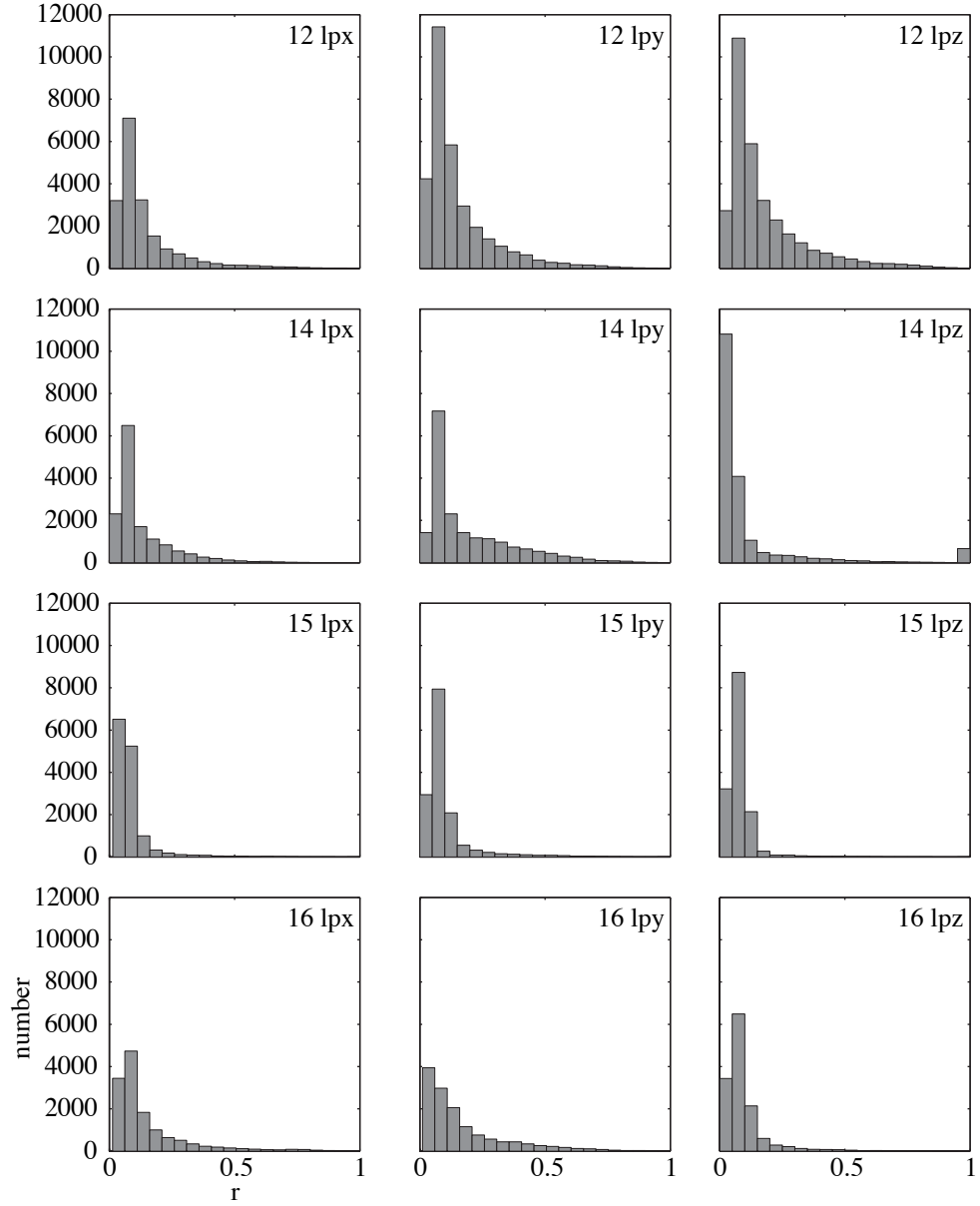


Figure 2.8 Correlation histograms. Histograms of correlation coefficient values for deep event group A1 (323 events). Correlations are performed station by station and component by component.

tion) for each event pair as a function of cross-correlation coefficient (Figure 2.9). Above an absolute correlation coefficient of ~ 0.2 , the median standard deviation in time shifts is less than 0.1 seconds, which is smaller than the data sampling interval and reflects accurate timing. Below this value, the variability in time shifts increases dramatically.

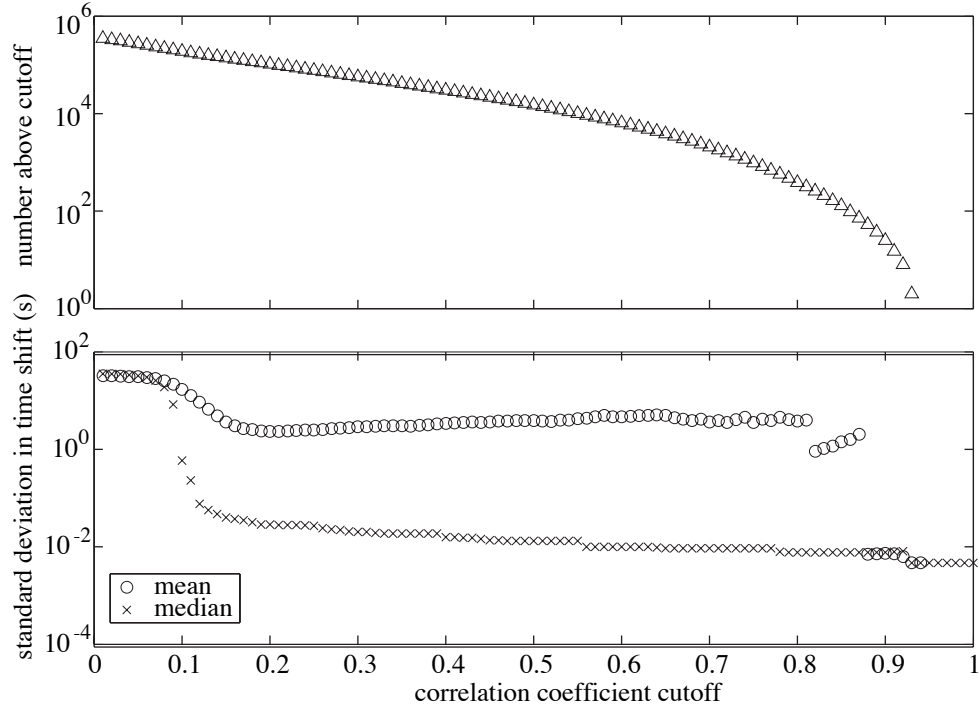


Figure 2.9 Variability in time shifts. The mean (o) and median (x) standard deviation in time shifts (seconds) versus correlation coefficient cutoff for correlations performed between members of the deep event group A1 (peak mode). Also shown is the total number of event pairs falling above the cutoff (triangles). The discontinuities in the mean value occur when anomalously high standard deviations are dropped as the cutoff is raised.

Stacking A1 events

We generate deep event group stacks from event pairs meeting an absolute correlation coefficient cutoff of 0.2 or higher. The traces were despiked and appropriately time-shifted, and negative polarity events were flipped before stacking. We make separate stacks for both the flat and peaked station modes, and normalize

Table 2.1 Number of catalogued A1 events stacked.

Station	Channel	Number of A1 in Target Stack		Available A1 Stacked	
		peak	flat	peak [†] (%)	flat [‡] (%)
12	lpx	139	51	61.8	60.7
	lpy	154	55	68.4	65.5
	lpz	63	59	28.0	70.2
14	lpx	144	-	61.3	-
	lpy	165	-	70.2	-
	lpz	19	-	8.1	-
15	lpx	26	13	17.0	17.8
	lpy	40	24	26.1	32.9
	lpz	9	15	5.9	20.6
16	lpx	75	48	63.0	57.1
	lpy	70	51	58.8	60.7
	lpz	46	26	38.7	31.0

[†] Out of 225, 235, 153, and 119 A1 events for stations 12, 14, 15, and 16 respectively.

[‡] Out of 84, 73, and 84 A1 events for stations 12, 15, and 16 respectively.

the stacks by the number of contributing traces. Our cross-correlation selection criterion results in the retention of between 17% and 71% of the catalogued A1 events for the horizontal channel stacks and up to 39% of the catalogued events for vertical channel stacks (Table 2.1). Despiking before stacking allows for greatly improved signal-to-noise, as shown in Figure 2.10. Stacks for deep event group A1 on all long-period components are shown in Figure 2.11 for the peak mode and Figure 2.12 for the flat mode. In general, cleaner stacks result for stations/channels with more events.

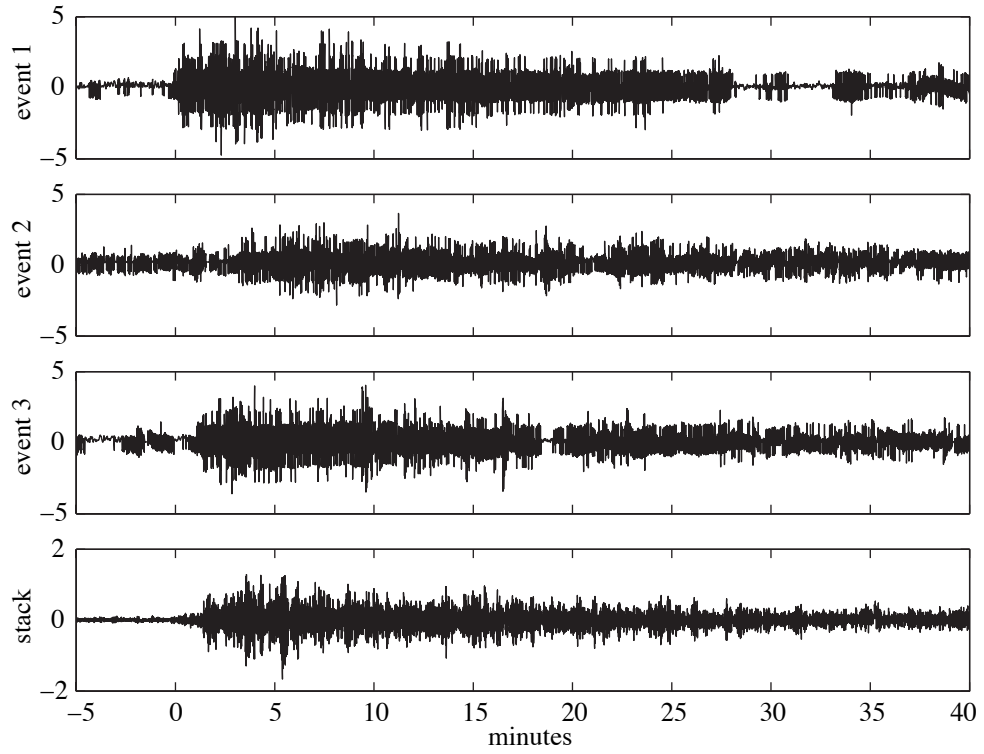


Figure 2.10 Example traces and stack. A1 stack and representative traces (all are station 12, lpx component). Event 1 occurred on 1970/009 at 0203 UT. Event 2 occurred on 1971/080 at 1628 UT. Event 3 occurred on 1973/201 at 1902 UT.

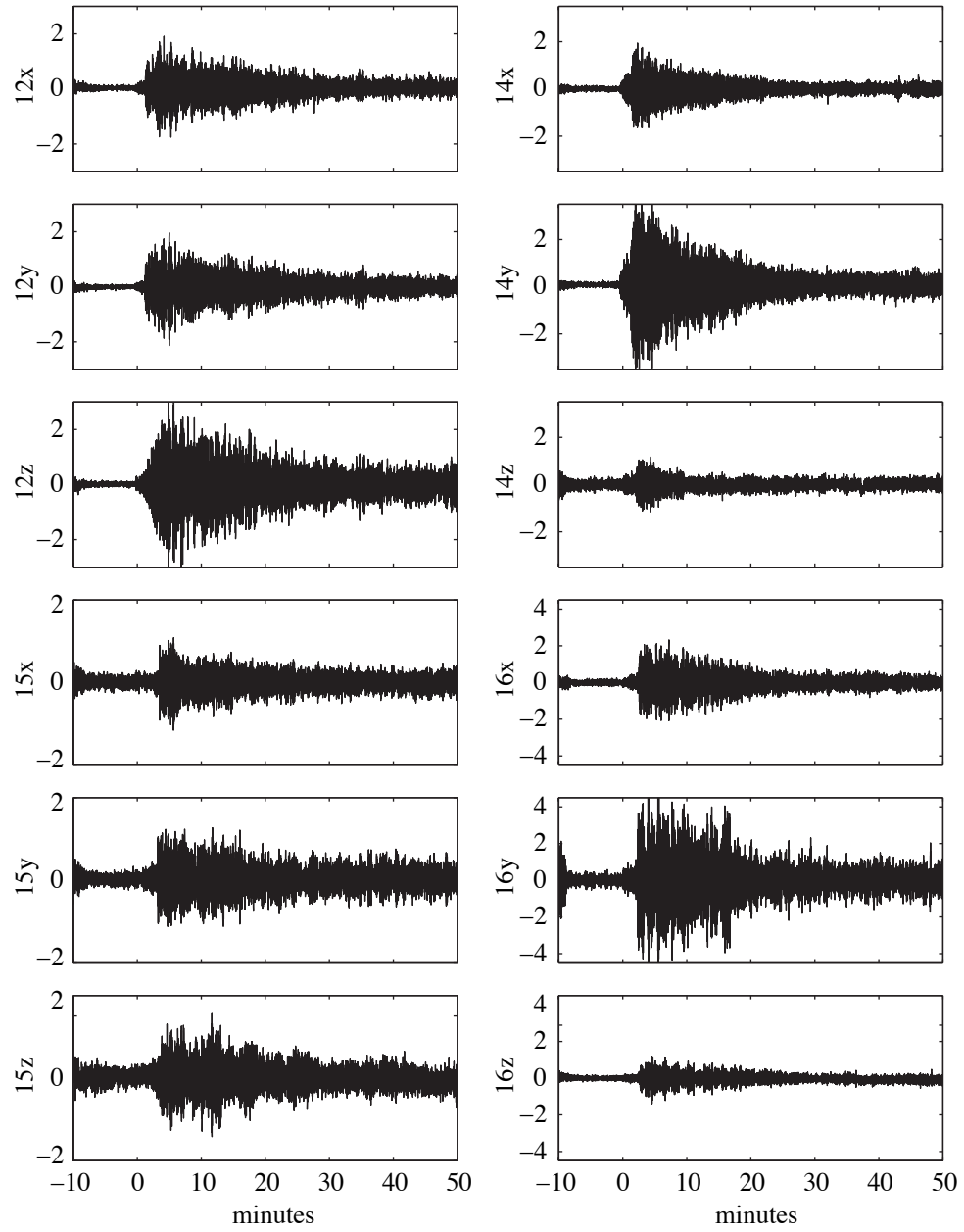


Figure 2.11 A1 peak mode stacks. For each station, all long-period components are plotted on the same scale to show amplitude variability. Note differences in scaling among stations.

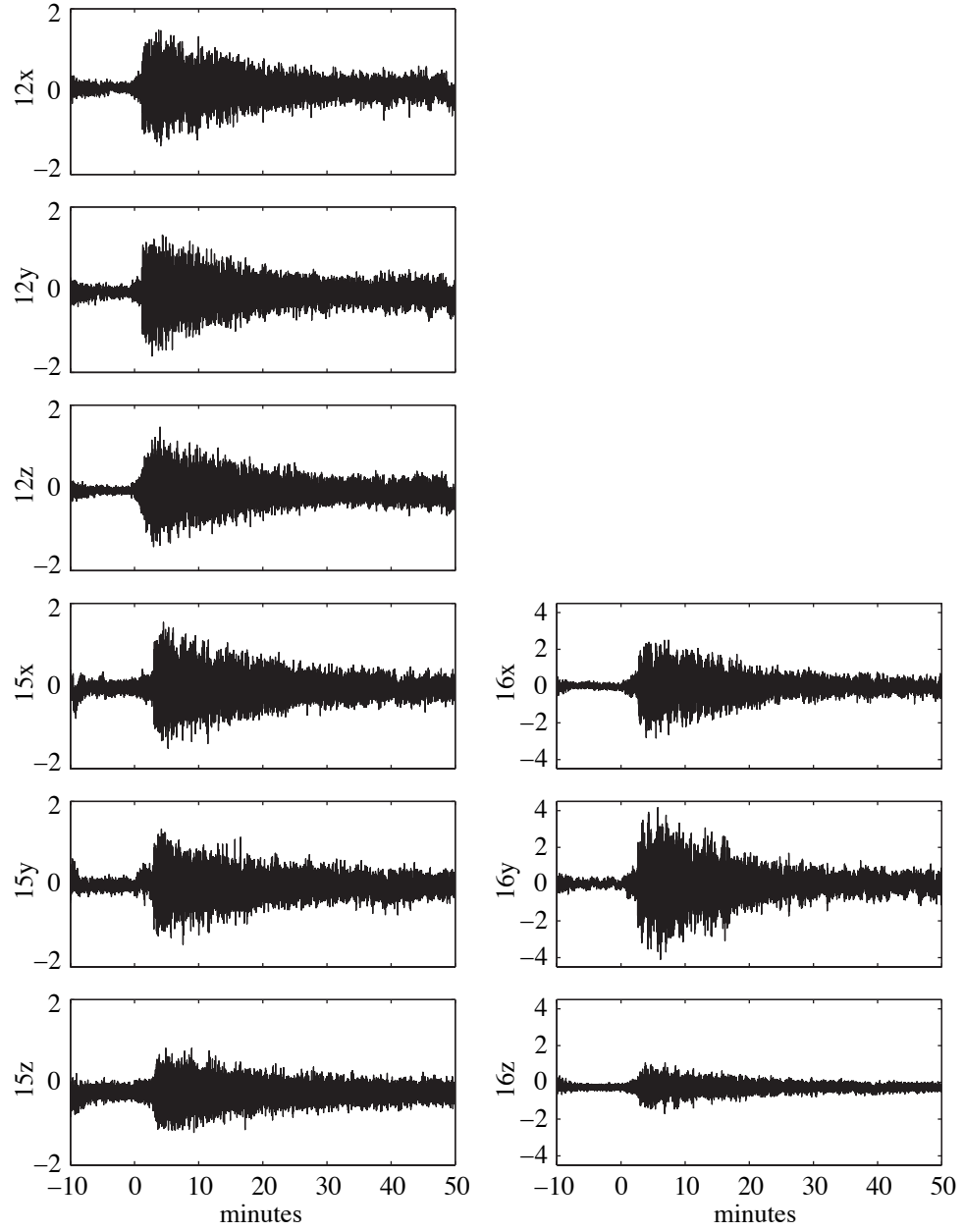


Figure 2.12 A1 flat mode stacks. (with the exception of station 14, which was not operated in flat mode).

2.5 Search for new A1 events in the continuous data

To begin the search for new events in the continuous data, a target trace must be selected for cross-correlation. We create and use the event data stacks described in the previous section for the deep event group A1 as identified by Nakamura et al. (2004). We focus on this group because it has the largest number of catalogued events (323) of all the identified source regions. The next largest group (A8) has 224 events. In addition to being numerous, A1 events are also generally well-characterized (perhaps because of the proximity of the A1 epicenter to the instruments), presenting a good starting point for the search for new events. However, our methods can be extended to other deep event groups: the main limitation is the computation time required for the continuous cross-correlations.

We compute cross-correlations of the A1 stacks with the continuous data on a station by station, component by component basis using a 30-minute window of the target stack. (Peak and flat mode times are treated separately.) While the relatively long window length creates an overall reduction in correlation coefficient values, it also reduces the number of false returns. Results for the long-period components of station 12 are shown in Figures 2.13a-2.13c. The left column shows the time of occurrence of each peak in the cross-correlation function. For clarity, points representing previously catalogued events are not shown; the remaining points represent possible new events.

Because the signal-to-noise ratio for events is often close to unity, absolute values of the cross-correlation coefficient (r) are typically low (see Figure 2.13), and it is important to establish criteria for distinguishing a potential new event from noise. We minimize incorrect detection of events in two ways. First, we observed that true cross-correlation peaks between the target trace and the continuous data often are accompanied by adjacent peaks with absolute values almost as high as that of the true peak, but located at time shifts approximated by the dominant

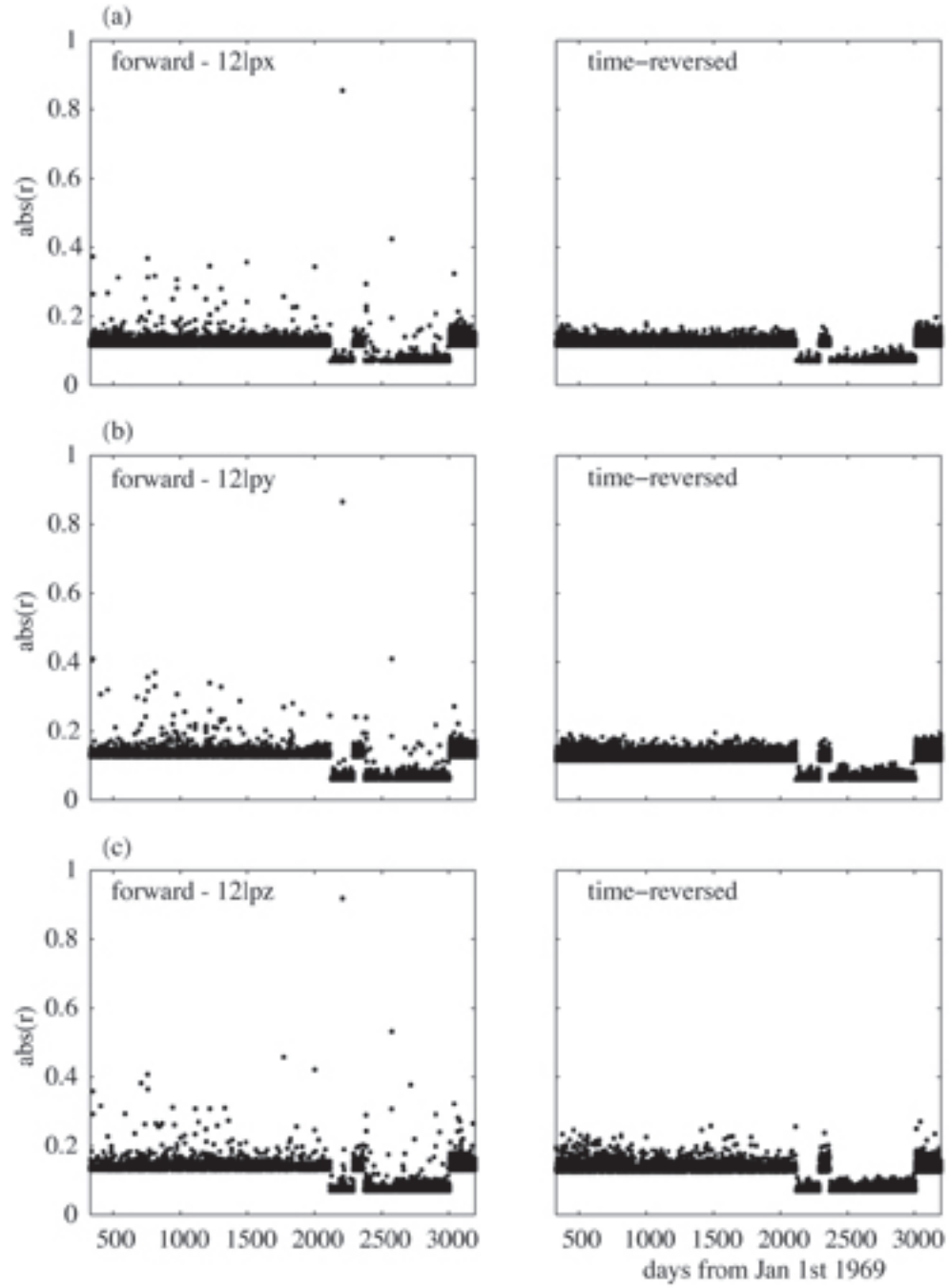


Figure 2.13 Correlation coefficient versus time. (a) Absolute correlation coefficient versus time for A1 lpx continuous cross-correlations on station 12. The discontinuities represent times when the station was operated in the flat mode. For both the peak and flat modes, the lower coefficient limit (y-axis) is set depending on the overall number of correlations returned, and may differ among stations or components. (b) Results for lpy. (c) Results for lpz.

period of the seismogram. We suppress these by not accepting peaks within ~ 1.2 minutes of a peak with a higher absolute value in r (to account for polarity flips). Second, we estimate the maximum cross-correlation coefficients characteristic of noise in the data by performing cross-correlations in which we time-reverse the target trace. This gives a target trace with the same amplitude and frequency content as the real trace but with physically meaningless phase behavior. Cross-correlation peaks resulting from time-reversed targets provide a measure of correlated noise in the data set. Results from the time-reversed correlations performed on the long-period channels of station 12 are shown in Figures 2.13a-2.13c (right column).

To ensure that our correlation method is successfully detecting new A1 events, we first check that a significant percentage of known A1 events (the points removed from the left-column plots of Figures 2.13a-2.13c) are identified. Because a subset of these events comprise the target stack, they tend to correlate highly. For the lpx, lpy, and lpz components on station 12, we successfully identify 80%, 90%, and 77% of catalogued A1 events during the continuous cross-correlations, in good agreement with the percentage of events used in generating the target stacks for these channels (Table 1).

To calculate the number of remaining points representing new events, we select a cross-correlation cutoff that discriminates between noise and events. In Figures 2.13a-2.13c (left), points falling above this cutoff represent new events and points falling below represent noise. This cutoff is set using a multiple of the absolute maximum correlation coefficient returned by the time-reversed correlations. We also can choose whether we require a new “event” to appear on more than one channel or station. Figure 2.14 shows the number of new events returned as a function of the cutoff multiplier for four different channel/station constraints.

Using a cutoff multiplier of one (i.e. a threshold cross-correlation coefficient equal to the maximum value returned by the time-reversed correlations) and a channel/station constraint of two, we identify 123 new A1 events (Table 2.2). This is a conservative estimate; by relaxing the cutoffs we could obtain additional

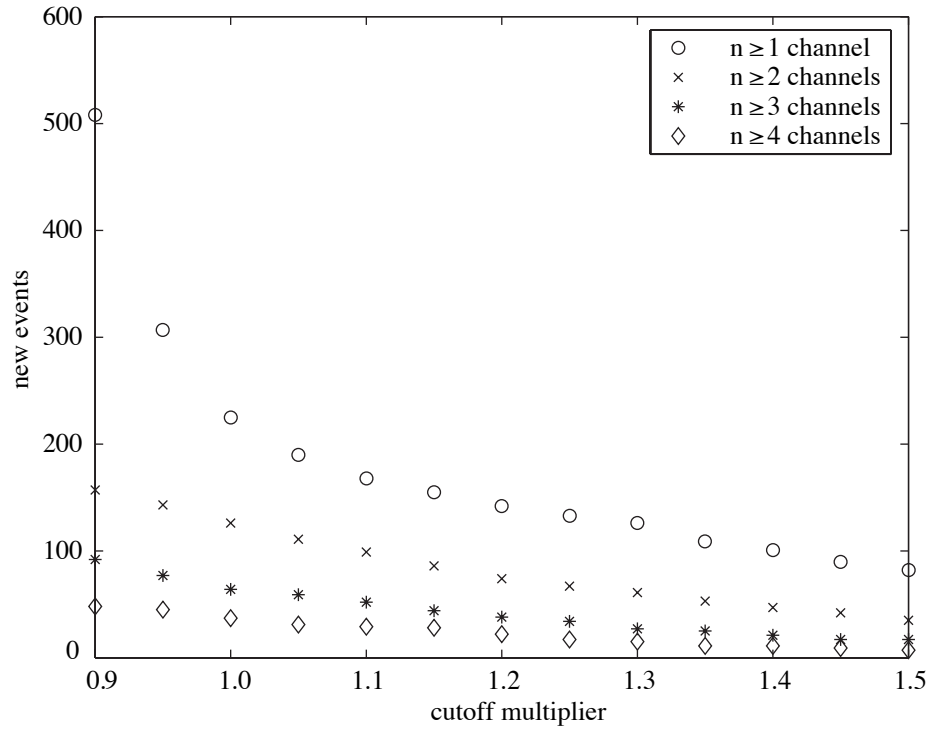


Figure 2.14 Number of events versus cutoff. Number of new events versus cutoff multiplier for varying numbers of channels.

events at the cost of likely including some false correlations. We note that our requirements are more stringent than those originally employed in the identification of lunar events: events listed in the existing lunar catalog need only appear on a single channel on a single station. The numbers of new events observed on each station and channel are specified in Table 2.3. In the continuous data, most of the individual new event waveforms cannot be visually distinguished from background noise. However stacking improves the signal-to-noise ratio and the new events are visible. In Figure 2.15 we stack each component separately using the events listed in Table 2.3. Channels where the number of events was too small to produce a visible signal are not shown.

Table 2.2 Newly identified A1 events.

Year	Day [†]	Hour:Min.	Year	Day	Hour:Min.	Year	Day	Hour:Min.
1969	346	08:20	1972	234	16:56	1975	30	23:08
1969	348	02:30	1972	235	17:47	1975	32	11:04
1970	40	08:21	1972	264	08:03	1975	116	08:15
1970	95	23:47	1972	264	22:40	1975	194	07:07
1970	324	15:48	1973	10	00:22	1975	196	00:17
1970	342	00:48	1973	34	13:10	1975	197	01:11
1971	4	16:51	1973	36	16:12	1975	198	02:03
1971	10	08:39	1973	50	13:09	1975	198	15:17
1971	24	22:07	1973	155	06:48	1975	222	14:43
1971	25	22:48	1973	172	10:46	1975	225	21:22
1971	81	17:33	1973	175	01:43	1975	246	10:47
1971	90	08:28	1973	183	08:38	1975	252	09:35
1971	108	07:09	1973	187	12:42	1975	281	04:21
1971	134	20:56	1973	202	18:34	1975	360	00:32
1971	135	08:18	1973	309	05:03	1976	22	01:04
1971	214	12:44	1973	336	22:36	1976	23	11:14
1971	219	14:49	1973	337	10:59	1976	103	13:49
1971	220	10:40	1973	338	01:32	1976	119	12:44
1971	227	05:11	1973	338	10:52	1976	160	19:18
1971	244	06:15	1973	339	11:44	1976	190	07:08
1971	245	11:11	1973	350	06:02	1976	217	17:28
1971	246	22:57	1973	351	08:51	1976	240	15:34
1971	301	03:23	1974	10	16:13	1976	300	19:36
1971	308	18:15	1974	12	06:29	1976	347	20:07
1971	337	15:56	1974	41	02:18	1976	349	02:27
1972	13	21:37	1974	41	17:09	1977	13	02:12
1972	15	04:30	1974	42	05:40	1977	38	18:26
1972	41	00:10	1974	42	16:35	1977	77	07:01
1972	70	14:18	1974	70	17:25	1977	89	02:47
1972	80	09:24	1974	83	03:32	1977	91	22:48
1972	97	11:43	1974	97	21:18	1977	103	19:41
1972	99	03:29	1974	98	14:31	1977	119	16:01
1972	124	22:21	1974	110	00:32	1977	131	13:23
1972	126	21:36	1974	110	21:28	1977	146	03:45
1972	156	00:45	1974	128	19:58	1977	146	23:27
1972	181	13:34	1974	176	15:07	1977	148	12:23
1972	205	17:14	1974	205	10:16	1977	161	17:01
1972	209	00:13	1974	206	07:56	1977	173	07:38
1972	209	01:08	1974	346	02:06	1977	183	21:07
1972	233	08:29	1975	6	13:41	1977	258	17:10
1972	234	07:00	1975	22	02:06	1977	258	19:13

[†] All days are listed as Julian days.

2.6 Discussion: Analyses of complete A1 cluster

Our discovery of 123 new A1 events (a 38% increase) enables several avenues of further investigation. Here we report initial analyses that revise and extend previous work. Combined with the previously catalogued A1 events, we have formed a complete list of all A1 events available in the Apollo lunar seismic

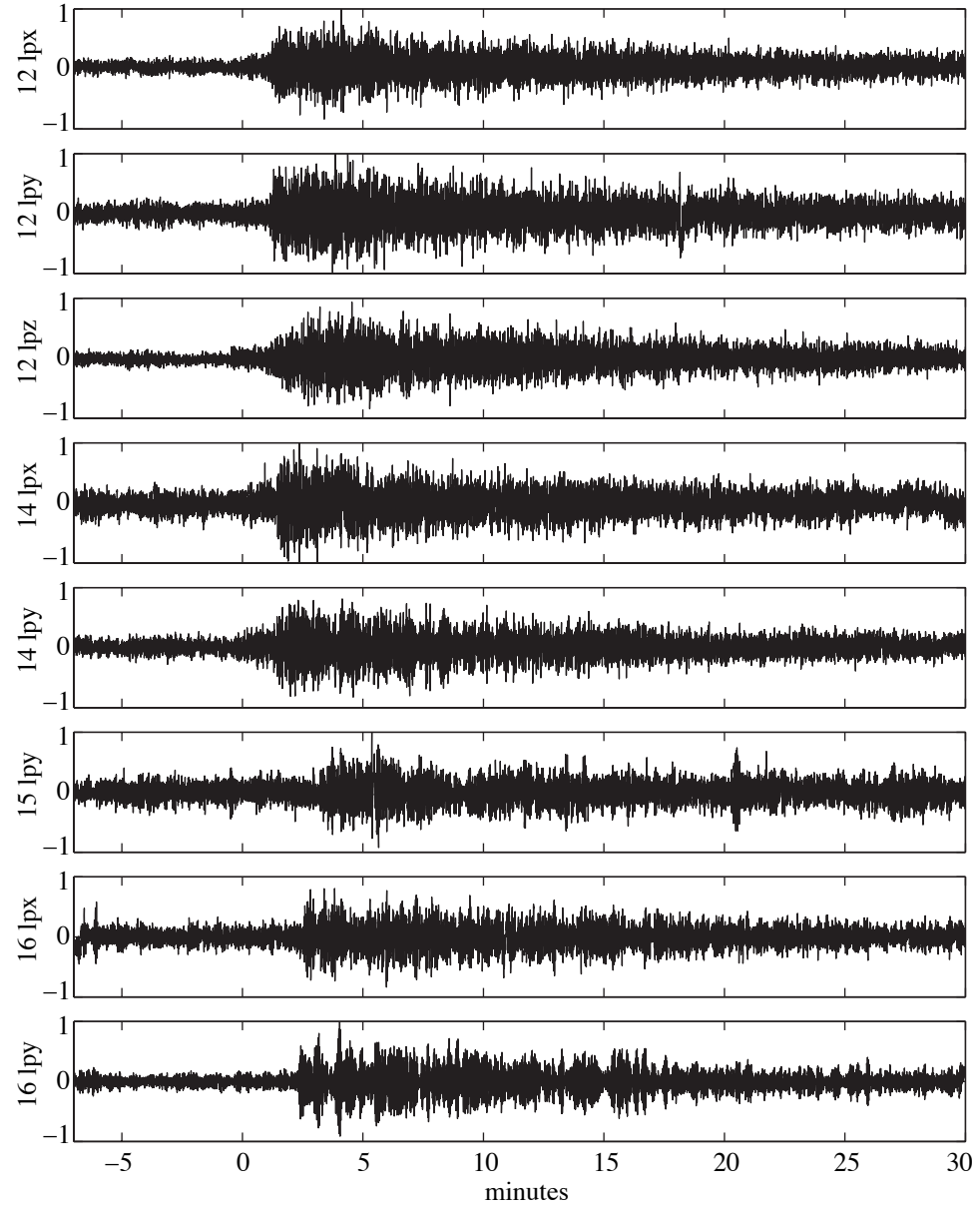


Figure 2.15 New event stacks for deep event group A1. Shown are stacks for station 12 lpx, lpy, and lpz; station 14 lpx and lpy; station 15 lpy; and station 16 lpx and lpy. Not shown are the channels where the number of events was too small to produce a visible signal.

Table 2.3 New A1 events detected per channel.

Station	lpx	lpy	lpz
12	82	82	67
14	60	82	4
15	12	23	6
16	61	65	28

data. This allows us to produce improved waveform stacks for the A1 cluster using a weighted iterative stacking method. From these optimized stacks, we make seismic phase picks for comparison with picks from previous studies, and generate revised location estimates using specific velocity models. With the new catalog, we will also be better able to investigate the temporal distribution of A1 events and its implications for tidal periodicities present in A1 occurrence times.

2.6.1 Generation of optimized stacks

Because A1 events in the original catalog are of variable quality, stacking these events using a simple arithmetic average of traces may not produce as clean a stack as a method that gives more weight to highly-correlating traces or those having a better signal-to-noise ratio. We employ a weighted iterative stacking method to ensure events are selected and stacked to create a representative trace with high signal-to-noise and the clearest seismic phase arrivals. Using a single high-quality A1 event as the target trace, we perform cross-correlations with all events in the new, complete catalog. This allows us to identify not only known A1 events, but also A1 events that were either listed in the catalog as ‘unclassified’ or incorrectly classified as members of other deep clusters.

Events correlating with the target at $r \geq 0.2$ are considered for stacking. Before the stack is formed, each individual trace is weighted by the squared correlation coefficient, r^2 . We also attempted weighting by r , higher powers of r , and the signal-to-noise ratio, but weighting with r^2 produced a stack with the most

Table 2.4 Number of A1 events in optimized stacks.

Station	channel	#A1 events
12	lpx	154
	lpy	166
	lpz	138
14	lpx	130
	lpy	191
	lpz	-
15	lpx	48
	lpy	76
	lpz	65
16	lpx	131
	lpy	46
	lpz	94

easily discernable seismic phase arrivals. The cross-correlation procedure is then repeated, this time using the weighted stack as the target. To optimize the stack, the process is repeated until the number of events added to the stack stabilizes. We find good convergence after four iterations. Optimized peak mode stacks for the lpx component on all stations are shown in Figure 2.16 and the number of events in each stack is summarized in Table 2.4.

2.6.2 Travel time picks

P- and S-wave arrival picks made from our optimized A1 stacks are shown in Figure 2.17. Our S-P differential times show good agreement with comparison times from Nakamura (1983) and Lognonné et al. (2003) as summarized in Table 2.5. This is to be expected, as A1 is the largest and most-studied deep cluster. Future application of our method to less well-characterized clusters will be of particular interest, especially to those groups whose location has not previously been well-constrained.

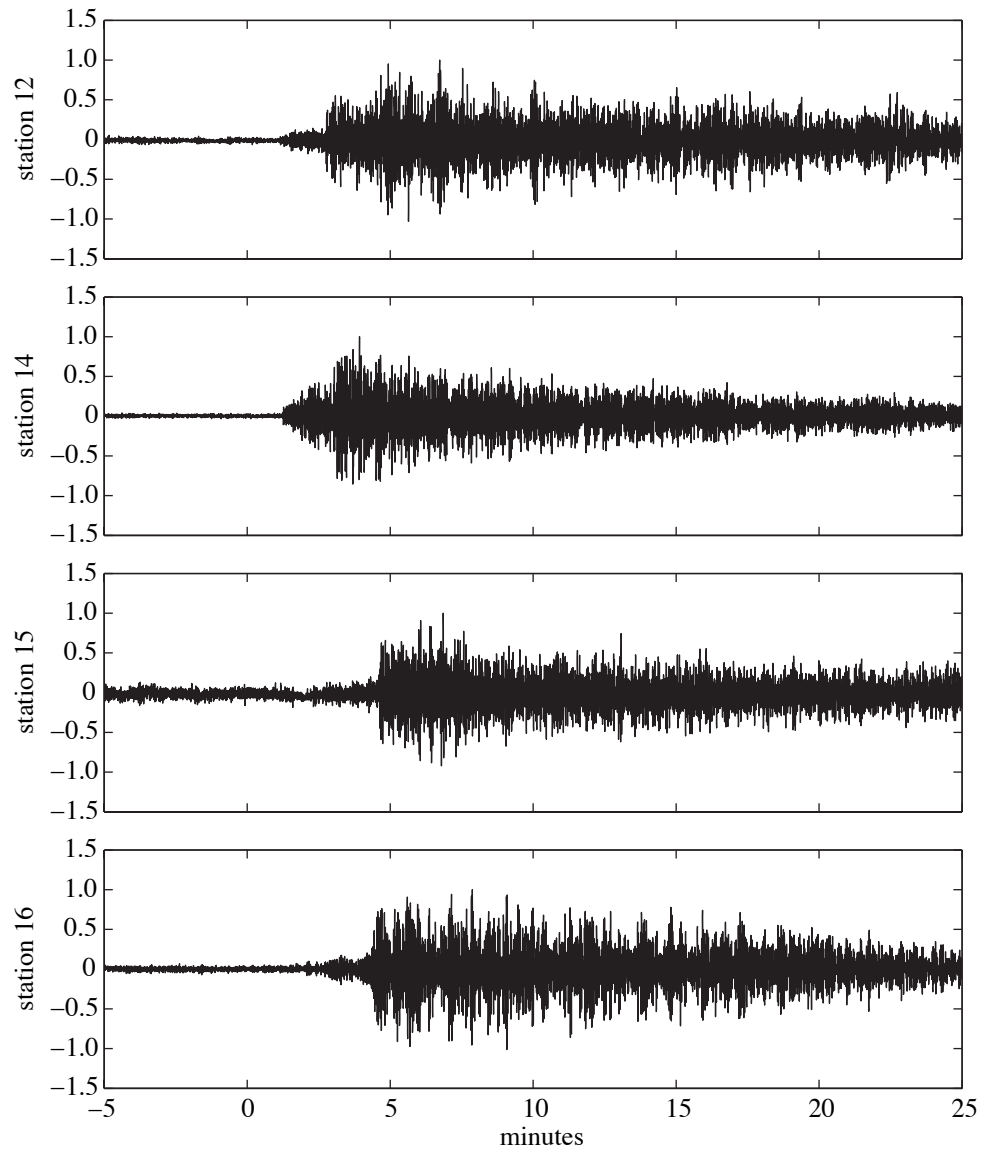


Figure 2.16 A1 optimized stacks. Optimized peak mode stacks for the lpx component on all stations.

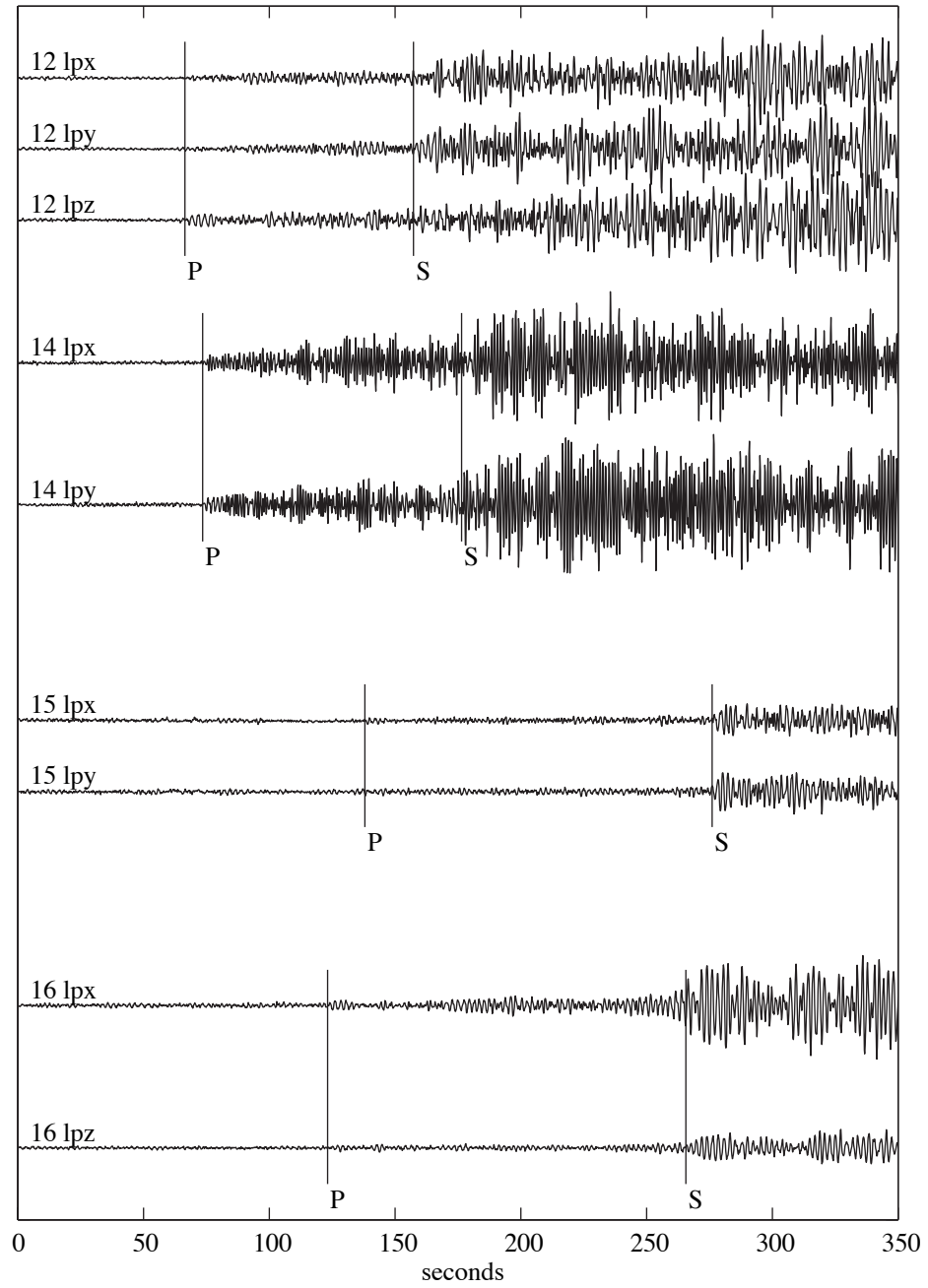


Figure 2.17 A1 arrival time picks. P- and S-wave arrival time picks plotted on A1 long-period event stacks for all available channels on all stations.

Table 2.5 Travel-time picks for cluster A1. A1 picks and S-P differential times: a comparison.[†]

Station	P	σ_p	S	σ_s	S-P this study	Nakamura, 1983	Lognonné et al., 2003
12	66.4	2	157.3	10	90.9	99.7	98.1
14	73.5	3	176.5	11	103.0	103.2	105.8
15	138.0	4	276.1	9	138.1	148.1	145.8
16	123.1	4	265.7	10	142.6	137.9	138.1

[†] All picks in seconds from reference time 1973/273 04:12; σ_p and σ_s represent uncertainty in P and S picks (seconds)

2.6.3 Location estimates

We use the travel time picks reported in Table 2.5 along with two representative seismic velocity models (Nakamura, 1983; Lognonné et al., 2003), to re-estimate the A1 cluster location. Clearly cluster location trades off with velocity structure and a more complete study would include joint forward modeling of a set of cluster locations and deep lunar velocity structure. Using an initial guess for the hypocenter location, we ray trace through a specified velocity model using a grid search algorithm to find the best-fit cluster location in a least squares (L2-norm) or robust (L1-norm) sense.

The L1 (L2) best fit latitude, longitude, and depth for the Nakamura (1983) and the Lognonné et al. (2003) velocity models are given in Table 2.6, along with a recent A1 location estimate by Nakamura (2005), and the estimate given in Lognonné et al. (2003). Generally good agreement among location estimates is seen, as would be expected for the relatively well-characterized A1 cluster. Differences in locations reflect a combination of (1) uncertainties in travel time estimates, (2) trade-offs with velocity structure, and (3) possible spatial extent of the cluster. The largest discrepancy between our preliminary location estimates and those previously published is in the cluster depth; however, our A1 depths reported here are consistent with the recent estimate of 867 ± 29 km of Nakamura (2005).

Table 2.6 A1 location estimates.

Velocity model	norm	lat.	lon.	depth (km)
Lognonné et al. (2003)	L1	-11.9	-38.1	843
Lognonné et al. (2003)	L2	-13.3	-38.4	863
Nakamura (1983)	L1	-13.2	-40.8	846
Nakamura (1983)	L2	-14.3	-40.2	838
Nakamura (2005) estimate		-15.7	-36.6	867
Lognonné et al. (2003) estimate		-17.40	-38.40	917

2.6.4 Temporal Distribution

A complete record of moonquake occurrence times is crucial to studying tidal triggering of moonquakes. Correlations between moonquake occurrence times and lunar tidal cycles have been noted in previous studies (Lammlein et al., 1974; Lammlein, 1977; Toksöz et al., 1977). Using previously catalogued and our new A1 events, we tested the dependence of moonquake occurrence times on tidal variations by calculating the anomalistic phase of each event. The anomalistic month represents the time it takes the Moon to travel from one perigee to the next (~ 27.55 days). The anomalistic phase of our complete set of A1 moonquakes relative to a reference date is shown in Figure 2.18. The periodicity of A1 moonquakes is apparent, with events occurring near perigee in 1970 and gradually shifting to before perigee in 1974. New events show phase behavior consistent with previously identified A1 moonquakes, as expected. This plot also illustrates how our event search fills in the temporal distribution of events.

As noted by Lammlein (1977), A1 moonquakes are controlled not only by the anomalistic phase (most closely linked with tides), but also by the orientation of the moon’s orbit with respect to the ecliptic, which is described by the nodical month (27.21 days). These two periods determine the location and orientation of the moon relative to Earth, and their sum yields a period with a “beating” that causes a phase shift every 6 years. On the anomalistic phase versus time plot in Figure 2.18, the shift in 1974 is due to this 6-year variation, with occurrence times

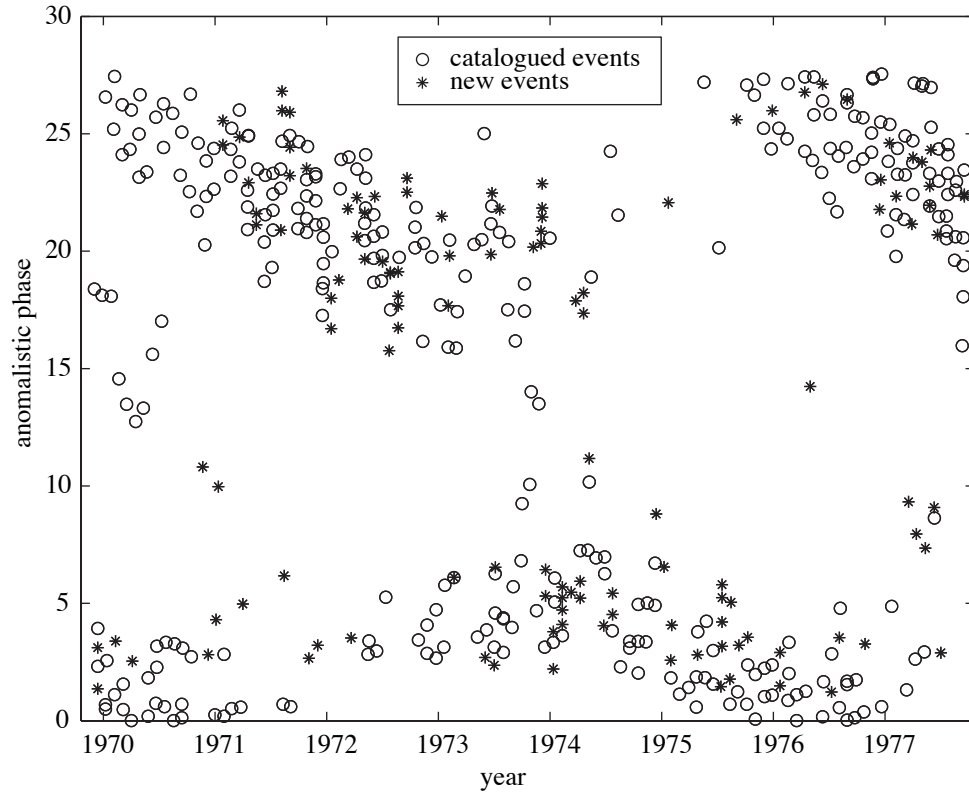


Figure 2.18 A1 anomalistic phase. Anomalistic phase of new and catalogued A1 moonquake occurrences versus time. New events show phase behavior consistent with previously identified A1 moonquakes.

gradually switching from before perigee passage to after.

Robust analyses of A1 moonquake occurrence times are possible using our revised catalog. In addition, the extension of our new event search and stack optimization to all deep event clusters will create a more complete picture of the temporal and spatial distribution of lunar seismicity. Such a data set would form the basis for examining the driving mechanism of deep moonquakes.

2.7 Conclusions

Analysis of the continuous event data has proven to be fruitful. Although previous studies did a remarkable job of identifying events by visual rather than

automatic means, our comprehensive event search has shown the analysis of the continuous Apollo lunar seismic data to be worthwhile, as additional events are readily detectable using cross-correlation methods. Furthermore, modern computing capabilities have proven essential for obtaining reliable results, as lunar seismograms are of limited quality compared to terrestrial seismograms. The extensive data processing described in Section 2 is essential to our results.

Focusing on the A1 deep cluster has allowed us to conduct our initial investigations on a group of events with previously documented characteristics (Lammlein, 1977; Lammlein et al., 1974; Nakamura, 1978; Toksöz et al., 1977). Our discovery of 123 new A1 events prompted our development of stack optimization methods, as stacking waveforms from a given deep event group provides the means for identifying seismic phases that may be difficult to discern on individual seismograms. These improved stacks have led to travel-time picks and source location estimates for A1 similar to those of previous studies. For other deep event groups, which may not be as thoroughly well-characterized, our approach may prove instrumental in improving our understanding of the spatial and temporal qualities of moonquake source regions.

The new A1 events show occurrence patterns consistent with previously-catalogued A1 events. The extension of our search to all deep event groups will provide a more complete catalog needed for further analyses of tidal variations in the deep moonquake occurrence times.

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3

Temporal and spatial properties of some deep moonquake clusters

3.1 Abstract

Using the event search method of Bulow et al. (2005), we have found 503 new deep moonquakes among the eight largest (in terms of total number) near-side source regions, increasing the number of identified events for each cluster an average of 36% over the existing catalog. These new events provide an improved deep event catalog, with which we explore some temporal and spatial aspects of deep moonquakes. First, we examine the spectra of moonquake occurrence times at each deep source region, and observe known tidal periodicities, notably those at ~ 27 days and 206 days. Application of spectral methods for the analyses of point processes (discrete events) allows us to resolve closely-spaced tidal periods not previously seen in moonquake data. Second, we pick seismic phase arrival times from optimized stacks of events from each source region. We use these picks, along with published velocity models, to relocate the nine source regions. Source regions A1 and A18 are the best located, with 95% confidence bounds of less than $\pm 5^\circ$ in latitude and longitude, and consistent with estimates from different

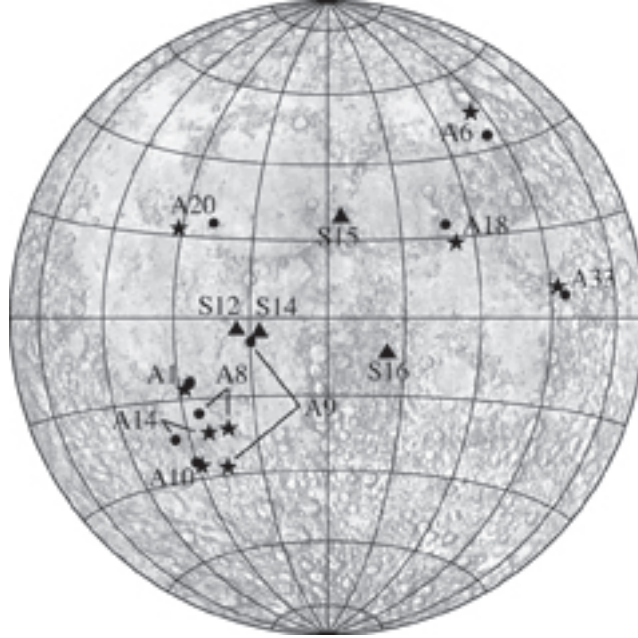


Figure 3.1 Cluster location map. Shaded relief map of the near side of the Moon (USGS, 2002) showing locations of seismic stations numbered according to the Apollo mission on which they were deployed (triangles). The nine deep moonquake source regions relevant to this paper are also shown with locations from Nakamura (2005) (circles) and Lognonné et al. (2003) (stars); their depths range from 853 to 995 km. Note in Lognonné et al. (2003) the A10 cluster is listed as A24; these clusters have been determined to be the same (Nakamura (2003) p. 202). Also note that the A33 source is located on the far side (longitude 115.8° E). Grid interval is 20° and centered on 0° longitude.

studies. The locations of source regions A8 and A9 are poorly constrained, with uncertainties in latitude of up to $\pm 28^\circ$ resulting from the absence of clear phase arrivals at station 15. Large trade-offs exist between relocation estimates and choice of velocity model, and the lack of reliable seismic phase arrivals severely affects location error.

3.2 Introduction

During the Apollo missions, a small network of seismometers was deployed on the near-side surface of the Moon as part of the Apollo Lunar Surface Experiment Package (Figure 3.1). From 1969 through 1977, these instruments

continuously telemetered digitized seismic data to Earth, where they were stored on magnetic tape. Computers of that era were not capable of handling large quantities of data, so early lunar seismology studies were limited to analyses of only a relatively small number of seismograms, or to derived products such as the arrival-time data set of Nakamura (1983). Thanks to modern computing power, this once-formidable data set is now easily stored and manipulated, and several recent studies have examined the original event waveforms (Khan et al., 2000; Lognonné et al., 2003; Nakamura, 2003, 2005).

Many types of seismic events were detected by the Apollo network, including meteoroid impacts, booster rocket and lunar module surface impacts, and both shallow and deep moonquakes. The original catalog (Nakamura et al., 1981) lists over 12,000 events. This paper focuses on the behavior of deep moonquakes, most of which occur between 800 and 1100 km depth (Lognonné et al., 2003; Nakamura, 2005), and originate at discrete source regions (often referred to as clusters) within the Moon.

In Bulow et al. (2005), we presented an automated method to search through the continuous lunar seismic data for deep moonquakes that were undetected by earlier studies. The entire continuous data set had previously been explored visually, see e.g. Nakamura et al. (1980). Application of the automated method to A1, the largest moonquake cluster (in terms of number of events), allowed us to successfully recover 123 new moonquakes. In Section 2 of this paper we present results from the extension of that method to seven additional near-side deep event source regions (A6, A8, A9, A10, A14, A18, A20), and one far-side source (A33). The new and old events provide a complete catalog of all resolvable deep moonquakes from the eight largest near-side source regions (no new events were detected for the far-side region, A33).

We use both the new and old events to assess some spatial and temporal properties of deep moonquakes. First, we address the tidal signatures present in the times of deep moonquakes. We examine periodicities in moonquake occurrences,

both in our complete data set and at individual source regions. Second, we compare several location estimates for deep moonquake source regions. We relocate our 9 source regions using two lunar velocity models and two choices of misfit criteria. Because the eight near-side clusters analyzed in this paper comprise approximately 50% of the deep moonquakes for which arrival-time data was used in deriving velocity models (Nakamura, 1983; Lognonné et al., 2003), their locations exert a large influence on the inferred velocity structure of the lunar mantle.

3.2.1 Tidal periodicities present in deep moonquake occurrence times

Among the first observations of the lunar seismic data was the realization that some moonquakes tend to occur with tidal periodicity, presumably reflecting the dynamics of the Earth-Moon-Sun system (Ewing et al., 1971). Later studies observed monthly and fortnightly signals in the occurrence times of what were determined to be deep moonquakes by examining histograms of the number of deep events per day as a function of time during a portion of the experiment at each of the four stations (Lammlein et al., 1974; Lammlein, 1977). Peaks in the corresponding spectra were clearly seen (e.g., Figure 2 of Lammlein (1977)). A large spectral peak was observed near 27 days, which is close to the periods of the anomalistic and nodical months (see next paragraph). Longer-period variations in the occurrence times and amplitudes of deep moonquakes were also suggested by these studies; in particular a 206-day modulation due to the Sun’s perturbations on the lunar orbit, and a 6-year modulation caused by the relative precession of perigee and the ascending node of the Moon’s orbit.

The monthly periods are important because they exert the greatest influence over the tides raised on the Moon by the Earth. The monthly buildup and release of tidal stress and strain within the Moon has been suggested as a possible trigger of deep moonquake activity (Ewing et al., 1971; Lammlein, 1977; Cheng

and Toksöz, 1978; Minshull and Goult, 1988). The anomalistic month (27.554550 days) is the average time between perigee passages. Perigee is the point of closest approach to Earth in the Moon’s elliptical orbit, where the Earth’s gravitational influence on the Moon is strongest. The nodical month (27.212221 days) is the average time between ascending or descending nodal passages; nodes are the intersections of the lunar orbit with the ecliptic. Motion of the sub-Earth point north and south of the lunar equator occurs mainly at the nodical period, whereas east-west motion of the sub-Earth point, and variations in Earth-Moon distance, occur mainly at the anomalistic period. Both of these motions influence the spatial and temporal patterns of tidal stress.

In Section 3, we refine and extend previous analyses of tidal periods present in moonquake occurrence. First, as we use events from the entire duration of the experiment (including our newly discovered events), our multitaper spectral method resolves longer periods, such as the 206-day period. The larger number of events also contributes to better resolution at monthly periods. These improvements permit more accurate comparison of observed spectral peaks to those present in the dynamics of the Earth-Moon-Sun system. Second, in addition to traditional spectral estimation procedures, we calculate spectra using a “spike-train” approach, which is well-suited to the analysis of time series composed of discrete events (Daley and Vere-Jones, 2003). This technique reveals fine structure, in particular at 27-28 days, not seen in the spectra computed from event occurrence histograms.

3.2.2 Locations of deep moonquake source regions

The locations of our nine moonquake source regions reported in two previous studies (Nakamura, 2005; Lognonné et al., 2003) are shown in Figure 3.1, along with the locations of the four seismic stations. The large differences among computed moonquake source locations are mainly due to the lack of reliable seismic

phase arrival times (P- and S-wave picks) (Nakamura, 2005). In addition, stations 12 and 14 are close together, meaning there is a limited number of possible source-receiver geometries, even for clusters with reliable arrivals. This results in large trade-offs between 1-D velocity structure and source location.

Arrival picks for deep moonquakes are typically selected from stacked seismograms. Stacking is possible because each deep event source region appears to produce its own unique waveform, so seismograms from the same cluster will correlate with each other and can be arithmetically averaged to produce a representative, composite seismogram with improved signal-to-noise. By using the stack optimization technique discussed in Bulow et al. (2005) and incorporating our new events, we compute revised stacks for each source and pick seismic phase arrivals.

We use these picks and the velocity models of Nakamura (1983) and Lognonné et al. (2003), to relocate the nine clusters. Locations estimated using both L1-norm (mean absolute value) and L2-norm (least squares) misfit criteria are presented in Section 4, and discussed in section 5.

3.3 New event report

Seismic events were originally identified from the Apollo data by visual inspection of compressed seismograms (Nakamura et al., 1980). Despite this method’s ability to generate an event catalog of impressive size, it did not allow for detection of events near or at the noise threshold. Additionally, after it was discovered that moonquakes occur with tidal periodicity, the data were inspected closely only around those times when moonquakes were expected.

We have employed a method to search objectively for deep events throughout the continuous lunar seismic data set using a cross-correlation technique to identify new events (Bulow et al., 2005). A similar technique was used previously to identify earlier cataloged but unclassified events (Nakamura, 2003). In this study, all references to the original event catalog (Nakamura et al., 1981) refer

to the version updated by Nakamura (2003), dated January 2004. We take advantage of the repeatable waveforms produced by each moonquake source region, and stack seismograms from a given source to create a single representative trace. This trace is then used as a target for cross-correlation with the entire continuous data set. Because the stack has higher signal-to-noise than any individual event, it increases the possibility of identifying low-amplitude events that are not visually distinguishable from noise. In Bulow et al. (2005) we reported the successful application of this approach to A1, the deep event group with the largest number of moonquakes. We recovered 123 new events, which is a 38% increase over the catalog updated with events from Nakamura (2003).

We have extended our search to seven other near-side clusters (A6, A8, A9, A10, A14, A18, and A20) and one far-side cluster (A33). The seven near-side clusters were chosen because they comprise the largest number of contributing events after A1, each consisting of at least 100 events. Also, arrival times from all of our near-side clusters have been used in recent estimates of seismic velocity structure (Lognonné et al., 2003; Gagnepain-Beyneix et al., 2006), and so we can examine the sensitivity of phase arrival picks to the addition of any newly identified events. Finally, the geographical distribution of the eight near-side clusters that we have investigated is roughly representative of the complete deep moonquake population. However, there are still limitations in establishing deep moonquake locations, as we discuss later.

For each deep cluster we generate target stacks: one per channel for each station, separately for the two modes of instrument response (for a description of instrument response, see Lammlein et al. (1974)). The target stacks are cross-correlated with the appropriate continuous records. Times at which the cross-correlation coefficient rises above a critical value indicate times of possible events. We use the same selection criteria as in Bulow et al. (2005) – new events must appear on at least 2 channels or stations. Because events recovered in this manner may not be visually distinguishable from noise, we also check that new moonquake

seismograms for a given cluster stack coherently. Stacking improves the signal-to-noise ratio, and the new events are visible.

For the seven near-side clusters, we recovered 380 previously unidentified deep moonquakes from the continuous data, as listed in Table 3.1. The percent increase over the number of cataloged events (Nakamura et al., 1981) for each cluster ranges from 20% to 54%, with the greatest increase for cluster A14 (Table 3.2). The average increase in events for these seven clusters is 36%, comparable to our result for A1.

The number of new events returned by our search method depends on both the number of original events and the percentage of high signal-to-noise events in the target stack. Our analysis eventually fails to return new events as these decrease. In such cases the target stack does not have sufficient signal-to-noise to retrieve low-signal events from the continuous data. This was the case for the far-side cluster A33, for which we detected no new events.

3.4 Spectral analyses of deep moonquake occurrence times

Early studies of deep moonquakes detected periodicities in time series of the number of events per day recorded at each of the four seismic stations, or peaks in the corresponding spectra (Lammlein et al., 1974; Lammlein, 1977). These studies considered all known deep events, but predated the termination of seismic data collection. Hence they used only a subset of the complete data set now available. The addition of new events to the catalog increases the temporal coverage of the data set by filling gaps in the time series where no events were previously recorded.

In this section, we discuss two methods of recovering periodicities in deep moonquake times. These analyses have two important differences from previous

Table 3.1 New events.

A#	year	day	hr:mn	channels	A#	year	day	hr:mn	channels
A06	1970	143	15:47	12xyz	A10	1971	259	20:42	12yz, 14xy
A06	1970	168	12:50	12yz	A10	1971	295	13:20	14xy, 15xy
A06	1970	284	4:35	12xyz	A10	1971	311	1:09	14xy, 15y
A06	1971	80	9:05	12xyz, 14x	A10	1972	148	5:33	14xy
A06	1971	216	16:43	12xyz, 15xy	A10	1972	177	2:43	14xy, 15y
A06	1971	218	9:17	15xy	A10	1974	247	6:37	12xy, 14xy, 15xy
A06	1971	244	16:37	15xyz	A10	1975	46	11:05	14xy
A06	1971	246	5:48	12xy, 14y, 15y	A10	1975	73	16:14	12xyz, 15y, 16xz
A06	1972	294	23:55	16xy	A10	1975	101	22:17	12xy, 14y
A06	1973	176	22:48	15xy, 16xz	A10	1975	155	2:28	12xyz, 14y, 16x
A06	1974	259	16:13	16xy	A10	1975	265	13:10	12z, 14y, 16y
A06	1974	277	14:28	14y, 16xyz	A10	1975	276	15:25	14y, 16y
A06	1974	304	9:44	12xyz, 14y, 16xyz	A10	1975	292	6:42	12z, 16xy
A06	1974	316	14:47	16xy	A10	1975	318	2:28	12z, 16xy
A06	1975	51	1:25	12xyz, 14y	A10	1976	66	6:30	14xy
A06	1975	194	9:59	15y, 16xy	A10	1976	102	15:57	12xz, 16xy
A06	1975	222	2:13	16xyz	A10	1976	118	6:54	16xy
A06	1975	270	10:30	12z, 15xz, 16xy	A10	1976	120	23:46	12xz, 16xy
A06	1975	276	12:32	12xy, 16xyz	A10	1976	145	16:34	14xy
A06	1975	277	18:37	15xy, 16xy	A10	1976	156	19:45	12xz, 14y, 16y
A06	1975	304	9:05	12xyz, 15xy, 16xyz	A10	1976	282	11:25	12z, 16xy
A06	1975	304	10:04	12z, 15y, 16xy	A10	1976	310	10:18	12z, 16xy
A06	1975	307	15:29	15y, 16xyz	A10	1976	310	14:14	12z, 16xy
A06	1975	329	18:58	12xyz, 15xyz, 16xy	A10	1976	319	6:48	16xy
A06	1975	330	8:26	12xyz, 15xyz, 16xy	A10	1976	322	8:19	14y, 16xy
A06	1975	332	15:29	12xyz, 15xyz, 16xyz	A10	1976	338	14:26	12z, 14xy, 16xy
A06	1975	334	21:03	12xyz, 15xyz, 16xyz	A10	1976	339	9:31	12z, 16xy
A06	1975	358	11:44	12xyz, 15xz, 16xyz	A10	1976	366	14:08	16y, 16y
A06	1976	20	10:35	12xyz, 15xyz	A10	1977	33	22:00	14xy, 16y
A06	1976	21	0:57	12xyz, 15xyz, 16z	A10	1977	133	14:13	12z, 14xy
A06	1976	47	23:26	15xyz, 16xyz	A10	1977	135	16:34	12xy, 14xy
A06	1976	48	17:27	15xyz, 16xy	A10	1977	172	8:11	14xy
A06	1976	76	1:08	15y, 16xy	A10	1977	191	19:01	12yz, 14xy
A06	1976	105	11:08	15yz, 16xy	A10	1977	241	21:15	14xy, 15xy, 16xz
A06	1976	130	4:21	15y, 16xy	A10	1977	251	16:18	14xy
A06	1976	130	17:47	12z, 15xyz, 16xyz	A14	1969	344	14:43	12xy
A06	1976	133	16:07	15xy, 16xy	A14	1970	33	20:57	12xyz
A06	1976	159	16:13	15y, 16xyz	A14	1970	254	0:09	12xyz
A06	1976	183	13:46	14y, 15xyz, 16xy	A14	1971	80	7:13	14xy
A06	1976	184	19:43	15y, 16xy	A14	1971	137	5:08	12xy, 14xy
A06	1976	264	12:14	16xy	A14	1971	161	19:12	12xyz, 14xy
A06	1976	292	16:09	15y, 16xy	A14	1971	188	13:10	14xy
A06	1976	295	1:58	15y, 16xy	A14	1971	190	8:28	12xy, 14xy
A06	1976	297	7:19	15y, 16xy	A14	1972	17	5:48	12xz, 14xy
A06	1976	321	0:23	14y, 15xy, 16xyz	A14	1972	44	10:18	14xy
A06	1976	324	18:21	15xyz, 16xy	A14	1972	129	0:08	12y, 16xy
A06	1976	348	19:26	12xyz, 14xy, 15z, 16xyz	A14	1972	209	10:54	16xy
A06	1976	349	22:29	15y, 16xy	A14	1972	261	6:15	16xy
A06	1977	64	8:30	15xy, 16xy	A14	1972	261	22:57	16xy
A06	1977	64	21:53	15y, 16xy	A14	1972	263	5:22	14x, 16xyz
A06	1977	93	3:58	14y, 15y, 16xy	A14	1972	264	4:34	16xy
A06	1977	121	18:06	14x, 15xyz, 16xyz	A14	1972	264	21:29	12xy, 14xy, 16xy
A06	1977	148	10:39	14x, 15xy, 16xyz	A14	1972	289	21:59	16xyz
A08	1972	39	20:05	12xyz, 14xy	A14	1972	290	14:58	14xy, 16xy

(continued)

Table 3.1 (continued)

A#	year	day	hr:mn	channels	A#	year	day	hr:mn	channels
A08	1972	287	15:46	14y, 16xy	A14	1972	292	20:30	16xy
A08	1972	340	16:43	16xy	A14	1972	293	14:13	16xy
A08	1973	167	3:40	16xy	A14	1972	322	2:04	16xy
A08	1973	195	15:44	16xy	A14	1972	350	7:48	16xy
A08	1973	196	18:16	16xy	A14	1973	8	11:30	12xy, 14y
A08	1973	223	23:43	16xy	A14	1973	10	8:40	14y, 16x
A08	1973	253	22:59	16xy	A14	1973	34	12:44	12xz, 14x, 16x
A08	1973	359	4:41	14y, 16xy	A14	1973	36	3:51	12x, 16x
A08	1973	362	16:23	16xyz	A14	1973	37	13:05	12xyz, 14xy
A08	1973	362	16:28	16xyz	A14	1973	118	22:36	12y, 16xy
A08	1974	50	6:39	16xyz	A14	1973	146	2:16	12x, 16xyz
A08	1974	52	2:38	16xy	A14	1973	147	10:03	12x, 14y, 16xy
A08	1974	52	5:36	16xy	A14	1973	173	12:24	16xy
A08	1974	52	13:41	16xyz	A14	1973	173	14:16	16xy
A08	1974	80	0:00	16xyz	A14	1973	203	9:14	12xy, 16xy
A08	1974	184	11:53	16xyz	A14	1973	204	5:31	12x, 14y, 16xy
A08	1974	214	18:33	16xy	A14	1973	229	11:30	14xy
A08	1974	240	3:40	16xy	A14	1973	256	2:53	16xy
A08	1974	244	3:47	16xy	A14	1973	256	21:19	12x, 14xy
A08	1974	245	4:21	16xy	A14	1973	283	15:25	16xyz
A08	1974	248	0:05	12xyz, 14xy	A14	1973	309	11:49	16xy
A08	1974	357	2:03	12xyz, 14xy	A14	1973	309	22:51	16xy
A08	1975	19	22:34	12xyz, 14xy, 15y	A14	1973	311	22:38	16xy
A08	1975	47	10:17	12xyz, 14xy	A14	1974	4	6:11	12x, 14xy, 16xyz
A08	1975	73	7:32	12xyz	A14	1974	51	10:33	16xy
A08	1975	130	20:29	16xy	A14	1974	56	7:36	16xyz
A08	1975	155	9:30	12xyz, 14y	A14	1975	49	9:10	14xy
A08	1975	182	20:41	12xyz, 16xyz	A14	1975	112	21:32	12xyz, 14y
A08	1975	184	10:43	16xy	A14	1976	350	14:42	14xy, 16xyz
A08	1975	276	10:20	16xy	A14	1977	89	3:25	16xy
A08	1975	277	2:11	16xy	A14	1977	89	15:56	12z, 16xyz
A08	1975	292	15:22	12xyz, 14y, 16xyz	A14	1977	104	7:56	16xy
A08	1975	293	15:51	16xy	A14	1977	148	21:37	12xy, 14xy, 16xyz
A08	1975	304	7:19	16xy	A14	1977	176	15:05	12y, 16z, 16xy
A08	1975	305	8:48	16xy	A14	1977	204	7:59	14xy, 16z, 16xy
A08	1976	36	22:52	16xy	A14	1977	229	2:32	14y, 12x, 16z, 16xy
A08	1976	37	0:59	16xyz	A14	1977	256	3:24	12z, 16xy
A08	1976	37	7:54	16xy	A14	1977	259	0:56	14y, 16xy
A08	1976	47	17:25	16xy	A18	1970	252	17:49	12xyz
A08	1976	47	18:43	16xy	A18	1970	279	23:52	12yz
A08	1976	47	21:44	16xy	A18	1971	22	0:17	12xy
A08	1976	75	20:01	16xy	A18	1971	23	14:31	12xy
A08	1976	76	8:28	16xy	A18	1971	50	6:08	12xy, 14z
A08	1976	102	3:00	16xy	A18	1971	50	15:32	12xy
A08	1976	118	16:58	16xy	A18	1971	51	4:37	12xyz
A08	1976	129	23:52	16xy	A18	1971	78	8:32	12xy, 14xyz
A08	1976	130	7:42	16xy	A18	1971	78	8:46	12x, 14xy
A08	1976	144	12:43	16xy	A18	1971	78	12:36	12xy, 14xy
A08	1976	145	17:41	16xy	A18	1971	79	4:01	12xy, 14xy
A08	1976	146	3:38	16xy	A18	1971	105	12:57	14xy
A08	1976	172	5:53	16xy	A18	1971	105	15:34	12z, 14xy
A08	1976	174	1:00	16xy	A18	1971	106	8:26	14xy
A08	1976	185	5:59	16xy	A18	1971	131	7:33	12xyz, 14xy
A08	1976	213	10:36	16xy	A18	1971	186	6:40	12xyz, 14xy

(continued)

Table 3.1 (continued)

A#	year	day	hr:mn	channels	A#	year	day	hr:mn	channels
A08	1976	241	5:20	16xy	A18	1971	213	20:44	12x, 14xy
A08	1976	266	1:20	16xy	A18	1971	214	12:02	12y, 14xy
A08	1976	266	7:27	16xy	A18	1971	241	23:32	14xy
A08	1976	267	5:45	16xy	A18	1971	269	5:32	12y, 14xy, 15y
A08	1976	281	21:25	16xy	A18	1971	298	10:49	12y, 14xy, 15y
A08	1976	282	17:46	16xy	A18	1971	321	22:24	12y, 14y
A08	1976	283	16:40	16xy	A18	1971	349	11:16	12xyz, 14xy
A08	1976	292	15:25	16xy	A18	1972	40	0:52	14xy
A08	1976	293	10:41	16xy	A18	1972	95	13:01	12y, 14xy
A08	1976	293	14:57	16xy	A18	1972	122	10:26	12x, 14xy, 16xy
A08	1976	293	21:16	16xy	A18	1972	125	14:16	14xy
A08	1976	296	11:07	16xy	A18	1972	148	6:35	14xy, 16y
A08	1976	309	4:05	16xy	A18	1972	149	8:28	14xy, 16xy
A08	1976	310	6:04	16xy	A18	1972	151	1:48	16xy
A08	1976	310	14:14	16xy	A18	1972	176	14:56	14xy, 16xy
A08	1976	319	17:25	16xy	A18	1972	204	5:11	12xy, 14xy, 16xyz
A08	1976	321	6:11	16xy	A18	1972	231	16:30	16xy
A08	1976	321	6:51	16xy	A18	1972	286	1:07	14y, 16xy
A08	1976	321	9:39	16xy	A18	1972	287	11:25	14y, 16xy
A08	1976	321	16:05	16xy	A18	1972	340	6:12	16xyz
A08	1976	321	21:12	16xy	A18	1973	3	12:03	16xyz
A08	1976	324	9:52	16xy	A18	1973	5	22:13	14xy, 15y, 16y
A08	1976	338	1:48	16xy	A18	1973	37	6:29	14xy, 15x
A08	1976	350	0:46	16xy	A18	1973	362	16:12	14xy
A08	1976	350	4:34	16xy	A18	1973	364	1:40	14y, 16y
A08	1976	362	3:48	16xy	A18	1974	23	22:42	14y, 15xy
A08	1976	366	12:31	16xy	A18	1974	50	23:43	12y, 14xy, 15y, 16xy
A08	1977	57	22:09	12xyz	A18	1974	53	3:17	14y, 15x
A08	1977	63	9:45	16xy	A18	1974	190	14:43	12y, 14xy
A08	1977	64	8:05	16xy	A18	1974	216	16:06	16xy
A08	1977	65	15:15	16xy	A18	1974	218	9:15	12xyz, 14xy, 15xy, 16xy
A08	1977	79	5:10	16xy	A18	1974	272	15:11	14xy, 15y, 16xy
A08	1977	109	15:27	16xy	A18	1974	299	19:19	16xy
A08	1977	136	6:42	15y, 16xy	A18	1975	99	23:37	14y, 16xy
A08	1977	136	8:08	16xy	A18	1975	264	23:21	14y, 15xy, 16xy
A08	1977	146	23:57	16xyz	A18	1975	276	23:33	14y, 15xy
A08	1977	172	17:00	16xyz	A18	1975	303	17:27	14y, 15y, 16x
A08	1977	173	8:15	16xyz	A18	1975	319	17:55	15xy, 16xy
A08	1977	211	10:09	16xyz	A18	1977	89	9:33	12y, 14y, 15xy, 16xy
A08	1977	224	10:28	16xy	A18	1977	89	13:42	12y, 15y, 16xy
A08	1977	251	16:28	14xy, 16xy	A18	1977	89	20:48	12xy, 14xyz, 15xy, 16xyz
A08	1977	252	9:14	16xyz	A18	1977	115	22:54	12z, 14y, 15y, 16xyz
A08	1977	271	0:30	16xy	A18	1977	117	17:40	12xy, 15y, 16xyz
A09	1971	40	2:41	12xyz, 14xy	A18	1977	117	19:34	16xyz
A09	1971	204	22:54	12z, 14xy	A18	1977	145	4:43	12z, 14xyz, 15xy, 16xyz
A09	1971	230	22:31	12xyz, 14xy	A18	1977	166	11:52	16xyz
A09	1972	4	14:31	12xyz, 14xy	A18	1977	171	5:16	12y, 14xy, 16xy
A09	1972	27	10:33	12xyz, 14xy	A18	1977	172	23:48	14xy, 16xy
A09	1972	59	1:08	12xyz, 14xy	A18	1977	173	11:25	14xy, 15xy, 16xy
A09	1972	137	9:12	12y, 16xy	A18	1977	195	14:05	14y, 15y, 16xy
A09	1972	164	9:10	12xyz, 14x, 16xy	A18	1977	225	4:51	12z, 14xy, 15y, 16xyz
A09	1972	169	8:07	12yz, 14xy, 16y	A18	1977	227	0:48	16xy
A09	1972	246	10:51	12xyz, 14xy	A18	1977	227	22:12	16xyz
A09	1972	248	21:46	12x, 14xy, 16x	A18	1977	251	16:44	14y, 16xy, 16y, 16x

(continued)

Table 3.1 (continued)

A#	year	day	hr:mn	channels	A#	year	day	hr:mn	channels
A09	1972	272	17:39	12xy	A18	1977	254	21:36	16xy, 16y, 16x
A09	1972	277	17:11	12x, 16y	A20	1969	352	3:14	12xyz
A09	1973	232	4:38	12x, 16xy	A20	1971	282	10:28	12xy, 14xy
A09	1974	224	2:52	12xyz, 14xy, 16xy	A20	1972	14	18:48	12xyz
A09	1975	50	15:15	12z, 14xy	A20	1972	27	19:57	14xy, 15xy
A09	1975	77	21:07	16xy	A20	1972	81	10:18	12y, 14xy, 15y
A09	1975	183	20:23	12xyz, 14y, 16y	A20	1972	96	21:26	12xyz, 14xy
A09	1975	346	17:03	12yz, 14y, 16y	A20	1972	178	3:59	12y, 14xy, 15y, 16xy
A09	1976	282	16:49	12xyz	A20	1972	205	14:58	12xy, 14xy, 16xy
A09	1976	289	13:47	12xy	A20	1972	287	10:05	14y, 15xyz, 16xyz
A09	1976	310	9:16	12xz, 16y	A20	1972	313	23:30	12xy, 14xy, 16y
A09	1977	271	8:13	14xy, 16xy	A20	1972	341	11:50	12xy, 14xy, 15xy, 16xy
A09	1977	271	8:24	14xy, 16xy	A20	1973	3	1:00	14xy, 15y, 16xyz
A10	1969	332	3:39	12xyz	A20	1973	30	4:15	12xz, 14y, 15y, 16x
A10	1970	51	23:04	12xy	A20	1973	153	11:38	14xy, 16xy
A10	1970	79	15:50	12xy	A20	1973	166	4:19	12x, 14xy, 16xy
A10	1970	131	1:40	12yz	A20	1973	274	19:27	14xy
A10	1970	158	4:50	12xyz	A20	1973	316	21:57	12xyz, 14xy, 15xy, 16xyz
A10	1970	214	20:41	12xyz	A20	1974	19	13:32	12xyz, 14xy, 15xyz, 16xz
A10	1970	246	17:53	12xz	A20	1974	46	18:41	12xyz, 16xyz
A10	1970	269	16:04	12xy	A20	1974	73	23:22	12xyz, 14xy, 16xy
A10	1970	296	18:36	12xyz	A20	1974	73	23:27	12xyz, 14xy, 15z, 16xy
A10	1970	324	22:36	12xyz	A20	1974	237	19:20	12x, 14y, 16x
A10	1970	348	23:11	12xyz	A20	1974	281	11:32	12xyz, 14xy, 15y, 16x
A10	1971	37	18:54	12xyz, 14y	A20	1974	292	6:47	14y, 16x
A10	1971	39	5:23	12yz, 14xy	A20	1975	36	15:14	14xy, 15xy, 16xz
A10	1971	69	20:08	14xy	A20	1975	64	5:51	14y, 15y, 16x
A10	1971	98	5:11	12yz, 14xy	A20	1975	162	0:58	12xyz, 14y, 15xy, 16x

studies. First, we use events from the full time span of the experiment, including our new events. Second, we only use events from the nine moonquake groups for which we conducted new event searches, as we are interested in detecting fine structure (in particular, sensitivity to closely-spaced monthly periods) in moonquake occurrence times. Lognonné and Johnson (2007) have recently shown that the spectral characteristics of these nine clusters match those of the deep moonquake catalog (Nakamura et al., 1981).

3.4.1 Multitaper method

We first apply an approach similar to that used previously. We generate a series of moonquake times for the nine clusters and calculate the number of moonquakes per 24-hour day and the corresponding power spectrum. Previous studies

Table 3.2 Number of original and new events by cluster.

cluster	original [†]	new	% increase
A1	320	123	38%
A6	132	53	40%
A8	224	98	44%
A9	123	24	20%
A10	185	50	27%
A14	106	57	54%
A18	143	71	50%
A20	136	27	20%
A33	64	0	0%

[†] from catalog Nakamura et al. (2004)

did not report the details of the spectral estimation technique used (Lammlein, 1977); here we use the minimum-bias multitaper method of Riedel and Sidorenko (1995). We explored various choices for the number of tapers; Figure 3.2 shows the power spectrum computed using 6 tapers. This number allows us to retain frequency resolution at the expense of noisy spectral estimates, as is evident in the power seen at high frequencies.

Spectral peaks are seen at 13-14 days and 27-28 days, with some structure in the monthly peak. However, it is not possible to distinguish between the nodical and anomalistic periods. This conclusion holds even for much finer temporal binning of the data since the total number of moonquakes in our time series is still relatively small (1936 for the nine clusters analyzed in this study). A broad peak in the power spectrum is seen close to the previously-noted 206-day period, and the increase in power at the longest periods likely reflects the 6-year modulation of moonquake occurrence times. Increased smoothing using more tapers or the fully adaptive multitaper approach results in spectra with broader peaks at the monthly and fortnightly periods, and the loss of any resolution near 200 days. Thus this spectral approach, which is typically used in investigating tidal periodicities in terrestrial quakes (e.g., Tolstoy et al. (2002)), provides some insight into the lunar data but cannot distinguish fine structure in the spectrum, in particular

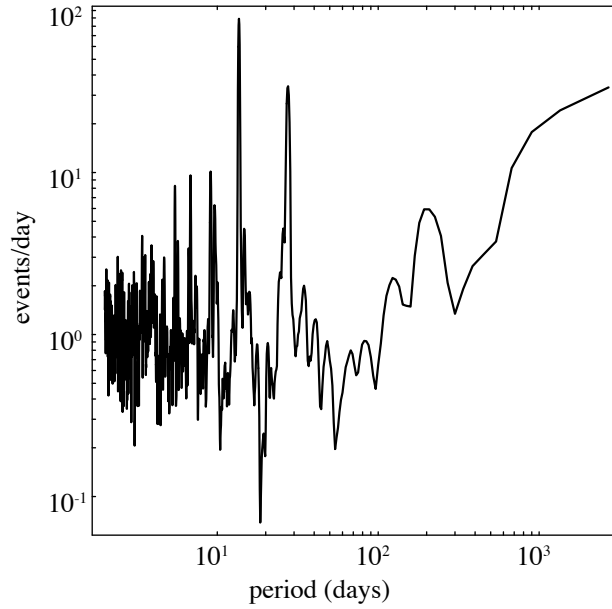


Figure 3.2 Multitaper spectrum. Power spectral density of the number of A1, A6, A8, A9, A10, A14, A18, A20, and A33 moonquakes per day computed using the multitaper spectral estimate. Horizontal axis is in days. Peaks at ~ 13 , 27, and 206 days can be seen, and power at the longest periods likely results from a 6-year modulation of moonquake occurrence times.

near periods of 1 month.

3.4.2 Spike-train method

We next adopt an alternative approach to investigating deep moonquake periodicities. We model the time series of deep moonquakes as a sequence of events occurring at discrete (error-free) times, where each event is represented by a delta function:

$$f(t) = \sum_{j=1}^N \delta(t - t_j). \quad (3.1)$$

The j th moonquake occurs at time t_j , and the summation is over the total number of moonquakes in the time series. This type of spike-train analysis has been applied, for example, to the spectral analysis of neuronal activity (see Buneo et al. (2003)). We construct a function representing the Fourier transform of a spike-train of N

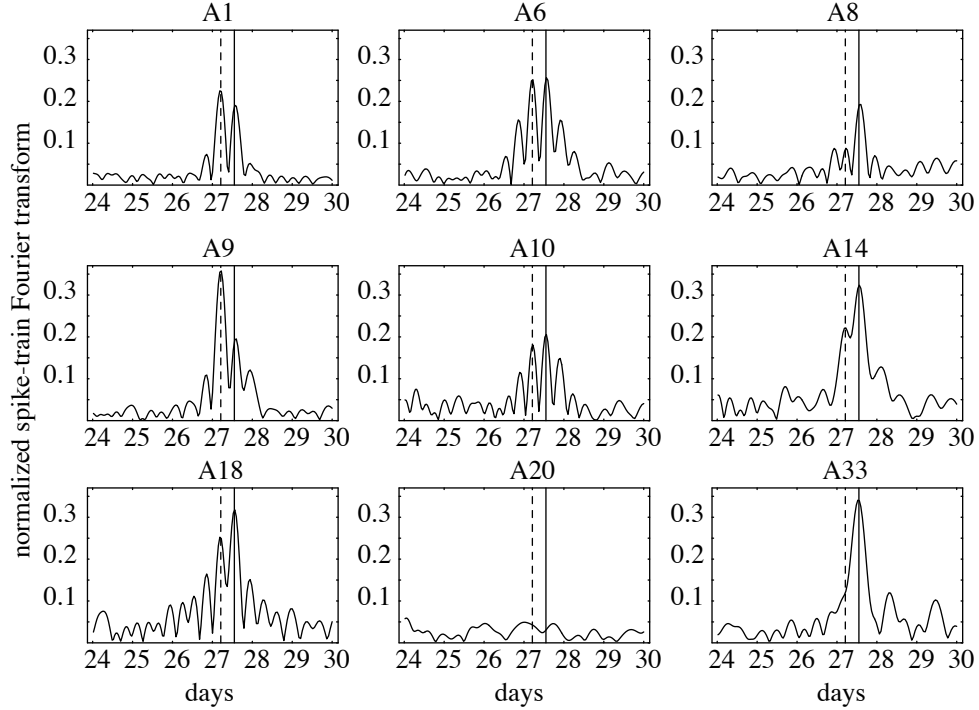


Figure 3.3 Spike-train spectra. Fourier amplitude spectra calculated using the spike-train analog for the nine deep event clusters shown in Figure 3.1. Each spectrum is normalized by the number of contributing events. Horizontal axis is in days. Note distinct peaks near ~ 27 days, with split peaks occurring near the periods of the nodical and anomalistic months (marked with vertical dashed and solid lines, respectively).

events by summing the Fourier transforms of the individual peaks:

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \sum_{j=1}^N e^{-it_j\omega} \quad (3.2)$$

This produces an exact spectrum of the finite series of input spikes, and retains the temporal resolution inherent in the original data set. Spectra computed using this method reveal detailed structure in the dominant monthly peak, and are sensitive enough to allow comparisons among spectra computed for individual clusters (Figure 3.3). Some clusters display split peaks at periods near 27 days, at the anomalistic and nodical months. The dominant period in each spectrum is listed in Table 3.3, with an additional column for spectra that show distinct splitting at ~ 27 days.

Of note is the lack of a monthly spectral peak for cluster A20. This is because A20 consists of two groups of events, each having a near-monthly periodicity but occurring at near-opposite monthly phases. This behavior can more readily be explained in the time domain. In Figure 3.4, we show phase plots for each moonquake cluster. The phase is defined as the modulus of the moonquake times with a reference period, in this case the nodical month. It is thus the remainder, in days, when an integer number of nodical months has been subtracted from the event time. All event times are measured in days from the J2000 epoch, so zero phase corresponds to January 1, 2000; during the Apollo experiment time span, a zero phase relative to the nodical period also occurred, for example, on January 20, 1971. The plots shown in Figure 3.4 complement the spectra in Figure 3.3 because they also indicate sensitivity to the nodical month. For those clusters listed in Table 3.3 having spectral peaks at the nodical month, there tends to be a favored phase at which events occur. For A20, two distinct groups of events are evident in Figure 3.4, spaced approximately 13 days apart. We computed spike-train spectra for these two groups separately, and found they both exhibit prominent spectral peaks at the nodical month. While the spectral peak for the lower group of A20 events in Figure 4 has a very slight side lobe at the anomalistic month (corresponding to the slight deviation from true nodical of that group in Figure 4), in Table 3.3 we report 27.2 days as the dominant period for A20.

3.5 Moonquake locations

We turn now to the spatial distribution of deep moonquakes. As shown in Figure 3.1, moonquake source locations vary among studies. We use arrival-time picks from stacks that include our new events, along with existing lunar seismic velocity models, to investigate whether the locations of deep moonquake clusters are well-constrained.

Table 3.3 Dominant periods of moonquake occurrence by cluster

cluster	peak 1/ <i>dag</i>	peak 2
A1	27.2	27.5
A6	27.5	27.2
A8	27.5	
A9	27.2	
A10	27.5	27.2
A14	27.5	27.2
A18	27.5	27.2
A20	27.2	
A33	27.5	

3.5.1 Method

As discussed in Bulow et al. (2005), we employ a weighted iterative stacking method to produce optimized event stacks with the clearest possible seismic phase arrivals. First, an initial high-quality target event is selected. Then, on a station-by-station, component-by-component basis, seismograms from the target event are cross-correlated with all events in our expanded catalog.

Events correlating with the target with absolute correlation coefficients $r \geq r_{cutoff}$ are considered for stacking, where the cutoff is determined separately for each stack. Before the stack is formed, each individual trace is weighted by r^2 . This increases the influence of highly-correlating events on the stack, improves the visibility of seismic phase arrivals, and produces a cleaner stack than a simple arithmetic average of seismograms.

The cross-correlation procedure is then repeated, this time using the weighted stack as the target. To optimize the stack, the process is iterated until the number of events added to the stack stabilizes. We find good convergence after four iterations. P and S arrival-time picks made from optimized stacks for the nine clusters we have analyzed are summarized in Table 3.4 (sample optimized stacks for A1 are shown in Figure 17 of Bulow et al. (2005)). Uncertainties in the travel time picks are also reported. For completeness, optimization was performed for

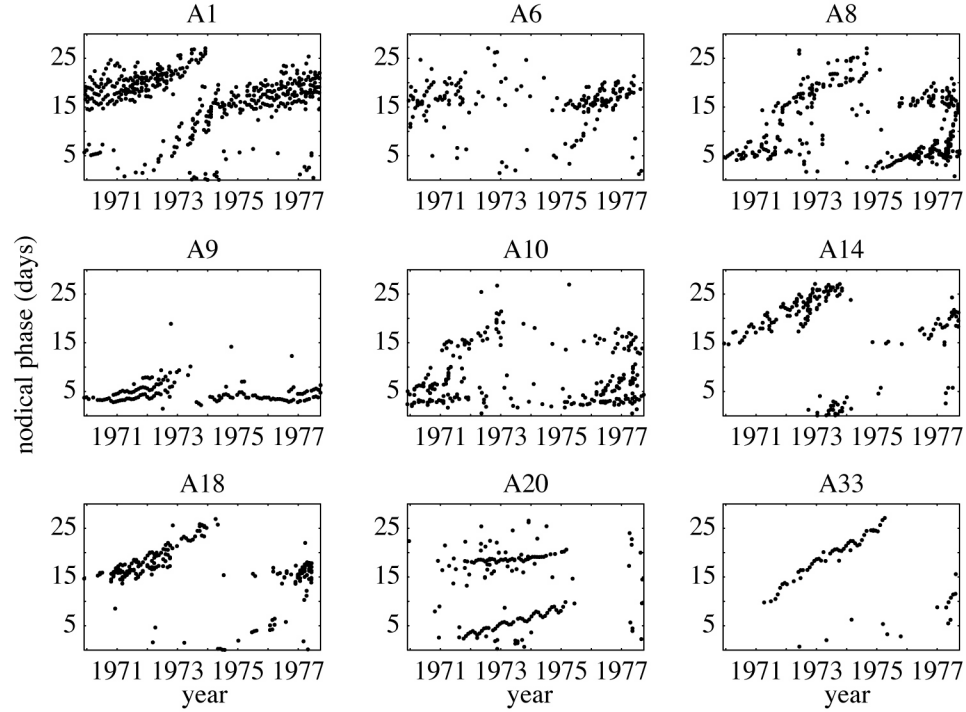


Figure 3.4 Phase plots. Nodal phase versus time for the nine deep event clusters shown in Figure 3.1. Phase is computed as the modulus of each event time with respect to the reference period of 27.21 days.

A33 despite the lack of new events detected for that cluster.

We use these arrival times along with two representative lunar seismic velocity models (Nakamura, 1983; Lognonné et al., 2003) to re-estimate the deep moonquake cluster locations. Because the arrival-time data provide poor coverage of the lunar crust and mantle, the velocity structure is not very well constrained, and there are large trade-offs between the chosen model and the resulting cluster location (Gagnepain-Beyneix et al., 2006; Lognonné and Johnson, 2007). Rather than further examine this trade-off, we investigate the sensitivity of location estimates to the number of arrival-time picks and their uncertainties, and the choice of misfit criterion for a particular velocity model. For each cluster we ray trace through a specified velocity model and use a grid-search algorithm to find the best-fitting cluster location, obtaining results for two misfit norms, L1 and L2. Each arrival-time pick is weighted by its estimated uncertainty.

Table 3.4 Seismic phase arrival picks. Picks in seconds from reference event time.

year	day	hr:min	cluster	P12	P14	P15	P16	S12	S14	S15	S16
1973	273	04:12	A1	66.4±2	73.5±3	138.0±4	123.1±4	157.3±10	176.5±11	276.1±9	265.7±10
1977	92	06:43	A6	118.2±4	119.5±11	82.6±4	110.6±10	300.7±4	285.6±4	171.5±4	232.1±4
1977	136	10:55	A8	23.2±5	29.4±11	-	-	90.0±2	92.1±7	-	147.8±4
1972	359	10:39	A9	-10.0±3	-24.0±4	-	-	76.5±6	73.2±7	-	112.1±7
1977	116	10:13	A10	63.2±7	67.6±7	-	-	173.4±6	187.9±2	-	235.2±3
1973	258	21:44	A14	-	-20.8±4	-	-	86.8±5	79.7±3	-	141.3±2
1972	179	15:56	A18	-	59.9±4	6.2±5	31.2±4	216.0±2	199.8±4	119.2±7	141.0±5
1974	116	09:18	A20	-	52.2±12	34.4±10	82.9±9	142.8±2	149.1±3	-	222.6±3
1973	359	15:16	A33	-	86.9±6	44.7±6	47.2±2	-	-	263.1±6	250.1±4

Table 3.5 Relocation estimates. Initial, L1, and L2 latitude, longitude[†], and depth[‡] (θ, ϕ, z) for two velocity models.

cluster	θ_0	ϕ_0	z_0	θ_{L1}	ϕ_{L1}	z_{L1}	θ_{L2}	ϕ_{L2}	z_{L2}
Nakamura (2005)									
A01	-15.7	-36.6	867	-16.0	-39.9	800	-16.5	-39.2	821
A06	43.5	55.5	844	34.0	35.3	800	36.7	39.8	906
A08	-23.7	-35.5	1086	14.9	-7.3	0	14.9	-7.3	5
A09	-6.0	-19.7	1037	-12.0	-13.6	823	23.7	-4.3	289
A10	-35.7	-40.3	988	1.5	-35.0	1214	16.9	-31.5	1169
A14	-29.6	-44.4	933	28.1	-16.0	707	-39.1	-23.7	300
A18	23.3	32.7	925	23.4	32.6	884	24.4	32.0	891
A20	23.7	-31.4	945	27.0	-27.6	841	26.6	-26.3	816
A33	5.1	115.8	877	7.9	116.2	851	10.6	115.8	808
Nakamura (2005) fixed-depth									
A08				-12.1	-20.1	850	-4.3	-18.0	850
A09				-5.0	-12.5	850	8.2	-10.0	850
A10				-42.6	-37.9	850	-41.7	-37.9	850
A14				22.8	-19.6	850	23.8	-19.0	850
Lognonné et al. (2003)									
A01	-17.4	-38.4	917	-16.1	-38.8	829	-15.5	-37.7	846
A06	49.7	54.7	860	35.2	36.5	860	35.3	36.5	938
A08	-28.0	-28.1	940	-5.2	-8.8	0	-10.4	-14.5	640
A09	-37.8	-30.8	975	-30.8	-15.9	561	25.0	-3.9	50
A10	-36.8	-38.9	980	-47.0	-36.3	709	-46.4	-36.3	700
A14	-28.7	-33.9	880	-32.1	-29.5	778	-37.7	-21.8	0
A18	18.6	34.7	882	21.1	29.8	921	23.4	29.4	906
A20	21.7	-41.0	1055	26.0	-26.9	877	25.9	-25.2	839
A33	6.9	117.9	887	-10.4	145.1	1378	11.6	111.0	928
Lognonné et al. (2003) fixed-depth									
A08				-8.5	-18.5	850	-4.4	-17.6	850
A09				-14.0	-13.8	850	-15.1	-13.8	850
A10				-43.0	-35.7	850	-41.9	-35.6	850
A14				-27.8	-29.0	850	-29.4	-28.9	850

[†] all latitudes/longitudes are in degrees

[‡] all depths are in kilometers

3.5.2 Results

Our new location estimates for the different velocity models and misfit criteria are given in Table 3.5, along with the previously published locations for each cluster (Nakamura, 2005; Lognonné et al., 2003). Note from Table 3.5 that the relocated depths of clusters A8, A9, A10, and A14 are highly variable and are sometimes outside the commonly accepted zone of 750-1000 km depth for deep moonquakes. These clusters have no picks from station 15 and only S-wave picks from station 16, severely limiting the ray geometry (Figure 3.1). Reliable depth estimates are not possible from the restricted pick information for these clusters. We recompute their locations, using a fixed depth given by the mean value of the other five source regions (~ 850 km). A similar approach was used in Nakamura et al. (1982).

These locations are plotted in Figure 3.5, together with 95% confidence regions at the best-fitting depth for each cluster, computed using chi-squared statistics for the L2-norm and the Nakamura (1983) velocity model. The larger error ellipses occur for those clusters with small numbers of picks and disparate individual location estimates. The confidence regions for A10 and A14 indicate the presence of two local minima in their misfit functions, both north and south of the equator. This phenomenon arises from the lack of picks from station 15 to the north, so that approximately symmetric solutions are possible on both sides of the nearly east-west line connecting the remaining stations. This also explains the north-south elongation of the A8 and A9 error ellipses.

Good agreement among the location estimates is seen for clusters A1 and A18, indicating that these locations are the most reliable and well constrained. Location estimates for clusters A6, A10, and A20 show more scatter, and those for clusters A8, A9, and A14 span large angular distances. Locations for A33 are consistent except for the L1 estimate using the Lognonné model.

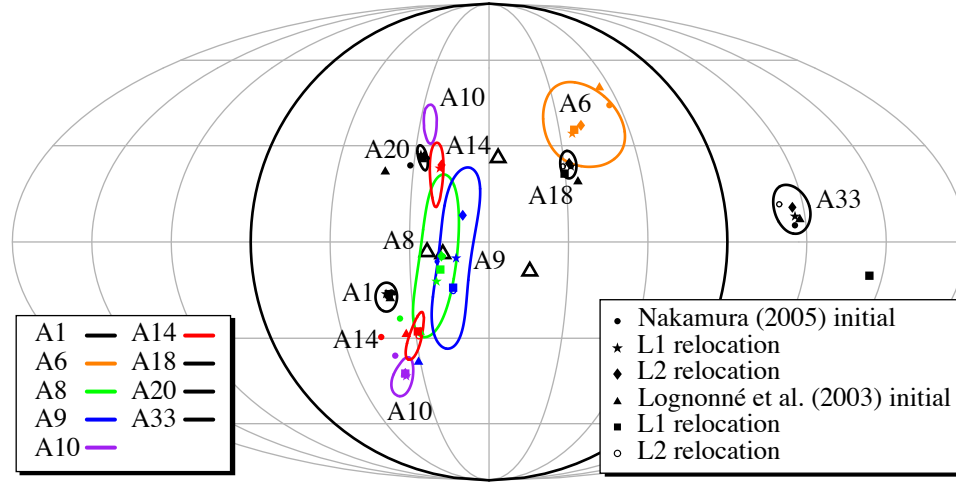


Figure 3.5 Relocation map. Published cluster locations from Nakamura (2005) and Lognonné et al. (2003) and our L1 and L2 relocations for each velocity model. Colors represent the moonquake clusters and symbols represent the different location estimates. The chi-squared 95% misfit contour is also shown for each cluster. The near side of the Moon is indicated by the heavy longitude lines. Station locations are open triangles.

3.6 Discussion

3.6.1 Temporal characteristics

Moonquake occurrence clearly exhibits tidal periodicities, as evidenced by the existence of peaks in the spectra at 1 month (due to the orbit of the Moon around the Earth) and 206 days (due to the perturbation of the Moon's orbit by the Sun); see Figures 3.2 and 3.3. Spectra calculated using the multitaper method display a single peak near 27 days, similar to those of Lammlein (1977). This similarity exists because the same type of time series is used to compute each spectral estimate – a histogram of number of moonquakes per unit time, where the time interval used for binning is 1 day. The 206-day period is better resolved than previously due to our use of events spanning the full length of the experiment (rather than the events between 21 April 1972 and 21 May 1974 used by Lammlein (1977)). However, despite our longer time series and increased number of events,

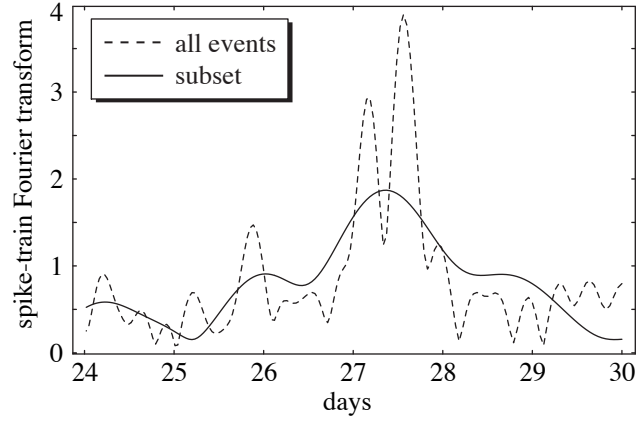


Figure 3.6 Spectrum of event subset. Spike-train spectra for both the full time series of events from our nine clusters (dashed line) and the subset (solid line) used in *Lammlein* [1977].

the multitaper method does not reveal any fine structure in the monthly spectral peak.

In Lammlein (1977), the single monthly peak is interpreted as the nodical period. In that study, it is then suggested that the lack of spectral peaks at the anomalistic month is due to its variable length (between 25 and 28.5 days with a period of 7.5 anomalistic months), and that moonquake occurrence times governed by this period would result in a broad spectral peak. Our Fourier spectra computed using the spike-train approach, however, resolve both the anomalistic (27.55 days) and nodal (27.21 days) monthly periods in moonquake occurrence times, when the full time series is used. When using the subset of events between 4/21/1972 and 5/21/1974, resolution at the monthly period is reduced (Figure 3.6). This is because $(\frac{1}{27.21} - \frac{1}{27.55})^{-1} \sim 2000$ days are necessary to resolve the peak, and the subset of data used in Lammlein (1977) covers only 761 days.

Among the clusters we have analyzed, the dominant period is usually the anomalistic month (clusters A6, A8, A10, A14, A18, and A33), with the nodical month often appearing as a secondary peak (Table 3.3). Some deep event clusters respond mainly to only one period, meaning any secondary peaks are small (clusters A8, A9, A20, and A33). We believe the split peaks, when present, represent a true

Table 3.6 Location errors. Latitude/longitude location error, rms residual at best-fitting location, and number of arrivals by cluster.

cluster	latitude $\pm$	longitude [†] $\pm$	residual (s)	arrivals
A1	4.5	4.3	3.5	8
A6	14.3	17.3	9.4	8
A8	25.1	9.3	12.3	5
A9	28.2	10.1	3.7	5
A10	46.9	11.9	4.1	5
A14	33.9	8.9	4.1	4
A18	4.3	3.5	3.2	7
A20	3.3	2.5	3.9	6
A33	7.5	6.9	3.3	5

[†] all latitude/longitude errors are in degrees

sensitivity of different clusters to similar forcing periods.

3.6.2 Spatial characteristics

A rough estimate of the uncertainties in the locations of each deep moonquake source region can be obtained by comparing published locations with our L1 and L2 norm solutions for the different velocity models and noting the size of the 95% confidence regions (Figure 3.5). Estimates of L2 location error in latitude and longitude (the mean N-S and E-W extrema of the 95% confidence limits) for our nine clusters computed using the Nakamura (1983) velocity model are listed in Table 3.6, along with the root-mean-square (rms) residual at the best-fitting location and the number of arrivals available. In general, the sizes and shapes of the 95% confidence contours reflect the scatter in the different individual relocation estimates.

Clusters that exhibit general agreement in location estimates and small error ellipses are those possessing *P*- and *S*-wave arrival-time picks on the greatest number of stations (Table 3.4). In particular, for accurate locations it is important to have picks from the three corners of the triangle defined by stations 15, 16, and either 12 or 14 (see Figure 3.1). Stations 12 and 14 are not separated enough

for their arrival-time information alone to provide much resolution. If picks are lacking from station 15, as is the case for clusters A8, A9, A10 and A14, then the location quality is poor and the possible locations scatter in a north-south direction roughly perpendicular to the line connecting stations 12 and 16, or can even possess multiple misfit minima, as is seen for A10 and A14. Locations for these clusters are very poorly constrained in latitude, although locations south of the equator are probably more likely than those to the north because of the lack of clear arrivals for these clusters at station 15.

We can compare our uncertainties with the uncertainties from Nakamura (2005). Note, Table 3.2 of that paper lists 1-sigma uncertainties in latitude and longitude computed from a single velocity model (Nakamura, 1983). So, twice those values (2-sigma) are comparable to our uncertainties estimated from the 95% confidence contours, which were computed from the same velocity model (Table 3.6). As expected, our latitude uncertainties for clusters A8, A9, A10, and A14 are considerably larger. Among the other clusters, the location estimates agree within the uncertainties, and the uncertainties in the location estimates computed from the same velocity model (Nakamura, 1983) are comparable.

The best and most robust locations (latitude, longitude, and depth) are obtained for clusters A1 and A18, with A6, A20, and A33 being slightly less well constrained. It is these clusters that provide the best estimates of the depths of deep clusters and the strongest constraints on deep lunar velocity structure.

3.7 Conclusions

We have conducted a new event search for nine deep moonquake clusters, eight on the near side and one on the far side. This has allowed us to recover 503 new events, an average increase of 36% over those reported in the catalog (Nakamura et al. (1981), updated 2004).

Investigation of moonquake occurrence times using multitaper spectral

estimation techniques confirms the presence of 27-day, 206-day, and possibly 6-year periodicities. The use of a longer time series and the addition of our new events produces better resolved spectral peaks at 27 and 206 days, compared with previous studies (Lammlein et al., 1974; Lammlein, 1977). The spike-train approach allows detection of fine structure at monthly periods and suggests that moonquake occurrence times exhibit multiple monthly periodicities corresponding to different forcing periods in the Earth-Moon system.

Arrival-time picks from stacks including our new events allow us to re-estimate deep moonquake source locations. There is considerable trade-off with velocity structure as noted in previous studies. Large discrepancies in location estimates for some clusters are due to the small number of clear seismic phase arrivals. In particular clusters for which there are no or few picks at stations 15 and/or 16 show large north-south scatter in location estimates.

The new events significantly enhance the lunar catalog for the eight largest near-side clusters. The assessment of location estimates suggests that two clusters – A1 and A18 – are well-located. The spectral characteristics of moonquake occurrence at these clusters are somewhat different, but both possess spectral peaks at the anomalistic and nodical months. The temporal and spatial constraints provided here can be used in future deterministic models of moonquake occurrence, and indicate that findings for better-located clusters may guide understanding of other deep moonquake source regions.

3.8 Acknowledgments

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press). The dissertation author was the primary researcher and author of the published work, and the co-authors directed and supervised the research which formed the basis for this chapter.

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4

The influence of Earth-Moon geometry on deep moonquake occurrence

4.1 Introduction

One defining characteristic of deep moonquakes, discovered early in the Apollo seismic experiment, is their tendency to occur with monthly periodicity, approximately 27 days apart (Ewing et al., 1971). This prompted early studies to investigate the relationship between tidal forcing and lunar seismic response (Toksöz et al., 1977; Lammlein, 1977; Cheng and Toksöz, 1978; Nakamura, 1978; Goult, 1979; Minshull and Goult, 1988). In these studies, tidal stresses generated in an elastic model of the Moon were linked to moonquake occurrence, but conclusions differed regarding fault geometry and relevant stress tensor terms.

Tidal stress models for moonquakes require several assumptions. The validity of an elastic model, the choice of failure criterion, and the existence (and orientation, if present) of a failure plane are all unknown. The above-referenced works have addressed different aspects of this problem. Some explore a variety of

models for lunar internal structure (Lammlein, 1977; Minshull and Goult, 1988); some perform grid searches for failure planes that maximize stress at the times of moonquakes (Goult, 1979; Minshull and Goult, 1988). An additional complication is that the choice of coordinate system varies, making comparisons among studies difficult.

In this paper we present an analysis of the geometry of the system, as an intermediate step in the process of computing tidal stress at the times of moonquakes. Variations in the position of the Earth with respect to the Moon control the gravitational tidal potential, which in turn is related to tidal stress. As a result, by considering the geometry of the Earth-Moon system we can explore any relationships between moonquake occurrence times and tidal forcing that are independent of the rheological response of the Moon. Of particular interest is whether there are coherent geographical patterns in lunar seismicity.

Previous studies have investigated geometric effects on deep moonquake occurrence (Lammlein et al., 1974; Lammlein, 1977; Nakamura, 1978). In the subsets of data analyzed (limited both in time span and in number of clusters as well as number of events within a cluster), the total number of deep moonquakes per nodical month (27.21 days) was found to be greater during those times when the eccentricity of the lunar orbit was greatest. This corresponds to times when the difference in Earth-Moon separation at perigee and apogee is maximized, as are the longitudinal librations. Both of these variations cycle through a 206-day periodicity due to the perturbing influence of the Sun on the lunar orbit.

While this alignment of event occurrence with a specific phase of the 206-day cycle of the lunar orbit might be true of overall deep moonquake activity, it may not always be true for individual moonquake clusters. Also, by binning event occurrence over the nodical month, resolution at the monthly timescale (and shorter) is lost. Since the Earth-Moon distance (and other parameters) varies almost as much over the course of one month as it does from month to month, it follows that moonquake occurrence may be sensitive to geometrical behavior

on the monthly time scale as well. It is this behavior that we are interested in investigating.

In addition to moonquake occurrence times, previous studies have also linked deep event amplitudes to the geometry of the Earth-Moon system. In general, large amplitude events were observed to coincide with times of maximum orbit eccentricity, that is, both the occurrence times and amplitudes were observed to depend on the same attribute of lunar motion (Lammlein et al., 1974; Lammlein, 1977; Nakamura, 1978).

Lammlein et al. (1974) investigated amplitudes with respect to the selenographic position of the sub-Earth point, considering events from a single cluster recorded at a single station. At individual clusters, amplitudes were observed to depend on specific values of the sub-Earth latitude and longitude. However, their approach was incomplete, since not all deep moonquakes are detected at all stations. Furthermore, the use of a single channel for amplitude estimations is questionable, since amplitudes are often inconsistent from channel to channel on a given station, and on a single channel over the duration of the experiment (Bulow et al., 2005; Nakamura et al., 1981). Finally, both thermal noise and variable instrument sensitivity (due to different operating modes) make consistent amplitude determination difficult, especially for low-signal events.

For these reasons, we examine only how deep moonquake occurrence times, not event amplitudes, are related to the selenographic position of the Earth. By focusing on a large number of individual deep moonquake source regions, we can ask whether global patterns in moonquake occurrence times and corresponding geometry exist. Exploration of multiple moonquake clusters also addresses a deficit in the current literature, as several iterations of event catalogs and cluster locations have been presented since the last major study of this topic (Nakamura et al., 1981, 2004; Nakamura, 2003, 2005; Bulow et al., 2005, 2007). In this paper, we present an analysis of 6 parameters that characterize Earth position and velocity, at the times of moonquakes from 51 clusters (Figure 4.1). The 6 parameters

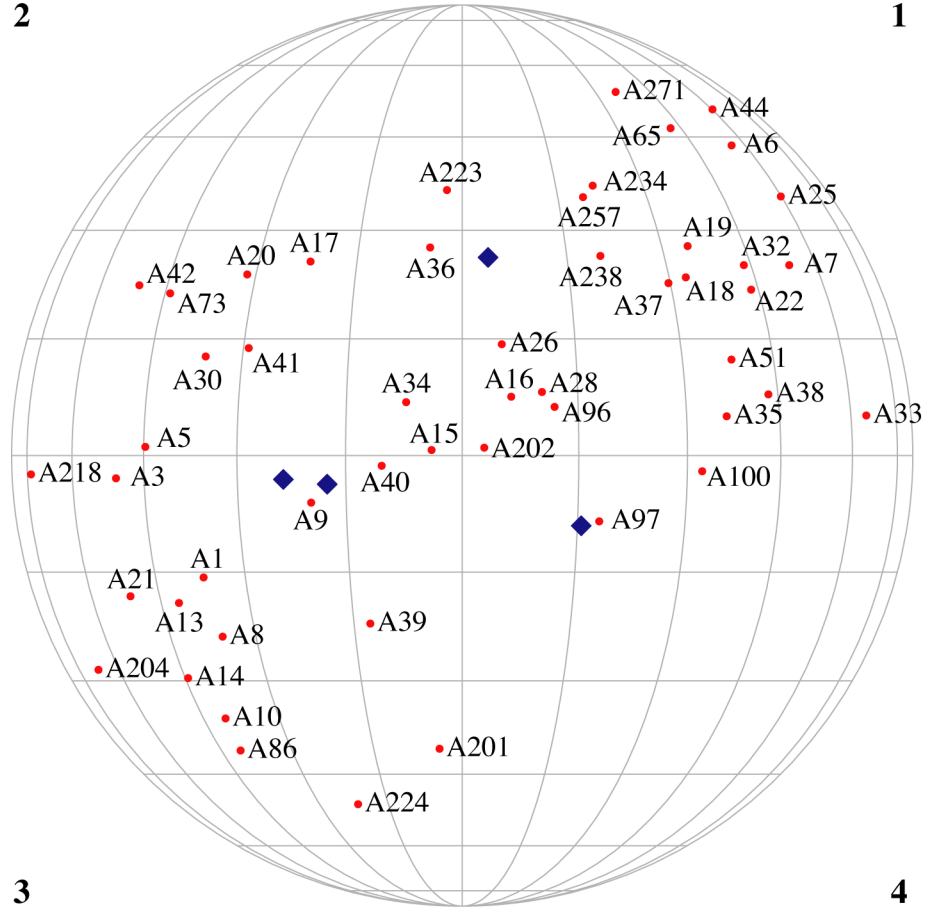


Figure 4.1 Deep moonquake cluster location map. Map of the nearside of the Moon showing the 51 clusters (red circles) analyzed in this study. Note A218 and A33 are farside clusters; their longitudes have been projected onto the nearside for plotting. The seismic stations (blue diamonds) are, from the West, Apollo 12, 14, 15, and 16. The NE/NW/SW/SE quadrants of the nearside are labeled 1/2/3/4 respectively, and the number of clusters in each quadrant is 23/11/15/2.

are: Earth-Moon distance, sub-Earth latitude, sub-Earth longitude, and the rates of change of these values. The 51 clusters we consider represent all located clusters (Nakamura, 2005) that include at least 35 events in the latest catalog (Nakamura et al., 2004).

No previous study has investigated the relationship between moonquake occurrence and rate of change of the Earth-Moon geometry. This is potentially important to tidal stress calculations, as the rate of change of the Earth-Moon

geometry controls the stress rates. As we shall see, for some clusters it can predict moonquake occurrence quite well. We combine this new result with a clear definition of our coordinate system, a thorough explanation of our revised orbital model, and a quantification of the extent to which deep event occurrence depends on the position of the Earth.

4.2 The lunar orbit

The position of the Moon with respect to the Earth is completely described by the following parameters (Kopal, 1969):

1. Earth-Moon distance: The distance varies partly as a consequence of the mean eccentricity of the Moon's orbit around Earth ($e = 0.0549$), so that the Moon is sometimes closer to the Earth, and sometimes farther away. The average time from perigee to perigee is 27.55 days (one anomalistic month). The eccentricity is also perturbed by the Sun.
2. Latitudinal optical libration: The sub-Earth latitude varies as a consequence of the inclination of the Moon's equatorial plane to the plane of its orbit around Earth. It is analogous to the way in which the seasons arise from Earth's orbit about the Sun. The sub-Earth latitude varies with a mean period of 27.21 days (one nodical month).
3. Longitudinal optical libration: The sub-Earth longitude varies as a consequence of the near-synchronous rotation and slightly non-uniform orbital revolution of the Moon, with the result that the Moon's rotation sometimes leads and sometimes lags its orbital position. The sub-Earth longitude varies with a mean period of 27.55 days (one anomalistic month).

The sub-Earth point is the instantaneous position where the line connecting the centers of the Earth and Moon intersects the lunar surface. We can track

the latitudinal and longitudinal librations of the Moon by following the trajectory of the sub-Earth point as it moves over the lunar surface. The extent to which the geometry of the Moon's orbit contributes to moonquake occurrence can be explored by plotting the following variables as functions of time and displaying them both at uniform $\frac{1}{2}$ -day time steps and at the times of moonquakes: (1) Earth-Moon distance, (2) Selenographic sub-Earth latitude, (3) Selenographic sub-Earth longitude, (4) Earth-Moon distance rate, (5) Sub-Earth latitude rate, (6) Sub-Earth longitude rate.

Because most deep moonquakes are known to originate from discrete source locations within the Moon, we treat moonquakes from each region separately. This will allow us to investigate global patterns of moonquake occurrence. In our selenographic coordinate system $(\hat{r}, \hat{\theta}, \hat{\phi})$, r is radial distance from the origin, θ is latitude measured North from the lunar equator, and ϕ is longitude measured East from the prime meridian.

We compute the Earth-Moon distance (r) and the selenographic latitude (θ) and longitude (ϕ) of the Earth from the JPL DE405 ephemerides (see Appendix 4.A), and examine how they (and their time derivatives) vary over the course of the Apollo seismic experiment (11/19/1969 – 9/30/1977).

4.3 Position of the Earth at the times of moonquakes

In Figure 4.2, we show the position and velocity of the Earth in terms of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ as functions of time over the Apollo experiment. Note that dr/dt and ϕ are correlated, and that r and $d\phi/dt$ are inversely correlated. This is a consequence of Kepler's second law (conservation of angular momentum): the specific angular momentum $r^2 d\phi/dt$ is a constant of motion.

We can investigate whether any of the six geometric variables influence

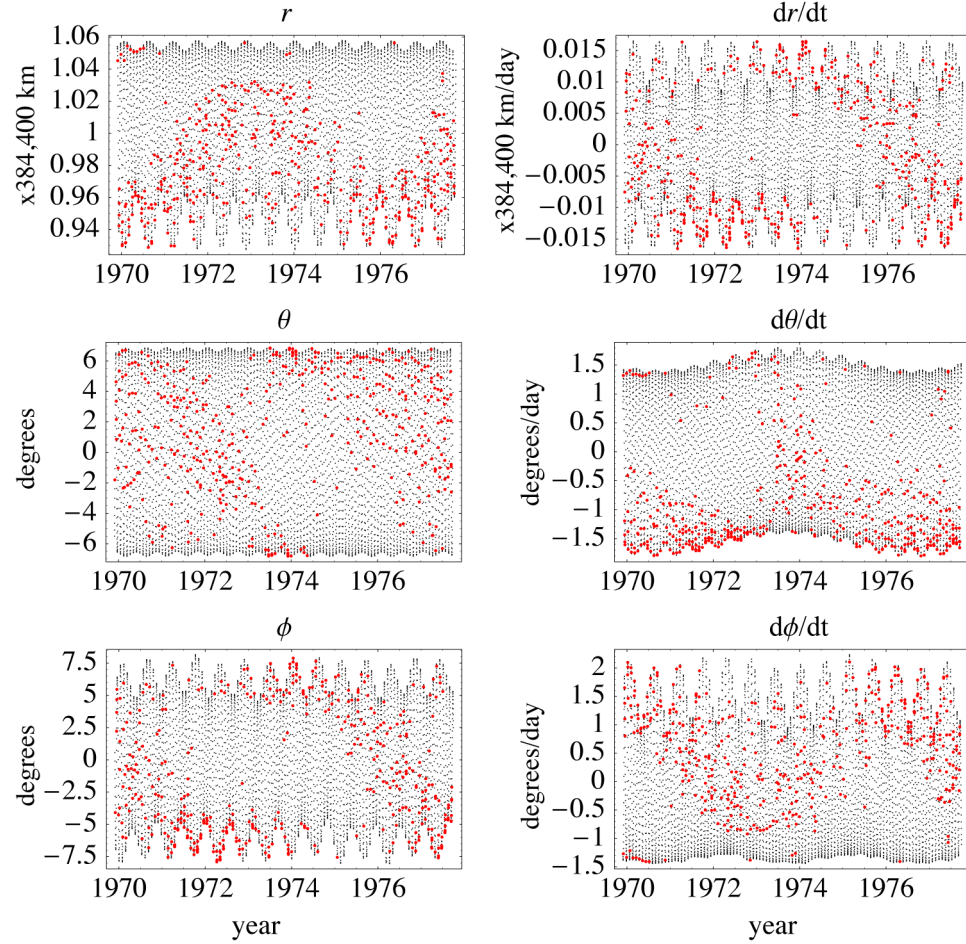


Figure 4.2 Geometrical parameters versus time. Geometrical parameters (r, θ, ϕ) and ($dr/dt, d\theta/dt, d\phi/dt$) versus time in years. Note (r) is normalized such that 1 equals the semi-major axis of the lunar orbit, 384,400 km. Small black dots are uniform $\frac{1}{2}$ -day time steps; red dots represent the times of A1 moonquakes. In addition to the monthly variation, note the 206-day modulation, due to the Sun's perturbations on the lunar orbit, and the longer 6-year modulation, due to the physical precession of perigee of the Moon's orbit.

moonquake occurrence by overlaying on such plots the event times for a particular deep source region. It is apparent from Figure 4.2 that A1 moonquakes occur more often when the Earth is closer to the Moon. If moonquake occurrence is indeed related to tidal forcing, then this makes sense since the gravitational influence of the Earth (and hence the tidal stress) is larger when the two bodies are closer together. But, stress also depends on the orientation of the two bodies. The values

of θ and ϕ at the times of A1 moonquakes at first glance prefer northern latitudes and extrema of longitude, but do not clearly favor one orientation.

We can further investigate whether particular Earth-Moon geometries are favorable to moonquake occurrence by computing histograms of the parameters (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ at the times of moonquakes over the course of the Apollo experiment (Figure 4.3a). If certain values of these parameters are important to moonquake occurrence at a given cluster, we would expect to see associated peaks in the histograms. However, two important issues must be addressed before continuing:

1) How well do such histograms represent what we are interested in measuring? For example, if moonquakes from a given cluster always occur, once per month, at minimum r for that month, that would be of interest. However, the distribution of r at moonquake times might not reflect this fact since the value of the minimum r varies from month to month. As a result, moonquakes occurring at local minima in r would be distributed over several histogram bins.

2) What are the distributions of the background values of r , θ , and ϕ , independent of moonquake occurrence? Moonquakes from a given cluster may prefer extrema of r , but that preference may be less significant when, due to the ellipticity of the lunar orbit, extrema of r are more/less highly populated over long periods of time (Figure 4.3b).

We can remedy these problems in two steps (see Appendix 4.B for details). First, because we are primarily interested in what happens on the monthly time scale, we demodulate the (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ time series. Demodulation removes the longer-period (206-day and 6-year) variations from the time series, with the result that extrema on the monthly time scale will always occur at constant values. In Figure 4.4a, we show the result of demodulating θ over the duration of the Apollo experiment and at the times of A1 moonquakes.

Second, we apply a transformation to make the distribution of the parameters evaluated at $\frac{1}{2}$ -day time steps uniform, in order to remove the effect of

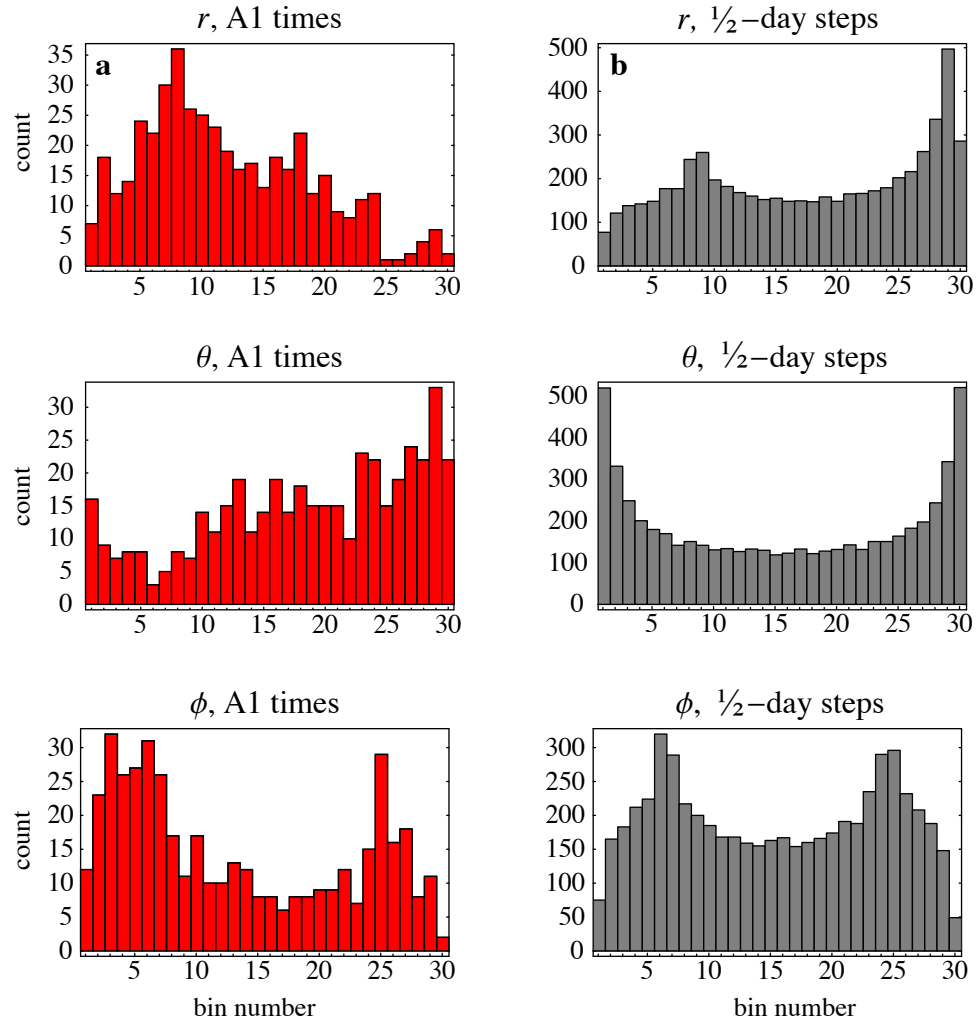


Figure 4.3 Histograms of (r, θ, ϕ) . (a) Histograms of (r, θ, ϕ) at A1 moonquake times (red, left) over the course of the Apollo experiment. (b) Histograms of (r, θ, ϕ) at uniform $\frac{1}{2}$ -day time steps (grey, right). There are 30 bins in each histogram which correspond to equi-spaced bins in (r, θ, ϕ) .

the non-uniform lunar orbital motion. This can be accomplished by taking the inverse sine of twice the demodulated values of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$, as shown for θ in Figure 4.4b.

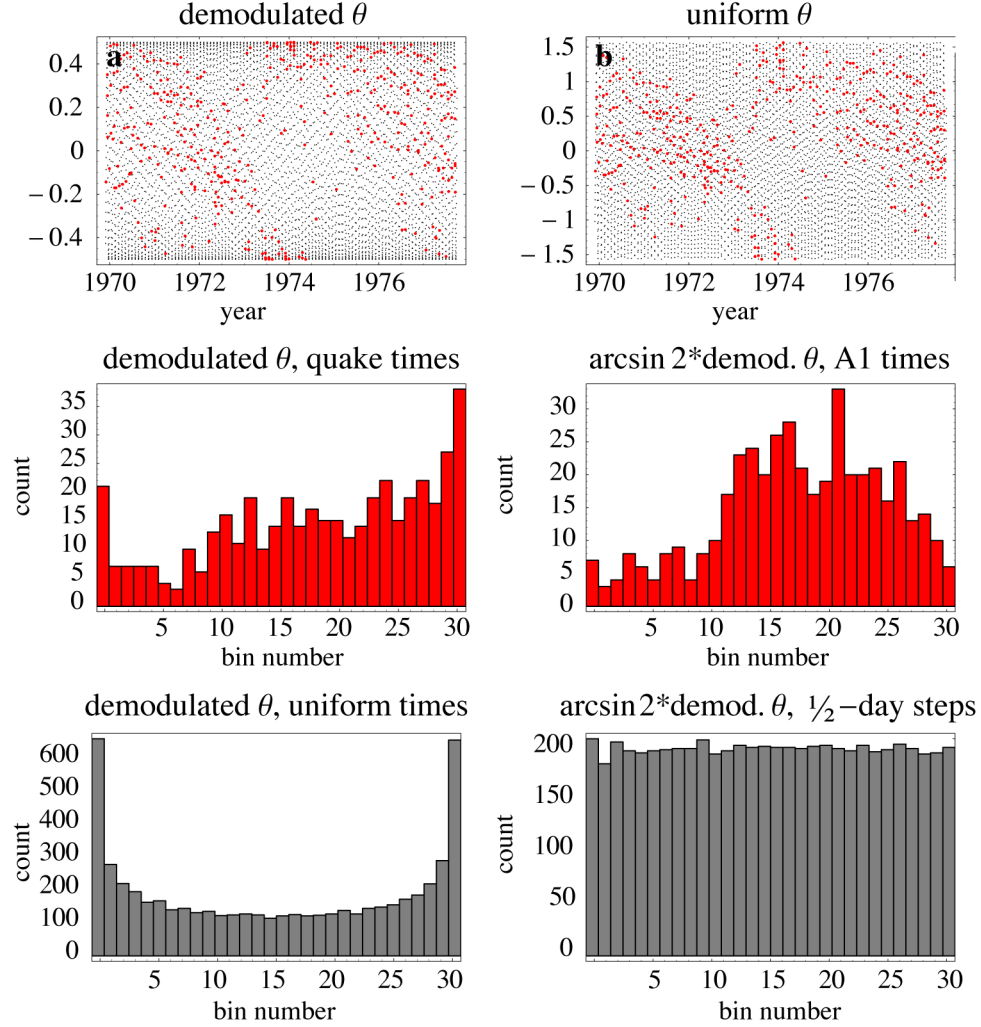


Figure 4.4 Demodulation example. (a) Time series and histograms for demodulated θ at A1 moonquake times and at uniform $\frac{1}{2}$ -day time steps. Note that at uniform time steps, the distribution of demodulated θ is non-uniform. (b) Time series and histograms for the inverse sine of twice the demodulated θ at A1 moonquake times and at uniform $\frac{1}{2}$ -day time steps. Note that at uniform time steps, the distribution of the inverse sine of twice the demodulated θ is essentially uniform. In these and all subsequent histograms, the 30 bins are equi-spaced for the transformed parameters (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$, and do not correspond to equi-spaced bins in the untransformed parameters.

4.4 Interpretation of histogram results

Our goal in the analysis of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ is twofold: first, we are interested in quantifying how well the times of moonquakes from

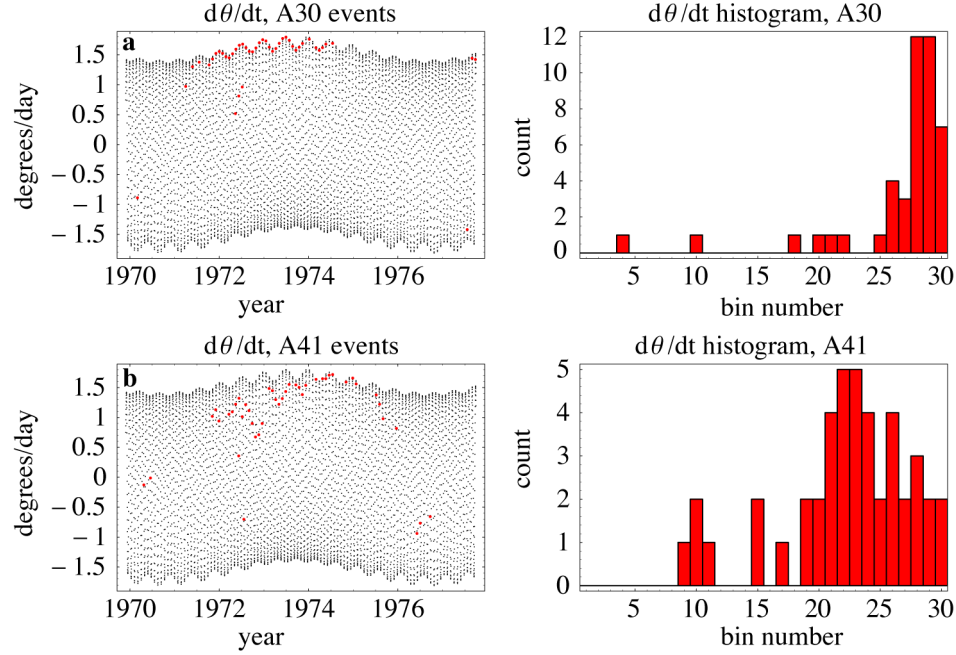


Figure 4.5 Example of large-skewness distribution. (a) Example of a large-skewness distribution ($d\theta/dt$ at the times of A30 moonquakes). On the left, $d\theta/dt$ is plotted with red dots at the times of A30 moonquakes. On the right is the histogram computed from that distribution following the method outlined in Section 3. (b) Same for nearby cluster A41.

individual clusters respond to Earth position (r, θ, ϕ) and rate of change of Earth position $(dr/dt, d\theta/dt, d\phi/dt)$. Second, we would like to know whether spatially nearby clusters respond in similar ways. If nearby clusters respond similarly to the position of the Earth (i.e. if failure occurs at similar times in the lunar orbit) then this suggests that physical properties governing the seismic response to tidal forcing do not vary strongly over cluster-to-cluster distances. If nearby clusters do not respond similarly to the geometrical parameters, then we know that local structure must be important to failure at individual clusters. To address these questions, we computed histograms using the method outlined in the previous section for 51 moonquake clusters (Figure 4.1).

We can identify clusters with potentially interesting behavior by computing the moments of the distributions of Earth position (r, θ, ϕ) and rate of change of Earth position $(dr/dt, d\theta/dt, d\phi/dt)$. We compute the mean ($\bar{x}$), variance, skew-

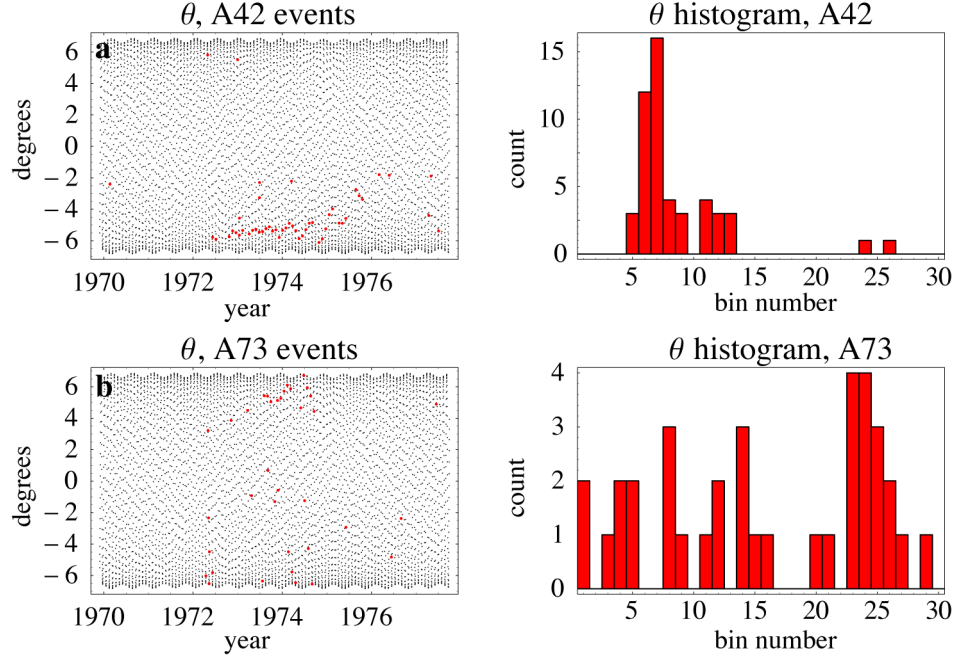


Figure 4.6 Example of large-kurtosis distribution. (a) Example of a large-kurtosis, small variance distribution (θ at the times of A42 moonquakes). (b) Same for nearby cluster A73.

ness, and kurtosis:

$$\text{mean } \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (4.1)$$

$$\text{variance} = \frac{\mu_2}{n-1} \quad (4.2)$$

$$\text{skewness} = \frac{\sqrt{n} \mu_3}{\mu_2^{\frac{3}{2}}} \quad (4.3)$$

$$\text{kurtosis} = \frac{n \mu_4}{\mu_2^2} \quad (4.4)$$

where μ_k is the moment $\sum_{i=1}^n (x_i - \bar{x})^k$. Among a given sample of deep moonquake clusters, histograms with comparatively large (absolute) skewness likely represent clusters that prefer extrema of the distribution in question. Histograms with comparatively small variance and/or large kurtosis can be used to identify clusters which favor a certain value in the distribution (not just extrema). Several examples from quadrant 2 of the Moon's near side are shown in Figures 4.5 through 4.7.

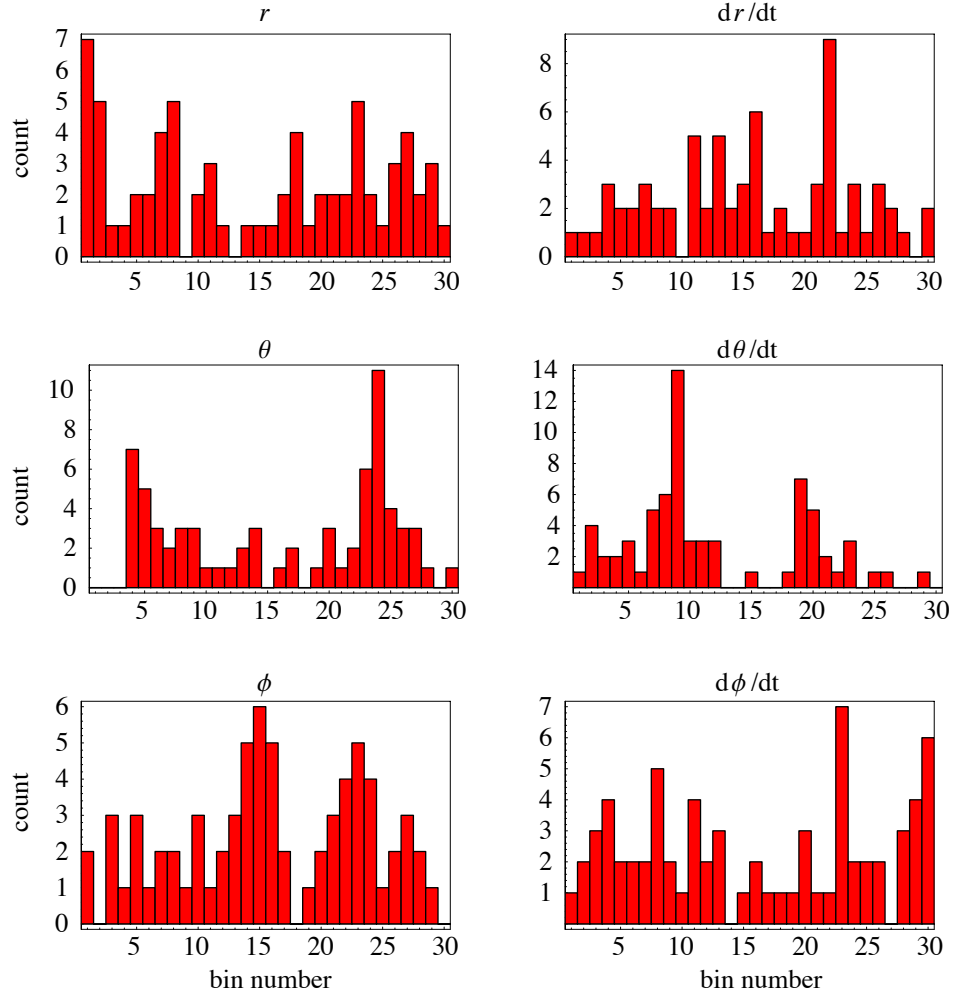


Figure 4.7 Example cluster with no favored geometry. Histograms of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ at the times of A35 moonquakes. This is an example of a cluster with no favored orbital state.

In Figure 4.5a, we show a cluster with a highly skewed distribution: $d\theta/dt$ at the times of A30 moonquakes. With the exception of a few outliers, A30 moonquakes occur almost exactly at times which are local maxima of $d\theta/dt$. For comparison, Figure 4.5b shows the distribution of $d\theta/dt$ for nearby cluster A41. While not as highly skewed, this distribution is similar to that of A30, and favors values near maximum $d\theta/dt$.

In Figure 4.6a, we show a cluster with a large-kurtosis distribution: θ at the times of A42 moonquakes. In this example, A42 moonquakes occur when

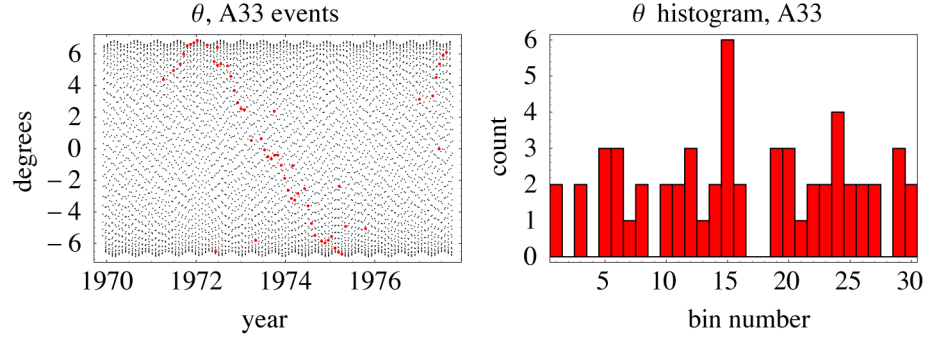


Figure 4.8 Example distribution with linear trend. Example distribution which displays a linear trend in θ at the times of A33 moonquakes. The histogram (computed using the method outlined in Section 4.3) does not reflect the non-random behavior of θ at the times of A33 moonquakes.

the sub-Earth latitude is near -5° . In Figure 4.6b, we show the θ distribution for nearby cluster A73. In contrast to the previous example (Figure 4.5), these two nearby clusters do not respond similarly to the same parameter (θ). The A73 moonquakes do not strongly prefer a single θ value.

There are also clusters that exhibit no favored orbital state, such as the distributions shown in Figure 4.7 for cluster A35. The times of occurrence of A35 moonquakes exhibit no significant correlation with any parameter of the position or velocity of the Earth. A limitation of our histogram analysis is that it cannot capture the behavior of distributions which possess linear trends in moonquake occurrence, as shown in Figure 4.8 for θ at the times of A33 moonquakes. Cases such as this which possess obvious systematic trends are potentially interesting, but because the values taken on by θ at the times of A33 moonquakes span the same range as the background distribution of θ , their counts will be spread over many bins. The resulting histogram has relatively low skewness and kurtosis estimates, grouping this behavior with truly uniform distributions in the present analysis.

To determine whether each cluster produces moonquakes at favored times in the orbital cycle, we tabulate the first four moments of each distribution for each cluster. Tables 4.1 through 4.6 list the mean, variance, skewness, and kurtosis of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ for all 51 clusters, arranged by quadrant. Along

Table 4.1 Moments of distributions, r .

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	-0.673	0.495	1.094	3.717	0
A7	25	53.2	1	-0.411	0.322	-0.414	2.254	0
A16	7.5	6.3	1	0.823	0.358	-1.64	5.205	0
A18	23.3	32.7	1	0.394	0.37	-0.34	3.174	0
A19	27.7	34.4	1	-0.789	0.136	-0.505	2.261	0
A22	21.6	43.6	1	-0.593	0.378	-0.283	1.807	0
A25	35.1	59.8	1	0.124	0.159	0.567	3.189	0
A26	14.3	5.2	1	0.157	0.574	-0.368	2.133	0.147
A28	8.1	10.3	1	1.069	0.081	-0.054	2.146	0
A32	25	43.6	1	0.764	0.294	-1.549	7.064	0
A33	5.1	115.8	1	1.215	0.333	-3.324	13.644	0
A35	5	36.1	1	-0.095	1.015	0.004	1.565	0.274
A37	22.5	29.7	1	-0.2	0.758	-0.143	1.623	0.616
A38	7.8	43.3	1	-0.038	0.435	-0.226	2.579	0.029
A44	50.2	60.2	1	-0.247	0.403	0.815	2.942	0
A51	12.3	37.7	1	0.913	0.306	-1.377	5.927	0
A65	46.6	42.3	1	-0.631	0.226	0.372	4.608	0
A96	6.2	11.9	1	0.283	1.129	-0.489	1.834	0.04
A202	1	2.8	1	-0.602	0.365	0.578	2.649	0
A234	36.8	21.2	1	0.495	0.487	-0.882	3.514	0
A238	26.3	20	1	-0.101	0.382	0.093	2.487	0.131
A257	35	19.1	1	-0.203	0.652	0.406	1.974	0.226
A271	53.8	35.2	1	0.315	0.745	-0.237	1.755	0.202
A5	1.1	-44.7	2	-0.899	0.27	1.984	8.869	0
A15	0.7	-3.9	2	-1.197	0.28	3.677	17.656	0
A17	25.5	-21.9	2	0.941	0.222	-0.551	2.018	0
A20	23.7	-31.4	2	-0.024	0.934	0.035	1.616	0.154
A30	12.7	-35.7	2	-0.796	0.265	0.07	1.771	0
A34	6.8	-7.2	2	0.277	0.251	-0.115	2.32	0.006
A36	27.5	-4.6	2	-0.208	0.263	1.107	4.103	0.004
A41	13.8	-29.2	2	-0.961	0.219	2.669	14.631	0
A42	22.2	-50.7	2	-0.162	0.918	0.179	1.731	0.776
A73	21.1	-44	2	0.257	0.827	-0.24	1.931	0.307
A223	36.1	-2.4	2	-0.729	0.219	2.132	8.457	0
A1	-15.7	-36.6	3	-0.52	0.418	0.571	3.068	0
A3	-2.9	-50.3	3	-0.47	1.082	0.673	1.887	0
A8	-23.7	-35.5	3	0.641	0.652	-1.081	3.102	0
A9	-6	-19.7	3	0.308	0.389	0.06	2.32	0
A10	-35.7	-40.3	3	0.692	0.584	-1.134	3.537	0
A13	-19.1	-41.7	3	0.402	0.289	-0.601	3.89	0
A14	-29.6	-44.4	3	-0.362	0.249	0.4	3.081	0
A21	-18.2	-50.8	3	0.153	0.408	-0.574	3.173	0.001
A39	-21.9	-12.7	3	0.675	0.677	-1.546	3.962	0
A40	-1.3	-10.3	3	-1.018	0.23	3.374	17.286	0
A86	-40.9	-40.6	3	-0.315	0.649	0.675	2.505	0.026
A201	-40.6	-3.8	3	-0.213	0.425	0.455	2.568	0.003
A204	-28.4	-66.6	3	0.346	0.25	0.778	3.514	0
A218	-2.4	-73.3	3	0.194	0.598	-0.759	2.773	0.001
A224	-50.7	-21.4	3	-0.309	0.363	-0.195	1.599	0
A97	-8.4	17.9	4	0.35	1.058	-0.583	1.78	0.006
A100	-2	32.2	4	0.321	0.708	-0.045	1.84	0.027

[†] Based on the K-S statistic.

Table 4.2 Moments of distributions, θ .

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	0.556	0.432	-1.062	3.783	0
A7	25	53.2	1	0.808	0.241	-1.165	4.96	0
A16	7.5	6.3	1	0.515	0.49	-0.366	2.498	0
A18	23.3	32.7	1	0.53	0.653	-1.059	3.032	0
A19	27.7	34.4	1	-0.442	0.476	-0.03	1.698	0.003
A22	21.6	43.6	1	0.969	0.056	-0.111	2.145	0
A25	35.1	59.8	1	0.019	0.703	0.295	1.96	0.336
A26	14.3	5.2	1	0.358	0.625	-0.66	2.396	0.008
A28	8.1	10.3	1	0.081	0.7	-0.211	2.147	0.569
A32	25	43.6	1	0.359	0.744	-0.199	1.446	0.027
A33	5.1	115.8	1	0.094	0.758	-0.087	1.919	0.93
A35	5	36.1	1	0.104	0.794	-0.23	1.462	0.095
A37	22.5	29.7	1	-0.125	0.24	-1.156	3.622	0
A38	7.8	43.3	1	0.388	0.663	-0.938	2.469	0
A44	50.2	60.2	1	-0.652	0.567	1.171	3.569	0
A51	12.3	37.7	1	-0.212	0.306	-0.755	2.717	0
A65	46.6	42.3	1	0.932	0.175	-1.121	5.026	0
A96	6.2	11.9	1	0.332	0.287	0.039	2.509	0
A202	1	2.8	1	0.105	0.681	-0.921	2.225	0.004
A234	36.8	21.2	1	0.323	0.312	-0.795	3.112	0.004
A238	26.3	20	1	0.07	0.158	-0.741	2.609	0.008
A257	35	19.1	1	0.103	0.29	-0.513	2.934	0.015
A271	53.8	35.2	1	0.113	0.545	-0.152	2.519	0.353
A5	1.1	-44.7	2	0.295	0.463	-1.189	3.387	0
A15	0.7	-3.9	2	-0.184	0.603	0.056	2.234	0.099
A17	25.5	-21.9	2	0.835	0.059	-2.429	10.624	0
A20	23.7	-31.4	2	0.023	0.394	-0.362	2.785	0
A30	12.7	-35.7	2	-0.258	0.121	0.067	7.485	0
A34	6.8	-7.2	2	-0.126	0.245	-0.691	3.065	0.004
A36	27.5	-4.6	2	0.201	0.232	-0.265	3.74	0.001
A41	13.8	-29.2	2	-0.22	0.647	0.758	2.338	0.056
A42	22.2	-50.7	2	-0.735	0.184	2.741	11.393	0
A73	21.1	-44	2	0.047	0.836	-0.271	1.656	0.393
A223	36.1	-2.4	2	-0.047	0.721	-0.039	1.919	0.979
A1	-15.7	-36.6	3	0.24	0.519	-0.411	2.618	0
A3	-2.9	-50.3	3	0.334	0.457	-0.957	3.333	0.002
A8	-23.7	-35.5	3	0.199	0.477	0.032	2.166	0
A9	-6	-19.7	3	-0.35	0.205	1.303	4.554	0
A10	-35.7	-40.3	3	-0.011	0.651	0.429	2.046	0.003
A13	-19.1	-41.7	3	0.389	0.428	0.147	1.736	0
A14	-29.6	-44.4	3	-0.348	0.654	0.332	2.02	0
A21	-18.2	-50.8	3	-0.056	0.566	-0.29	2.176	0.068
A39	-21.9	-12.7	3	0.301	0.757	-0.568	2.109	0
A40	-1.3	-10.3	3	-0.513	0.668	1.106	3.223	0
A86	-40.9	-40.6	3	0.83	0.253	-1.924	6.777	0
A201	-40.6	-3.8	3	-0.348	0.645	0.472	2.118	0.008
A204	-28.4	-66.6	3	0.321	0.546	-0.377	2.691	0
A218	-2.4	-73.3	3	0.536	0.551	-0.762	2.573	0
A224	-50.7	-21.4	3	-0.045	1.118	0.042	1.431	0.423
A97	-8.4	17.9	4	0.267	0.231	0.077	3.907	0
A100	-2	32.2	4	0.16	0.556	-0.205	1.843	0.076

[†] Based on the K-S statistic.

Table 4.3 Moments of distributions, ϕ .

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	-0.489	0.438	0.522	2.587	0
A7	25	53.2	1	-0.979	0.296	1.515	5.515	0
A16	7.5	6.3	1	0.505	0.254	-0.803	6.305	0
A18	23.3	32.7	1	-0.933	0.286	1.001	3.878	0
A19	27.7	34.4	1	-0.806	0.157	0.779	2.8	0
A22	21.6	43.6	1	-0.866	0.339	0.675	1.957	0
A25	35.1	59.8	1	0.684	1.094	-1.283	2.881	0
A26	14.3	5.2	1	-0.478	0.753	0.556	1.916	0.002
A28	8.1	10.3	1	0.449	0.129	-1.232	5.737	0
A32	25	43.6	1	-0.01	0.676	-0.265	1.936	0.517
A33	5.1	115.8	1	-0.101	0.085	-0.389	6.065	0
A35	5	36.1	1	0.051	0.634	-0.197	2.043	0.486
A37	22.5	29.7	1	-0.744	0.359	0.514	2.306	0
A38	7.8	43.3	1	-0.699	0.766	1.28	3.563	0
A44	50.2	60.2	1	-0.725	0.564	1.563	4.693	0
A51	12.3	37.7	1	-0.508	0.265	-0.191	1.888	0
A65	46.6	42.3	1	-0.849	0.237	1.248	4.326	0
A96	6.2	11.9	1	-0.457	0.307	0.35	2.534	0
A202	1	2.8	1	0.276	0.907	0.086	1.349	0.095
A234	36.8	21.2	1	-0.726	0.328	1.409	6.635	0
A238	26.3	20	1	-1.03	0.168	1.278	5.015	0
A257	35	19.1	1	-0.826	0.138	0.221	2.609	0
A271	53.8	35.2	1	-0.61	0.404	0.684	2.642	0.001
A5	1.1	-44.7	2	0.166	0.48	-0.808	2.716	0.012
A15	0.7	-3.9	2	-0.088	0.147	-0.139	2.537	0
A17	25.5	-21.9	2	-0.224	0.526	-0.066	2.263	0.026
A20	23.7	-31.4	2	-0.081	0.655	0.077	1.88	0.364
A30	12.7	-35.7	2	0.478	0.701	-0.341	1.984	0.023
A34	6.8	-7.2	2	1.063	0.094	-0.712	3.943	0
A36	27.5	-4.6	2	-1.054	0.229	2.46	9.499	0
A41	13.8	-29.2	2	-0.294	0.348	0.447	2.086	0.029
A42	22.2	-50.7	2	-0.596	0.381	0.613	3.575	0
A73	21.1	-44	2	0.27	0.719	-0.418	2.042	0.205
A223	36.1	-2.4	2	-0.601	0.276	2.393	8.369	0
A1	-15.7	-36.6	3	-0.284	0.906	0.341	1.766	0
A3	-2.9	-50.3	3	-0.099	0.421	-0.724	2.522	0.005
A8	-23.7	-35.5	3	-0.107	0.517	0.12	2.31	0
A9	-6	-19.7	3	0.544	0.869	-1.004	2.67	0
A10	-35.7	-40.3	3	0.053	0.603	-0.063	2.31	0.008
A13	-19.1	-41.7	3	-0.872	0.439	1.808	6.881	0
A14	-29.6	-44.4	3	-0.923	0.363	2.255	8.311	0
A21	-18.2	-50.8	3	-1.009	0.19	1.036	3.637	0
A39	-21.9	-12.7	3	0.367	0.208	-0.768	3.36	0
A40	-1.3	-10.3	3	-0.362	0.17	0.628	2.784	0.001
A86	-40.9	-40.6	3	-0.764	0.28	0.495	2.595	0
A201	-40.6	-3.8	3	0.917	0.287	-1.847	7.62	0
A204	-28.4	-66.6	3	-1.077	0.25	2.278	10.084	0
A218	-2.4	-73.3	3	-0.709	0.478	0.883	3.075	0
A224	-50.7	-21.4	3	-0.45	0.961	0.41	1.402	0
A97	-8.4	17.9	4	-0.156	0.449	0.341	2.551	0.077
A100	-2	32.2	4	-0.409	0.735	0.575	2.22	0.004

[†] Based on the K-S statistic.

Table 4.4 Moments of distributions, dr/dt .

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	-0.517	0.458	0.515	2.481	0
A7	25	53.2	1	-1.013	0.31	1.626	6.2	0
A16	7.5	6.3	1	0.481	0.246	-0.783	5.684	0
A18	23.3	32.7	1	-0.936	0.25	1.156	4.885	0
A19	27.7	34.4	1	-0.827	0.164	0.58	2.374	0
A22	21.6	43.6	1	-0.916	0.359	0.748	2.028	0
A25	35.1	59.8	1	0.661	1.125	-1.279	2.867	0
A26	14.3	5.2	1	-0.494	0.706	0.582	1.92	0
A28	8.1	10.3	1	0.361	0.13	-0.616	3.537	0
A32	25	43.6	1	-0.06	0.607	-0.164	1.872	0.517
A33	5.1	115.8	1	-0.126	0.112	-0.129	3.56	0
A35	5	36.1	1	0.02	0.626	-0.068	2.025	0.615
A37	22.5	29.7	1	-0.736	0.33	0.379	2.13	0
A38	7.8	43.3	1	-0.697	0.798	1.34	3.585	0
A44	50.2	60.2	1	-0.775	0.549	1.615	4.825	0
A51	12.3	37.7	1	-0.521	0.27	-0.219	2.002	0
A65	46.6	42.3	1	-0.934	0.26	1.014	3.246	0
A96	6.2	11.9	1	-0.478	0.29	0.33	2.667	0
A202	1	2.8	1	0.233	0.901	0.077	1.427	0.236
A234	36.8	21.2	1	-0.738	0.321	1.229	5.779	0
A238	26.3	20	1	-1.059	0.161	1.579	6.052	0
A257	35	19.1	1	-0.841	0.151	0.081	2.57	0
A271	53.8	35.2	1	-0.625	0.355	0.716	2.769	0
A5	1.1	-44.7	2	0.195	0.507	-0.748	2.517	0.017
A15	0.7	-3.9	2	-0.116	0.141	-0.261	2.215	0
A17	25.5	-21.9	2	-0.255	0.511	0.083	2.419	0.007
A20	23.7	-31.4	2	-0.087	0.658	0.101	1.863	0.267
A30	12.7	-35.7	2	0.46	0.712	-0.366	1.996	0.055
A34	6.8	-7.2	2	1.052	0.106	-0.7	3.902	0
A36	27.5	-4.6	2	-1.071	0.225	2.264	8.666	0
A41	13.8	-29.2	2	-0.31	0.356	0.581	2.26	0.019
A42	22.2	-50.7	2	-0.626	0.361	0.795	4.115	0
A73	21.1	-44	2	0.276	0.77	-0.485	2.165	0.307
A223	36.1	-2.4	2	-0.634	0.285	2.353	8.681	0
A1	-15.7	-36.6	3	-0.276	0.941	0.359	1.746	0
A3	-2.9	-50.3	3	-0.097	0.445	-0.558	2.29	0.021
A8	-23.7	-35.5	3	-0.129	0.534	0.18	2.35	0
A9	-6	-19.7	3	0.539	0.864	-1	2.663	0
A10	-35.7	-40.3	3	0.024	0.575	0.072	2.372	0.026
A13	-19.1	-41.7	3	-0.842	0.436	1.878	7.165	0
A14	-29.6	-44.4	3	-0.94	0.346	2.458	9.169	0
A21	-18.2	-50.8	3	-1.004	0.196	1.124	4.207	0
A39	-21.9	-12.7	3	0.373	0.208	-0.879	3.527	0
A40	-1.3	-10.3	3	-0.407	0.171	0.499	2.416	0
A86	-40.9	-40.6	3	-0.815	0.278	0.712	2.952	0
A201	-40.6	-3.8	3	0.933	0.285	-1.784	6.646	0
A204	-28.4	-66.6	3	-1.04	0.247	2.239	9.809	0
A218	-2.4	-73.3	3	-0.728	0.483	0.927	3.067	0
A224	-50.7	-21.4	3	-0.435	0.965	0.4	1.369	0
A97	-8.4	17.9	4	-0.16	0.462	0.326	2.648	0.05
A100	-2	32.2	4	-0.449	0.748	0.617	2.392	0.002

[†] Based on the K-S statistic.

Table 4.5 Moments of distributions, $d\theta/dt$.

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	-0.523	0.582	1.053	3.583	0
A7	25	53.2	1	-0.391	0.503	0.894	3.173	0
A16	7.5	6.3	1	0.488	0.718	-0.67	2.331	0.003
A18	23.3	32.7	1	-0.534	0.347	1.174	5.075	0
A19	27.7	34.4	1	-0.826	0.343	0.972	3.188	0
A22	21.6	43.6	1	-0.616	0.056	-0.052	2.13	0
A25	35.1	59.8	1	0.712	0.383	-0.981	3.343	0
A26	14.3	5.2	1	-0.224	0.792	0.482	2.015	0.031
A28	8.1	10.3	1	0.343	0.887	-0.229	1.583	0.049
A32	25	43.6	1	0.271	0.688	0.094	1.634	0.093
A33	5.1	115.8	1	-0.355	0.784	0.394	1.974	0.013
A35	5	36.1	1	-0.382	0.529	0.522	2.209	0
A37	22.5	29.7	1	-1.232	0.132	1.658	5.092	0
A38	7.8	43.3	1	-0.507	0.429	0.907	3.35	0
A44	50.2	60.2	1	0.132	0.594	-0.802	2.661	0.01
A51	12.3	37.7	1	-0.556	1.174	0.92	2.235	0
A65	46.6	42.3	1	-0.371	0.394	1.076	3.874	0.004
A96	6.2	11.9	1	0.989	0.309	-1.647	5.134	0
A202	1	2.8	1	-0.694	0.318	1.659	5.18	0
A234	36.8	21.2	1	-0.964	0.21	2.078	9.333	0
A238	26.3	20	1	-1.246	0.049	0.384	2.472	0
A257	35	19.1	1	-1.15	0.13	1.017	4.72	0
A271	53.8	35.2	1	0.699	0.698	-1.107	3.258	0
A5	1.1	-44.7	2	-0.583	0.581	1.296	3.538	0
A15	0.7	-3.9	2	0.226	1.039	-0.281	1.638	0.124
A17	25.5	-21.9	2	-0.74	0.044	-1.84	7.981	0
A20	23.7	-31.4	2	-0.122	1.254	0.217	1.341	0
A30	12.7	-35.7	2	1.167	0.283	-3.033	12.639	0
A34	6.8	-7.2	2	0.789	0.966	-1.169	2.702	0
A36	27.5	-4.6	2	-1.15	0.154	2.037	8.316	0
A41	13.8	-29.2	2	0.725	0.306	-0.878	3.392	0
A42	22.2	-50.7	2	0.596	0.257	-2.224	8.656	0
A73	21.1	-44	2	-0.537	0.459	0.698	2.803	0
A223	36.1	-2.4	2	-0.094	0.962	0.135	1.698	0.654
A1	-15.7	-36.6	3	-0.709	0.591	1.263	3.922	0
A3	-2.9	-50.3	3	-0.731	0.388	1.571	4.783	0
A8	-23.7	-35.5	3	0.253	1.07	-0.231	1.458	0
A9	-6	-19.7	3	1.033	0.114	-2.213	15.847	0
A10	-35.7	-40.3	3	0.602	0.601	-0.908	2.913	0
A13	-19.1	-41.7	3	0.414	0.958	-0.387	1.571	0
A14	-29.6	-44.4	3	-0.596	0.513	0.857	3.122	0
A21	-18.2	-50.8	3	-0.88	0.335	1.484	5.971	0
A39	-21.9	-12.7	3	0.444	0.468	-1.044	3.206	0
A40	-1.3	-10.3	3	0.502	0.4	-0.656	3.009	0.001
A86	-40.9	-40.6	3	-0.447	0.355	1.631	5.929	0
A201	-40.6	-3.8	3	0.444	0.62	-0.558	2.274	0
A204	-28.4	-66.6	3	-0.488	0.814	0.789	2.384	0
A218	-2.4	-73.3	3	-0.161	0.732	0.466	2.095	0.031
A224	-50.7	-21.4	3	-0.105	0.503	-0.175	1.958	0.185
A97	-8.4	17.9	4	0.254	1.491	-0.568	1.557	0.002
A100	-2	32.2	4	-0.119	0.977	0.04	1.486	0.213

[†] Based on the K-S statistic.

Table 4.6 Moments of distributions, $d\phi/dt$.

cluster	lat.	lon.	quad.	mean	variance	skewness	kurtosis	prob. uniform [†]
A6	43.5	55.5	1	0.673	0.497	-1.12	3.742	0
A7	25	53.2	1	0.423	0.313	0.408	2.219	0
A16	7.5	6.3	1	-0.828	0.356	1.603	5.168	0
A18	23.3	32.7	1	-0.399	0.367	0.384	3.087	0
A19	27.7	34.4	1	0.791	0.141	0.549	2.061	0
A22	21.6	43.6	1	0.589	0.38	0.188	1.847	0
A25	35.1	59.8	1	-0.122	0.154	-0.427	2.998	0
A26	14.3	5.2	1	-0.171	0.59	0.423	2.099	0.114
A28	8.1	10.3	1	-1.082	0.09	0.115	2.03	0
A32	25	43.6	1	-0.768	0.3	1.615	7.298	0
A33	5.1	115.8	1	-1.2	0.323	3.29	13.513	0
A35	5	36.1	1	0.08	0.991	0.029	1.58	0.426
A37	22.5	29.7	1	0.203	0.782	0.191	1.596	0.387
A38	7.8	43.3	1	0.029	0.437	0.3	2.415	0.069
A44	50.2	60.2	1	0.247	0.409	-0.814	2.819	0
A51	12.3	37.7	1	-0.899	0.303	1.396	6.276	0
A65	46.6	42.3	1	0.63	0.224	-0.517	4.709	0
A96	6.2	11.9	1	-0.268	1.138	0.507	1.872	0.033
A202	1	2.8	1	0.596	0.372	-0.494	2.505	0
A234	36.8	21.2	1	-0.503	0.478	0.955	3.626	0
A238	26.3	20	1	0.114	0.376	0.058	2.416	0.048
A257	35	19.1	1	0.21	0.649	-0.363	1.898	0.226
A271	53.8	35.2	1	-0.323	0.707	0.292	1.772	0.179
A5	1.1	-44.7	2	0.906	0.277	-2.04	9.213	0
A15	0.7	-3.9	2	1.195	0.291	-3.709	17.921	0
A17	25.5	-21.9	2	-0.957	0.22	0.541	2.1	0
A20	23.7	-31.4	2	0.025	0.933	-0.001	1.629	0.419
A30	12.7	-35.7	2	0.791	0.293	-0.094	1.657	0
A34	6.8	-7.2	2	-0.3	0.248	0.218	2.371	0.006
A36	27.5	-4.6	2	0.189	0.276	-0.981	3.728	0.009
A41	13.8	-29.2	2	0.959	0.217	-2.603	14.04	0
A42	22.2	-50.7	2	0.158	0.914	-0.184	1.68	0.62
A73	21.1	-44	2	-0.251	0.803	0.218	1.946	0.27
A223	36.1	-2.4	2	0.725	0.218	-1.994	7.969	0
A1	-15.7	-36.6	3	0.523	0.42	-0.526	2.921	0
A3	-2.9	-50.3	3	0.468	1.066	-0.631	1.813	0
A8	-23.7	-35.5	3	-0.63	0.64	1.096	3.133	0
A9	-6	-19.7	3	-0.311	0.375	-0.025	2.431	0
A10	-35.7	-40.3	3	-0.69	0.583	1.117	3.527	0
A13	-19.1	-41.7	3	-0.396	0.28	0.643	4.05	0
A14	-29.6	-44.4	3	0.369	0.247	-0.383	3.08	0
A21	-18.2	-50.8	3	-0.149	0.409	0.642	3.279	0.003
A39	-21.9	-12.7	3	-0.675	0.684	1.592	4.081	0
A40	-1.3	-10.3	3	1.022	0.23	-3.576	18.643	0
A86	-40.9	-40.6	3	0.314	0.638	-0.719	2.558	0.038
A201	-40.6	-3.8	3	0.212	0.426	-0.513	2.675	0.004
A204	-28.4	-66.6	3	-0.361	0.253	-0.716	3.63	0
A218	-2.4	-73.3	3	-0.208	0.593	0.77	2.74	0.001
A224	-50.7	-21.4	3	0.312	0.36	0.164	1.672	0
A97	-8.4	17.9	4	-0.35	1.069	0.566	1.788	0.006
A100	-2	32.2	4	-0.319	0.716	0.093	1.841	0.027

[†] Based on the K-S statistic.

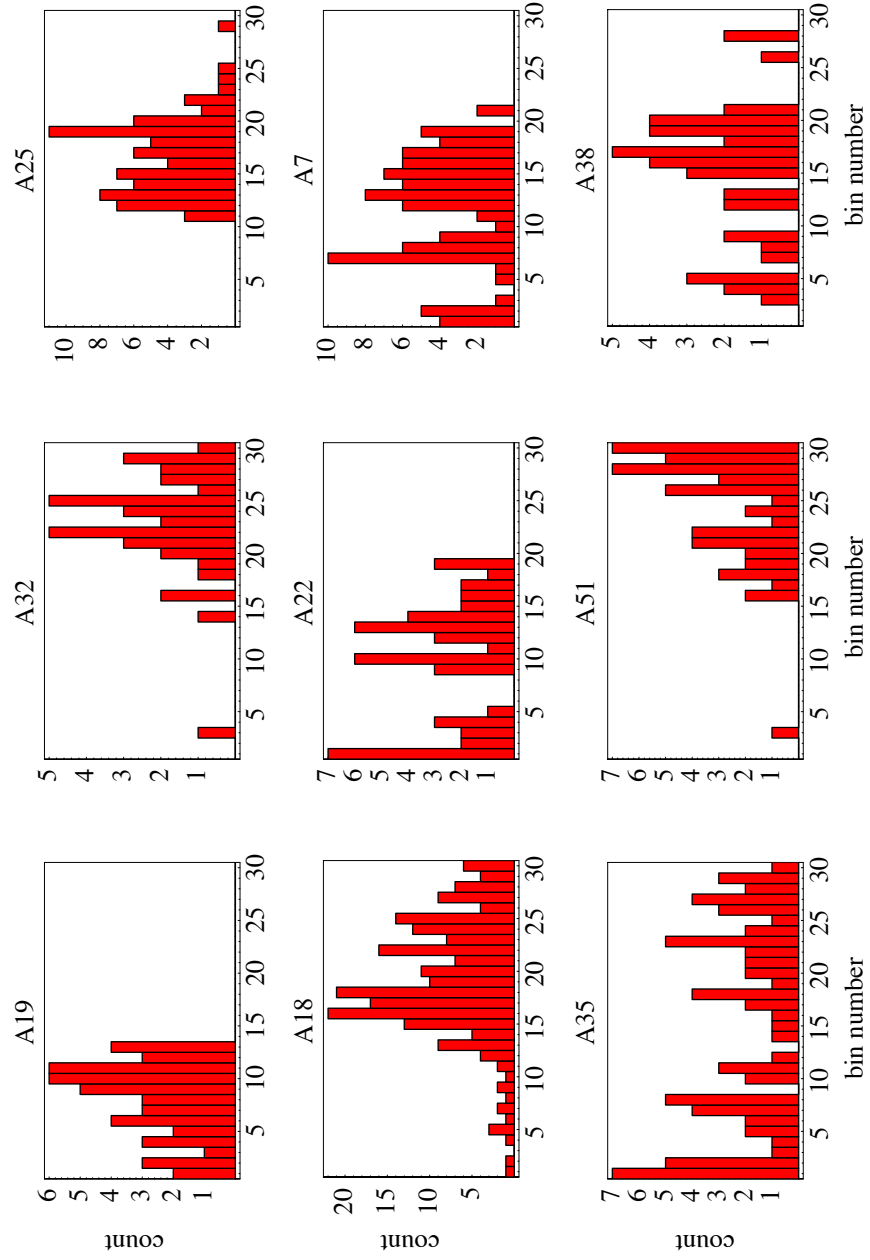


Figure 4.9 Normalized histograms of r for 9 clusters in quadrant 1.

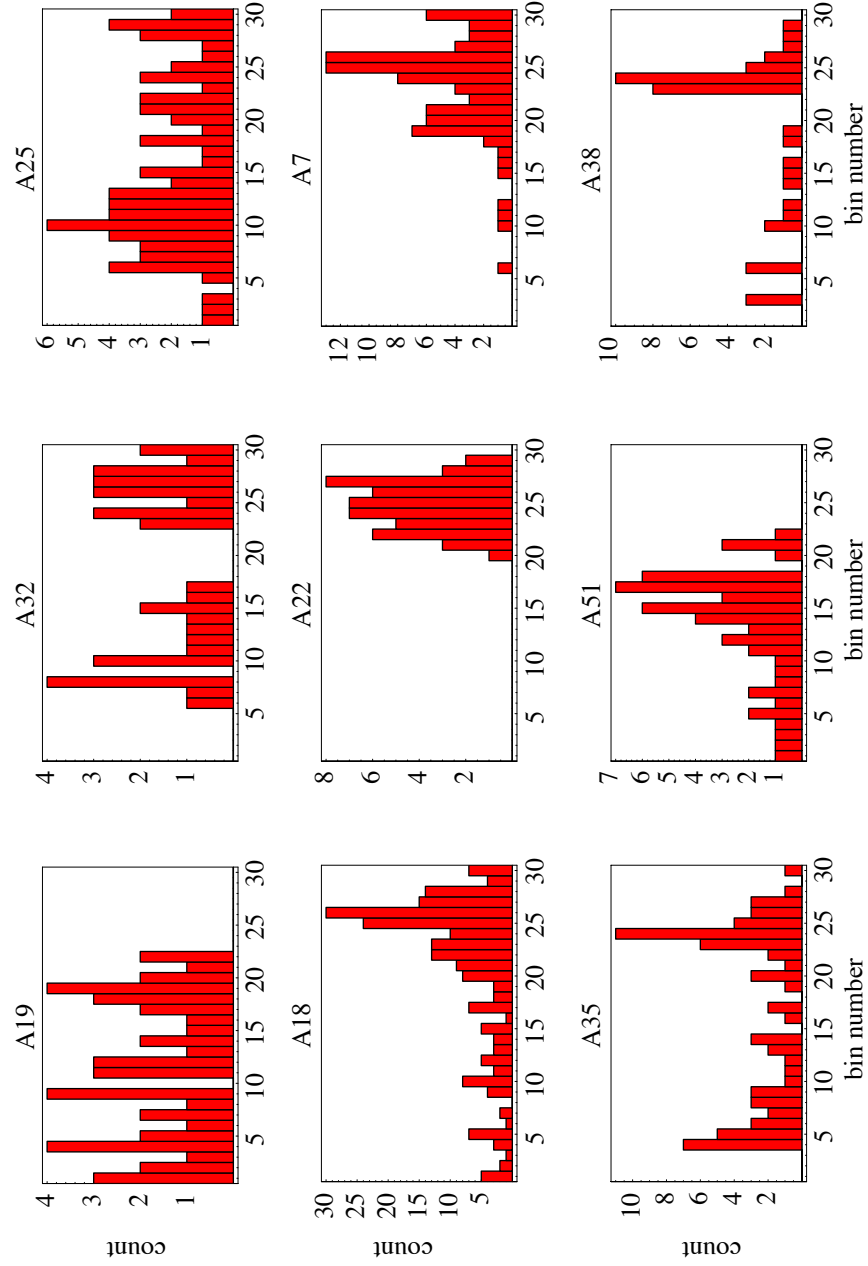


Figure 4.10 Normalized histograms of θ for 9 clusters in quadrant 1.

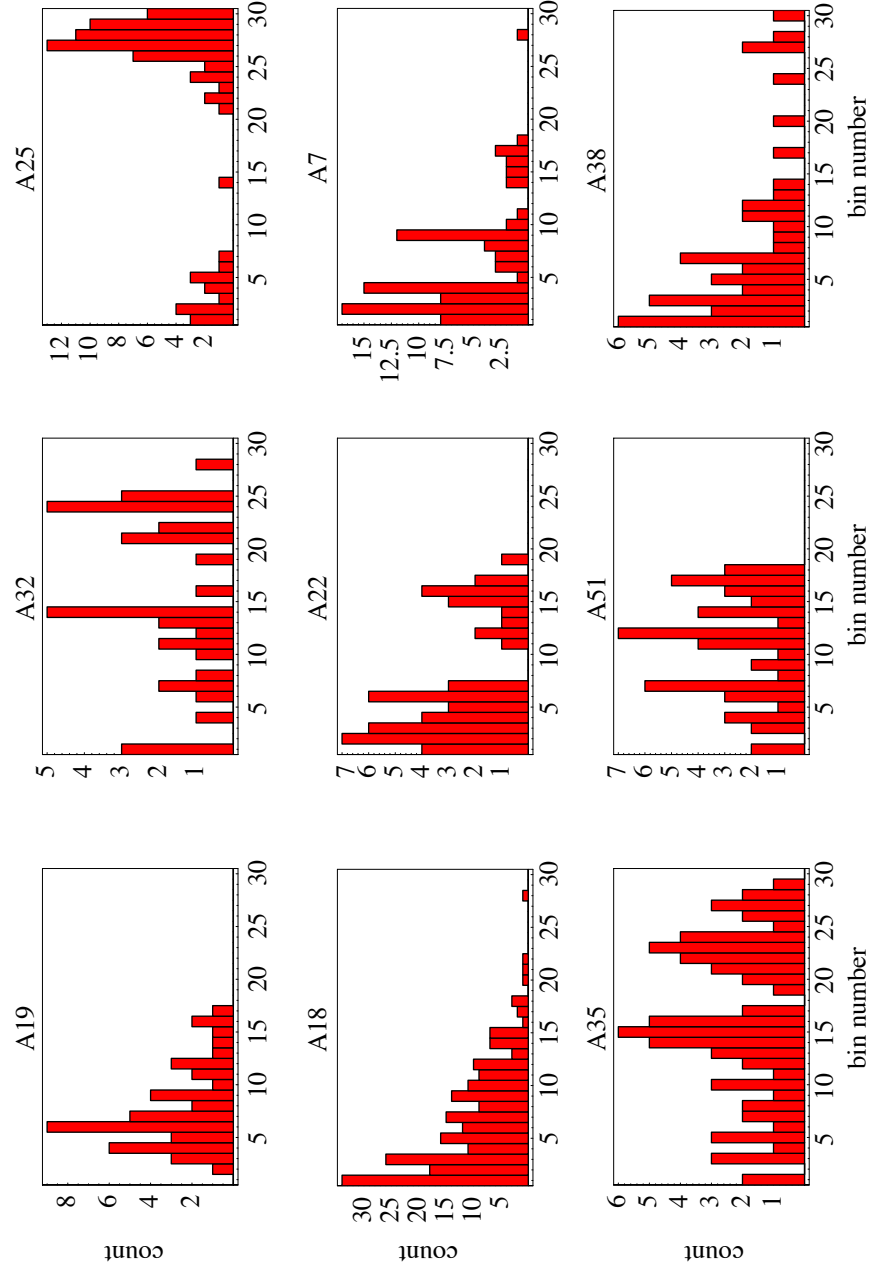


Figure 4.1.1 Normalized histograms of ϕ for 9 clusters in quadrant 1.

Table 4.7 K-S probabilities. Number of pairs of moonquake clusters with at least 80% probability of being drawn from the same underlying distribution.

$\Delta^\dagger$	number of pairs	r	θ	ϕ	dr/dt	$d\theta/dt$	$d\phi/dt$
$\Delta \leq 5^\circ$	6	0	0	1	0	0	0
$\Delta \leq 10^\circ$	40	0	1	1	0	2	0
$\Delta \leq 15^\circ$	79	1	2	4	2	2	0
$\Delta \leq 20^\circ$	144	4	2	6	4	3	1

[†] Angular separation.

with the location map shown in Figure 4.1, these tables show that while some clusters possess comparatively low variance, high absolute skewness, and/or high kurtosis, other nearby clusters may not. In fact, nearby clusters are sometimes skewed oppositely.

To illustrate the variability in response to the geometrical parameters among nearby clusters, histograms of (r, θ, ϕ) for 9 nearby clusters in quadrant 1 are shown in Figures 4.9 through 4.11. Each histogram is normalized by the number of events. Histograms of all six parameters for all 51 clusters (arranged by quadrant) can be viewed online at <http://igpphome.ucsd.edu/~rbulow/SUPPL/>.

To statistically quantify this behavior, we used the Kolmogorov-Smirnov (K-S) test to determine the extent to which each distribution is non-uniform (Press et al., 1992). The K-S statistic can be used to test whether it is possible to reject the null hypothesis that two subsets of data are drawn from the same underlying distribution. The last column of Tables 4.1 through 4.6 lists the probability computed from the K-S statistic that the cumulative distribution function (cdf) representing each histogram is the same as the cdf of a uniform distribution.

With the exception of a few clusters, the average probability that moonquakes respond in a uniform manner to any of the geometrical parameters is extremely low – approximately 0.05. This indicates that individual clusters tend to produce moonquakes at favored times in the orbital cycle.

We would next like to statistically quantify the extent to which nearby clusters respond similarly to each geometrical parameter (that is, whether they

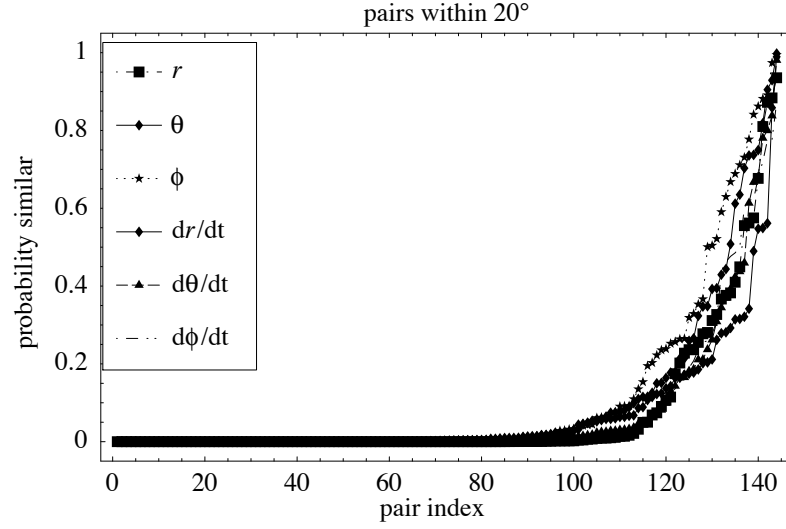


Figure 4.12 Similarity of cluster pairs with $\Delta \leq 20^\circ$. Probability based on the K-S statistic that a given pair of clusters with $\Delta \leq 20^\circ$ respond similarly to the parameters (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$.

produce moonquakes at similar times in the orbital cycle). To do so, we computed the K-S test statistic between nearby groups of deep moonquake clusters. Out of a total possible 1275 unique pairs of moonquake clusters, we selected four groups of pairs based on the angular separation Δ between clusters: $\Delta \leq 5^\circ$ (6 pairs), $\Delta \leq 10^\circ$ (40 pairs), $\Delta \leq 15^\circ$ (79 pairs), and $\Delta \leq 20^\circ$ (144 pairs). In Table 4.7, we show the number of pairs per Δ group with at least an 80% probability of being drawn from the same underlying distribution, based on the K-S statistic.

From Table 4.7, it is plain that close-by pairs of clusters rarely respond in the same way to the six geometrical parameters. In fact, for the 144 pairs of clusters within 20° of each other, a majority do not respond similarly at all to the six parameters (Figure 4.12). At the 80% significance level, a maximum of six cluster pairs are similar. At the 95% level, this number is reduced to two for pairs within $\Delta \leq 20^\circ$. For each parameter (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$, Table 4.8 lists the pairs associated with both the 80% and 95% significance levels.

Table 4.8 Highly similar pairs. Pairs with at least 80% or 95% probability of being drawn from the same underlying distribution

80%	
r	(A35, A37), (A20, A42), (A8, A10), (A5, A41)
θ	(A37, A51), (A3, A5)
ϕ	(A16, A28), (A6, A271), (A14, A21), (A19, A234), (A37, A234), (A19, A257)
dr/dt	(A19, A257), (A19, A234), (A6, A271), (A37, A234)
$d\theta/dt$	(A8, A13), (A3, A5), (A15, A28)
$d\phi/dt$	(A20, A42)
95%	
r	—
θ	(A3, A5)
ϕ	(A37, A234), (A19, A257)
dr/dt	(A37, A234)
$d\theta/dt$	(A15, A28)
$d\phi/dt$	—

4.5 Conclusions

We have observed that individual moonquake clusters can produce events at specific values of the geometrical parameters (r, θ, ϕ) or $(dr/dt, d\theta/dt, d\phi/dt)$. However, relatively few groups of nearby clusters respond similarly to those parameters. This result suggests that deep moonquake occurrence is only partly explained by the orbital motion of the Earth with respect to the Moon, and that local structure at individual clusters is likely important to failure. This warrants future studies of tidal stress, computed from the geometrical parameters and resolved on local failure planes.

Minshull and Goulty (1988) noted that A1 moonquakes sometimes occurred at or near peaks in the tidal stress, while the stress peaks themselves sometimes occurred at higher subsequent values each month. This behavior contradicts the hypothesis that moonquakes occur when the tidal stress reaches a threshold level. An alternative interpretation of the data is that deep moonquake occurrence times are partly controlled by stress rates, since the stress rate at quake times would

be constant (zero) if moonquakes only occurred at stress extrema. We have observed that some clusters respond strongly to parameter rates $(dr/dt, d\theta/dt, d\phi/dt)$. This is a new result and should be considered in future studies of tidal stress at the times of moonquakes.

Lastly, in our histogram analysis we observed that there is no way to differentiate between moonquake clusters that possess systematic trends in occurrence with respect to the geometrical parameters, and those with truly uniform distributions, through investigation of the histogram alone. Further work is needed to determine whether analyses that incorporate local structure will be able to differentiate between these two types of behavior.

4.A Appendix: Model of orbital motion

Most previous studies that address factors contributing to moonquake occurrence use the orbital model of Harrison (1963), which tabulates the functions of time necessary to compute the position of Earth as seen from the Moon. While Harrison’s formulation is widely used, we have found it to be both easier to understand and more accurate (as we will discuss later) to develop an independent formulation. Our basic approach is a Fourier series representation of the temporal variations in Earth-Moon distance, sub-Earth latitude, and sub-Earth longitude.

We begin by compiling tables of the relevant quantities (r, θ, ϕ) using MICA, the Multi-Year Interactive Computer Almanac (USNO, 2004). The MICA software is available from the U.S. Naval Observatory providing astronomical data for a wide variety of celestial objects. It uses the Jet Propulsion Laboratory (JPL) DE405 ephemerides for position calculations. This program can be used to compute values for the selenographic (Moon-centered) coordinates of the Earth and the Earth-Moon distance.

To represent these temporal variations, we compute the Fourier spectrum of each time series and examine the resulting peaks, then fit a Poisson series to the data, using the most significant frequencies. A Poisson series is a sum of sines and cosines, similar to a Fourier series, but differs in that the frequencies of the sinusoidal variations need not be integer multiples of a single base frequency. As a result, functions represented this way need not be strictly periodic, and are generally only quasi-periodic (Carpino et al., 1987; Bills, 2005; Lainey et al., 2006). To facilitate accurate selection of dominant frequencies, a long time span is best. We used 20,000 four-day time steps to generate a 219-year time span. This is important for recovering low-frequency peaks in the Fourier spectra.

Fourier spectra of (r, θ, ϕ) , shown in Figure 4.13, reveal several distinct periods due to the nature of the Earth-Moon-Sun orbits. All three coordinates display prominent monthly periodicity, as expected. The Earth-Moon distance

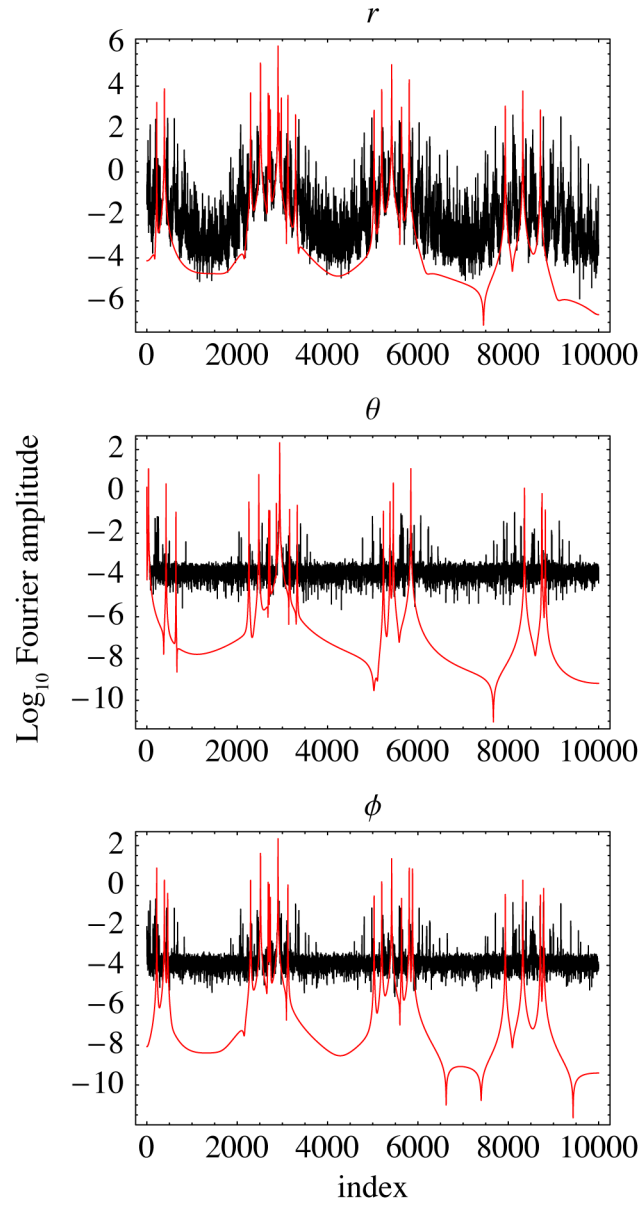


Figure 4.13 Fourier amplitude spectra of (r, θ, ϕ) . Logarithm (base 10) of the Fourier amplitude spectra of (r, θ, ϕ) in black, with our fits in red. Peaks in our fits correspond to the twenty largest-amplitude peaks in the spectra. Index is converted to frequency using Equation 4.6.

and sub-Earth longitude vary mainly at the period of the anomalistic month, and the sub-Earth latitude varies with the nodical month. The anomalistic month (27.55 days) is the mean time between passages of the Moon through perigees, while the nodical month (27.21 days) is the mean time between passages through the ascending node. Both of these periods deviate slightly from the sidereal month (27.32 days), which is the period as seen in an inertial frame. A 206-day variation in these parameters is a consequence of the Sun's perturbation on the lunar orbit. There is also a spectral peak at quite long periods; this is, in part, due to the ~ 6 -year beat period between the anomalistic and nodical months.

$$\frac{1 \text{ year}}{365.24 \text{ days}} \cdot \frac{1}{\frac{1}{27.21 \text{ days}} - \frac{1}{27.55 \text{ days}}} = 6.04 \text{ years} \quad (4.5)$$

Examining and identifying the spectral lines of each time series will allow the resulting frequencies to be fit by sines and cosines, which can be summed to build a representative function in time. Before calculating the Fourier spectra of the various time series, they are Hanning-tapered and de-meant to remove end effects and long-period drift.

The Fourier spectra of the various time series all exhibit similar behavior, with the largest peaks occurring at 1-year and 1-month intervals. Many smaller peaks exist, representing higher multiples of the main peaks and linear combinations of the two. To identify the spectral lines, the position of the peaks in the spectrum must be converted to frequencies. The mapping between the index x_i in the list of numeric values of the Fourier spectrum, and corresponding temporal frequency f is

$$f(x_i) = \frac{2\pi(x_i - 1)}{dt(L - 1)} \quad (4.6)$$

where dt is the time step and L is the number of points in the time series. For example, in the Earth-Moon distance (r) spectrum, a peak appears at $x \sim 2900$ cycles per L , corresponding to a frequency of 0.227732 cycles per day, or one cycle per anomalistic month ($2\pi/f = 27.55$ days).

Table 4.9 Number of functions by parameter. Number of function C_i , of the form given in equation 4.7, necessary to fit each time series to a fractional variance of 10^{-3} , 10^{-4} , and 10^{-5} .

	10^{-3}	10^{-4}	10^{-5}
Earth-Moon distance	4	9	14
sub-Earth latitude	3	6	9
sub-Earth longitude	6	11	17

Depending on the desired accuracy, Equation 4.6 is only good as a first approximation of the actual frequency of a spectral peak. This is because the positions x_i are discrete and may be slightly offset from the actual peak values. Therefore we fit an interpolated function to the spectra in order to better recover the input frequencies (and hence create a better fit to the data). We then fit sums of sines and cosines to the selected frequencies. Such an approach has been used to build synthetic representations of the outer planets and Galilean satellites' orbital motion (Carpino et al., 1987; Bills, 2005; Lainey et al., 2006). The fitted functions are of the form

$$C_i(t) = A_i \sin(f_i t) + B_i \cos(f_i t). \quad (4.7)$$

Each function C_i is summed to create the final fit to the time series. We can measure goodness of fit by computing the fractional variance, defined as the ratio of the variance of the fit (after i terms have been summed) to the variance of the data. Table 4.9 shows the number of C_i 's necessary to fit each time series to a fractional variance of 10^{-3} , 10^{-4} , and 10^{-5} .

Some time series require more terms to reach a given residual variance, because the monthly tidal period of the Moon's orbit around the Earth interacts with the longer period orbital variations to produce many combination frequencies. Identification of spectral features in each time series consists of noting that the period of a certain line corresponds to a known period. Table 4.10 lists the different fundamental periods present in the fitted time series, adapted from Bartels (1985). The tropical month is the period from one lunar equinox to the next; the amount

Table 4.10 Fundamental periods of the lunar orbit.

source	period	rate (radians/day)
tropical month	27.321582 days	$s = 0.2300$
tropical year	365.242199 days	$h = 0.0172$
Earth-Moon periapse period	8.847 years	$p = 0.0019$
Sun-Earth periapse period	20940 years	$p_s = 8.2153 \times 10^{-7}$
Earth-Moon node period	-18.613 years	$N = -0.0009^\dagger$

[†] note $N' = -N$

of time it takes the Moon to return to an ecliptic longitude of zero. The tropical year is the mean interval between vernal equinoxes (of the Earth).

For each function representing a position parameter of the Earth as seen from the Moon, the angular rate, period, sine and cosine coefficients, spectral peak amplitudes, and physical interpretation (identification of periods in the fit as integer multiples of the fundamental periods listed in Table 4.10) of the ten largest terms are shown in Table 4.11. Note some peaks visible in the spectra are not identified by Bartels (1985).

We have seen that it is possible to fit simple functions of time to the MICA-generated tabulations of the position of the Earth as seen from the Moon. A good balance between quality of fit and computation time is obtained with 20 frequencies (20 sine and cosine terms for a total of 40 terms) in each time series. With 20 frequencies, the fractional variances obtained for (r, θ, ϕ) are 2.6E-6, 1.3E-6, and 5.6E-6 respectively. The frequencies and coefficients of our fits are available for download from <http://igpphome.ucsd.edu/~rbulow/SUPPL/>. Spectra computed from our fitted equations are shown in Figure 4.13, with the full spectra computed directly from the time series for comparison.

We now compare the accuracy of our model with that of Harrison (1963). The JPL ephemerides DE405 represent the most accurate planetary positions available (Standish, 1998). We therefore use values computed using MICA as the standard to which we compare both our orbital model and that of Harrison (1963).

Table 4.11 Fit to parameters (r, θ, ϕ) . Angular rate, period, cosine and sine coefficients, spectral peak amplitudes, and physical interpretation of the periods of the ten largest terms in spectra of (r, θ, ϕ) .

rate (radians/day)	period (days)	cosine coeff.	sine coeff.	amp.	identity
Earth-Moon distance [†] (km)					
0.2280	27.5546	-17196.1533	11883.9886	20903.0350	$(s - p)$
0.1975	31.8119	-2704.1132	-2524.3606	3699.2735	$(s - 2h + p)$
0.4255	14.7653	-2922.7620	-439.0376	2955.5527	$(2s - 2h)$
0.4561	13.7773	-203.3171	532.4762	569.9726	$2s$
0.0305	205.8920	53.4105	-240.4148	246.2762	$2h$
0.4083	15.3873	197.6877	53.8397	204.8881	
0.6536	9.6137	-153.4855	74.6965	170.6967	$(3s - 2h)$
0.1803	34.8469	98.4147	116.2624	152.3233	
0.2108	29.8028	113.8588	-61.4835	129.3988	$(s - h)$
0.2452	25.6217	-79.2274	68.6124	104.8076	
sub-Earth latitude (degrees)					
0.2309	27.2122	4.3877	-5.0159	6.6641	$(s - N)$
0.4589	13.6912	0.0425	-0.3624	0.3649	$2s$
0.0029	2190.5610	-0.3836	0.1019	0.3969	N'
0.1946	32.2808	-0.0975	-0.1515	0.1802	$(s - 2h + p)$
0.4284	14.6664	0.0716	-0.0072	0.0719	$(2s - 2h)$
0.0334	188.2012	0.0020	0.0645	0.0645	$2h$
0.6564	9.5717	0.0322	-0.0274	0.0422	$(3s - 2h)$
0.6869	9.1465	-0.0110	-0.0196	0.0225	
0.4227	14.8655	-0.0086	-0.0036	0.0093	
0.1774	35.4103	0.0039	0.0079	0.0088	
sub-Earth longitude (degrees)					
0.2280	27.5546	3.5765	5.1784	6.2934	$(s - p)$
0.1975	31.8119	-0.8702	0.9325	1.2755	$(s - 2h + p)$
0.4255	14.7653	-0.0974	0.6490	0.6562	$(2s - 2h)$
0.0172	365.2587	0.0239	0.2095	0.2108	$(h - p_s)$
0.4561	13.7773	0.2004	0.0742	0.2137	$2s$
0.4618	13.6061	0.1912	-0.0250	0.1929	$(2s + N')$
0.0305	205.8922	-0.0601	-0.0133	0.0616	$2h$
0.6536	9.6137	0.0231	0.0477	0.0530	$(3s - 2h)$
0.1803	34.8469	0.0436	-0.0369	0.0571	
0.4083	15.3873	0.0120	-0.0441	0.0457	

[†] The series representation of r also has a constant term equal to 385001.0.

Table 4.12 Residual standard deviation. Comparison of our model (a Poisson series with 20 frequencies) and that of Harrison (1963) to the MICA data.

	r (meters)	θ (radians)	ϕ (radians)
<i>std. dev.</i> (<i>Harrison</i>)	3.54E+5	1.10E-3	5.33E-3
<i>std. dev.</i> (<i>Poisson</i> – 20)	2.42E+4	1.29E-4	1.90E-4

For each variable (sub-Earth latitude and longitude and Earth-Moon distance) we compute and tabulate the residual standard deviation ($std.dev.(data - model)$) using both our model and that of Harrison (1963). The results are shown in Table 4.12. In all cases, our fit to the MICA data results in a residual standard deviation that is one order of magnitude smaller than that of Harrison (1963).

4.B Appendix: Demodulating time series

To analyze the relationship between tides and moonquakes, we need to characterize variations in the Earth’s position (and velocity), as parameterized by the Earth-Moon distance (r), sub-Earth latitude (θ), and sub-Earth longitude (ϕ), over the course of the entire Apollo seismic experiment. We have already seen that (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$, when evaluated on uniform time steps, result in non-uniform distributions. The first step in our analysis is to demodulate these functions, so we can more closely examine their behavior on the monthly time scale. Then, we apply a simple transformation to the demodulated time series to remove the effect of the non-uniform lunar orbital motion.

We use envelope demodulation to remove the long-period variations from the time series $s(t)$. The envelope function $env(t)$ is computed using the analytic signal $s_a(t)$:

$$s_a(t) = s(t) + i\hat{s}(t) \tag{4.8}$$

where $\hat{s}(t)$ is the Hilbert transform (Bracewell, 2000):

$$\hat{s}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} s(x) e^{i\omega x} dx \right] \frac{\text{sgn}(\omega)}{i} e^{-i\omega t} d\omega \quad (4.9)$$

and ω is the frequency. As particularly relevant examples, the Hilbert transform of $\cos(\omega t)$ is $\sin(\omega t)$, and the transform of $\sin(\omega t)$ is $-\cos(\omega t)$. The envelope function of a signal can be computed by taking the modulus of the (complex) analytic signal:

$$\text{env}(t) = |s_a(t)| = \sqrt{s^2(t) + \hat{s}^2(t)} \quad (4.10)$$

In Figure 4.14 we show two sample time series and their upper and lower envelopes. For a de-meaned signal that is symmetric about zero, the lower envelope is equal to $-\text{env}(t)$, as shown in the left plot of Figure 4.14. For a time series not symmetric about its mean (Figure 4.14, right) the upper and lower envelopes computed using the analytic signal do not fit in the same way, but as we shall see, can still be used to demodulate a signal.

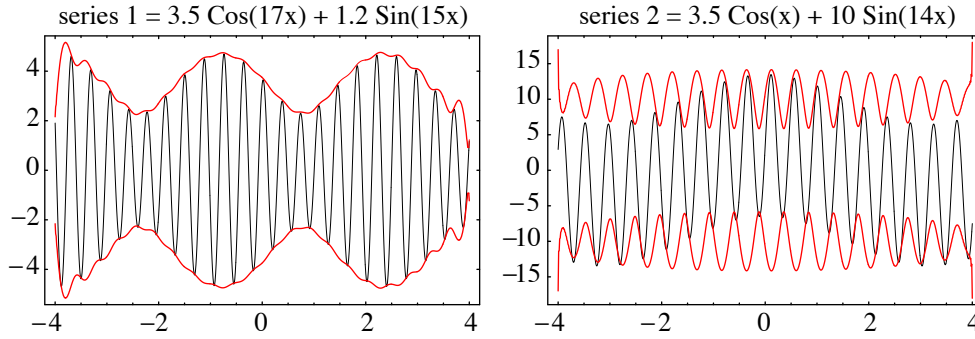


Figure 4.14 Example signal envelopes. Two test series with envelopes in red.

To demodulate a time series, we first remove its mean and compute the envelope functions. We then divide the de-meaned series by the difference between the upper and lower envelopes, evaluated at the times of the input series values. The result is a time series with a flat envelope consisting of values between $\pm \frac{1}{2}$ (Figure 4.15).

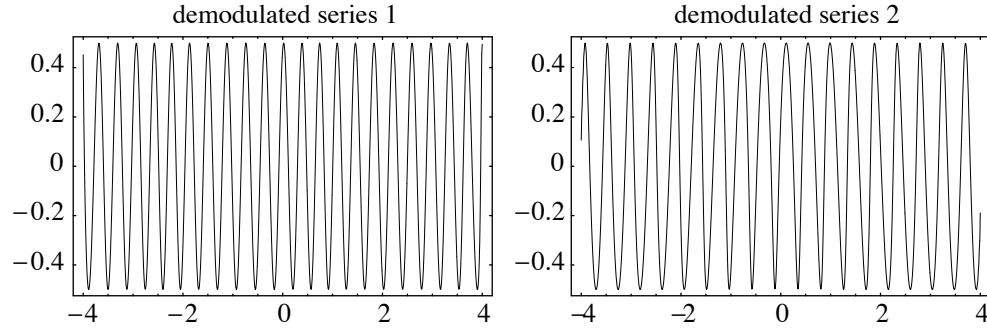


Figure 4.15 Demodulation example. The two test series from Figure 4.14 after demodulation.

In Figure 4.16, we show (r, θ, ϕ) with their envelopes. In this figure (as in Figure 4.14) it is evident that this method of demodulation will suffer from end effects, since the envelope algorithm does not achieve the desired results near the ends of the time series. To avoid this problem, we extend the time series of (r, θ, ϕ) evaluated at uniform $\frac{1}{2}$ -day time steps an additional 225 days on either end of the time span of the Apollo experiment before demodulating. The duration of the Apollo experiment spanned 11/19/1969 to 09/30/1977, and the $\frac{1}{2}$ -day time steps span 04/08/1969 to 05/13/1978.

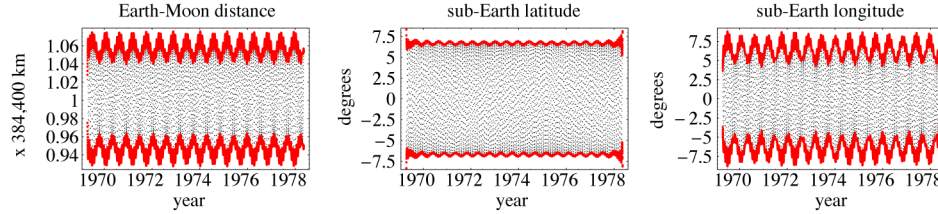


Figure 4.16 Envelopes for (r, θ, ϕ) . Earth-Moon distance (r), sub-Earth latitude (θ), and sub-Earth longitude (ϕ) vs. time, with envelopes in red.

While demodulation removes long-period variation from a time series, it does not remove the effect of the non-uniform lunar orbital motion. Comparison of the distributions of (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$ at quake times with the underlying distributions is difficult because of the non-uniformity of those distributions evaluated at $\frac{1}{2}$ -day time steps. We must therefore make the background distributions uniform, to ensure that the histograms computed at moonquake times

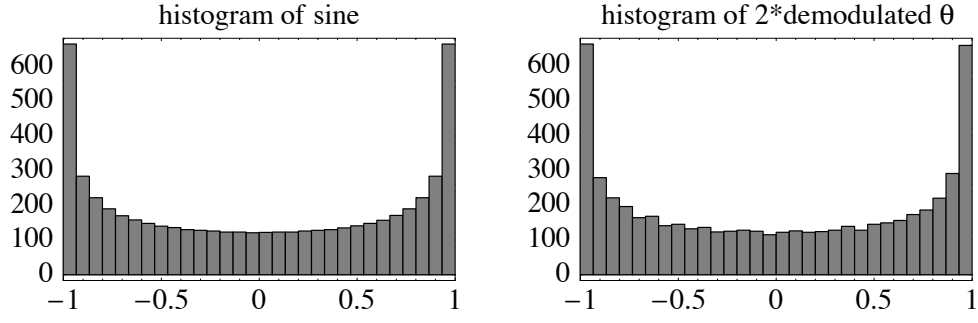


Figure 4.17 Histogram of sine function. Histograms of (left) sine evaluated between $-\pi$ and π and (right) twice the demodulated Earth latitude (θ) evaluated at $\frac{1}{2}$ -day time steps.

aren't contaminated by the uneven sampling of the Moon's orbital position with respect to the Earth. The process of demodulation turns the background (r, θ, ϕ) variations into sine waves. For comparison, histograms of both the sine function evaluated between $-\pi$ and π , and the demodulated sub-Earth latitude evaluated at $\frac{1}{2}$ -day time steps are shown in Figure 4.17. They are very similar. This means that the demodulated time series can be made uniform by simply multiplying them by two (to make their ranges span the values -1 to 1) and taking their inverse sine.

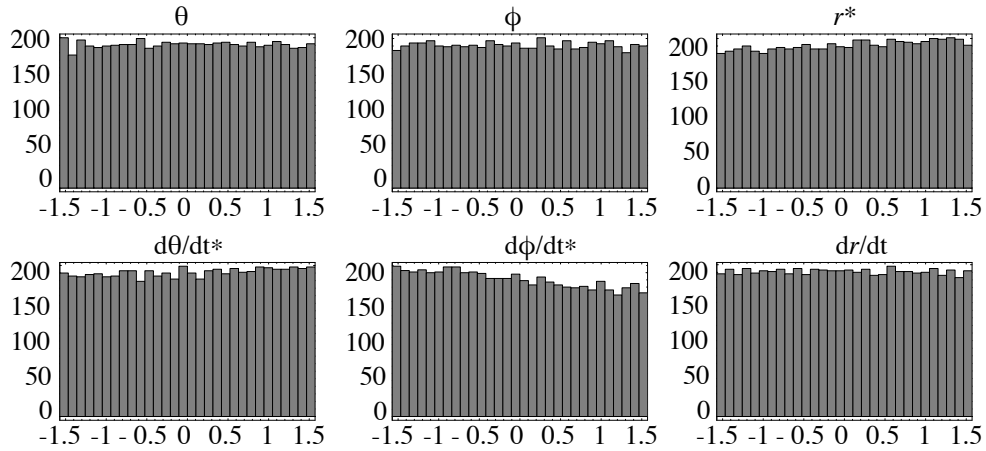


Figure 4.18 Histogram of demodulated parameters. Histograms of the inverse sine of twice the demodulated time series (r, θ, ϕ) and $(dr/dt, d\theta/dt, d\phi/dt)$. Note that the histograms for the three series not symmetric about their mean values r , $d\theta/dt$, and $d\phi/dt$ (marked with asterisks) are slightly non-uniform.

The effect of the ill-fitting envelope function for time series not symmetric about their mean values becomes evident in this step. As shown in Figure 4.18, application of the inverse sine function to demodulate such time series results in a background distribution which is still slightly non-uniform. Of our six orbital parameters, r , $d\theta/dt$, $d\phi/dt$ all behave in this way.

This problem can be remedied by application of multiple demodulations, before taking the inverse sine, to the offending time series. We find sufficient uniformity of the inverse sine of r , $d\theta/dt$, $d\phi/dt$ (statistically indistinguishable from uniform, based on the K-S statistic) can be obtained after four applications of the demodulation algorithm.

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5

The influence of tidal stress on deep moonquake occurrence

5.1 Introduction

Of the many characteristics of deep moonquakes, two are directly relevant to the relationship between tidal stress and deep moonquake occurrence. The first, as we have discussed previously, is their tidal periodicity (Ewing et al., 1971). Individual moonquake clusters can produce events at specific times in either the anomalistic or nodical month, two periodicities directly related to the position of the Earth with respect to the Moon, and hence influencing, at least in part, the stress state within the Moon.

The second relevant characteristic of deep moonquakes, evident in event seismograms, is their tendency to display large S-wave to P-wave arrival amplitude ratios (Lammlein et al., 1974). Because of this, early studies sought to find conditions under which deep moonquake occurrence could be linked to shear failure. For layered, elastic models of the moon based on seismic data, the maximum shear stress, while small (on the order of 1 bar), was observed to reach a broad peak in the active deep moonquake region, between approximately 600 and 1000 km

depth (Toksöz et al., 1977; Cheng and Toksöz, 1978). The value of this peak is primarily controlled by the choice of shear modulus profile $\mu(r)$, and Toksöz et al. (1977) found that any structure model consistent with seismic velocity models would produce a shear stress peak in the same depth range.

Despite the agreement between the depth of maximum shear stress and the active deep moonquake region, previous studies of the relationship between tidal stress and moonquake occurrence (Toksöz et al., 1977; Lammlein, 1977; Cheng and Toksöz, 1978; Nakamura, 1978; Goult, 1979; Minshull and Goult, 1988) were unable to draw concrete conclusions linking the two. Goult (1979) and Minshull and Goult (1988) performed coarse grid searches (30° intervals of dip and strike) for the failure plane that maximized shear stress at the times of A1 moonquakes. While moonquake occurrence times for a single cluster were found to coincide with shear stress peaks over short periods, no such correlation was found to extend throughout the entire period of operation of the seismic network.

Interestingly, Minshull and Goult (1988) noted some situations in which A1 moonquakes occurred at monthly stress peaks, over an interval during which the magnitudes of the stress peaks themselves were increasing from month to month. This behavior contradicts the hypothesis that moonquakes occur when the tidal stress reaches a threshold level. An alternative interpretation of the coincidence of moonquake times with monthly stress peaks is that some moonquake clusters are sensitive to stress rates, since the stress rate is constant (zero) at the times of stress extrema. In the previous chapter, we observed that event occurrence at some moonquake clusters correlated strongly with the rate of change of the Earth's position, lending support to this hypothesis. No previous study has attempted to link moonquake occurrence to the rate of change of tidal stresses.

Almost all of the previous work that has investigated the relationship between tidal stress and moonquake occurrence focused on a single deep event source region - A1, the largest in terms of total number of events (Nakamura et al., 2004; Bulow et al., 2005). The A1 cluster possesses a significant number of

opposite-polarity events, which previous studies attempted to account for in their stress models (Toksöz et al., 1977; Cheng and Toksöz, 1978; Goulety, 1979; Minshull and Goulety, 1988). Recent investigations (Nakamura, 2003) have identified at least 166 distinct deep moonquake clusters, of which only one other group (A20) also has a significant number of opposite-polarity events (Nakamura et al., 2004). The exploration of A1 alone is limiting both geographically (since the 166 deep moonquake clusters occur over a wide geographical area on the near side of the Moon) and behaviorally since the opposite-polarity events make A1 a group of moonquakes that may not be representative of the entire moonquake population.

In this study, we expand upon previous investigations of the relationship between tidal stress and deep moonquake occurrence in several ways. First, we examine the sensitivity of moonquake occurrence times to normal and shear stress, and the rates of change of normal and shear stress. Rather than impose a specific failure plane and/or failure criterion, we perform a grid search over all possible plane orientations to identify the plane that produces a linear combination of normal stress, shear stress, normal stress rate, and shear stress rate resulting in the most nearly constant values at the times of moonquakes. This allows us to use solely the times of moonquakes to determine which of these four stress criteria are most important, on an individual basis, to seismic event occurrence at each cluster.

In addition, we examine a large sample of deep moonquake source regions. We explore stresses at the times of moonquakes from the 51 deep clusters located by Nakamura (2005) that consist of at least 35 events as listed in the latest event catalog (Nakamura et al., 2004), taking into account the new events discovered for the eight clusters analyzed in Bulow et al. (2005) and Bulow et al. (2007). Locations of all 51 clusters are shown in Figure 4.1. Monitoring variations from cluster to cluster will allow us to determine whether global patterns in moonquake occurrence times and the corresponding stress state exist.

5.2 Building the stress tensor

We compute tidal stresses within the Moon due to elastic deformation following the method initiated by Love (1911) and refined by Alterman et al. (1959). For more recent presentations, see for example Wu and Peltier (1982) and Sabadini and Vermeersen (2004).

The gravitational interaction between the Moon and the Earth causes deformation on both bodies. The amplitude of the tidal deformation on and in the Moon is determined by the gravitational potential Φ of the tide-raising body (the Earth) and the internal structure of the Moon. The potential at any point in the Moon (r, θ, ϕ) due to the Earth satisfies Laplace's equation and can be expressed as a spherical harmonic expansion:

$$\Phi = -\frac{GM_E}{r_s} \sum_{n=0}^{\infty} \left(\frac{r}{r_s}\right)^n P_n(\cos\Delta) \quad (5.1)$$

where G is the gravitational constant, M_E is the mass of the Earth, r_s is the (time-varying) distance from the center of the Moon (the origin) to the center of the Earth, r is the radius within the Moon measured from the origin, and $P_n(x)$ is a Legendre polynomial of degree n . The angle Δ is the angle between the point (r, θ, ϕ) within the Moon and the position of the Earth (r_s, θ_s, ϕ_s) such that $\cos \Delta = \cos \theta \cos \theta_s + \sin \theta \sin \theta_s \cos(\phi - \phi_s)$, where θ and θ_s are selenographic co-latitudes (zero at the North pole of the Moon), and ϕ and ϕ_s are selenographic longitudes (increasing to the East from the lunar meridian).

We are interested in tidal deformation, which is dominated by the terms of harmonic degree $n = 2$. The imposed potential can be written:

$$\Phi_2 = \frac{GM_E r^2}{2r_s^3} (1 - 3 \cos^2 \Delta) \quad (5.2)$$

Associated with the deformation due to this imposed potential will be displace-

ments, strains, stresses, and changes in the Moon's gravitational potential. The elastic constitutive relation states that stresses are linearly related to strains:

$$\sigma_{ij} = \lambda \epsilon_{kk} \delta_{ij} + 2\mu \epsilon_{ij} \quad (5.3)$$

where σ_{ij} is the stress tensor, ϵ_{ij} is the strain tensor, λ and μ are the Lamé parameters, and δ_{ij} is the unit diagonal tensor. Our goal is to compute the stress σ_{ij} due to tidal deformation $\mathbf{u} = (u_r, u_\theta, u_\phi)$ in a form that can be evaluated at any time, at any place within the Moon, due to the time-varying position of the Earth.

The response of the Moon to the tidal influence of the Earth is linear, so for the degree-2 spherical harmonic term in the Earth's gravitational potential, there is a corresponding degree-2 deformation pattern on the Moon. In order to determine that pattern, we need to construct and solve a set of differential equations which govern the elastic-gravitational response of an initially spherical body. The standard approach is to expand the displacement vector, stress tensor, and gravitational potential perturbation in spherical harmonics, and determine the relationship between the corresponding radial factors. We now briefly summarize that process.

The values of the displacements $\mathbf{u} = (u_r, u_\theta, u_\phi)$ are proportional to the imposed potential and can be expressed as products of two terms: a radially-varying term y_i , and an angular term that can be expanded with Legendre polynomials:

$$u_r = \sum_{n=1}^{\infty} y_1(n, r) P_n(\cos \Delta) \quad (5.4)$$

$$u_\theta = \sum_{n=1}^{\infty} y_2(n, r) \partial_\theta P_n(\cos \Delta) \quad (5.5)$$

$$u_\phi = \sum_{n=1}^{\infty} \frac{y_2(n, r)}{\sin \theta} \partial_\phi P_n(\cos \Delta) \quad (5.6)$$

Note that the two non-radial components of the displacement vector, u_θ and u_ϕ , share a single radial factor, y_2 .

The elastic strain tensor is obtained via the gradient of the displacement vector. The components of the stress tensor that are strictly non-radial can be determined from the corresponding strain tensor components; those stress terms with a radial component ($\sigma_{rr}, \sigma_{r\theta}, \sigma_{r\phi}$) have both elastic and gravitational contributions. Their spatial variations can be expressed in a form which parallels that used for the displacement vector:

$$\sigma_{rr} = \sum_{n=1}^{\infty} y_3(n, r) P_n(\cos \Delta) \quad (5.7)$$

$$\sigma_{r\theta} = \sum_{n=1}^{\infty} y_4(n, r) \partial_\theta P_n(\cos \Delta) \quad (5.8)$$

$$\sigma_{r\phi} = \sum_{n=1}^{\infty} \frac{y_4(n, r)}{\sin \theta} \partial_\phi P_n(\cos \Delta) \quad (5.9)$$

where $y_3(n, r)$ and $y_4(n, r)$ are the corresponding radial factors for stress.

The perturbation to the Moon's gravitational potential due to these deformations can be similarly expressed:

$$\phi_1 = \sum_{n=1}^{\infty} y_5(n, r) P_n(\cos \theta) \quad (5.10)$$

It must satisfy Poisson's equation:

$$\nabla^2 \phi_1 = 4\pi G \rho_1 \quad (5.11)$$

which is a second-order differential equation. Any such second-order equation can be re-written as a set of coupled first-order equations.

Following the formulation of Alterman et al. (1959), the six radially-varying functions $y_i(n, r)$ describe the elastic-gravitational deformation of a body

in response to seismically-induced (e.g. Earth’s normal modes) or tidally-induced (as we consider) deformations. Since we are only interested in degree $n = 2$, we will subsequently drop the n -dependence of the y_i ’s. The radial factors are: y_1 , the radial factor of the radial component of displacement (u_r), y_2 , the radial factor of the tangential components of displacement (u_θ and u_ϕ), y_3 , the radial factor of the radial component of stress (σ_{rr}), y_4 , the radial factor of the tangential components of stress ($\sigma_{r\theta}$ and $\sigma_{r\phi}$), y_5 , the radial factor of the potential, and y_6 , the radial factor of the “potential stress,” defined such that the gradient of the potential is continuous across the surface of the Moon.

The differential equations for the y_i ’s can be written in matrix form (Wu and Peltier, 1982):

$$\frac{d\mathbf{y}}{dr} = \mathbf{A} \cdot \mathbf{y} \quad (5.12)$$

where $\mathbf{A}$ is a matrix consisting of coefficients from the equations of motion and $\mathbf{y}(r)$ is the solution vector $(y_1, y_2, y_3, y_4, y_5, y_6)$.

The solutions to this system of equations are subject to the following boundary conditions for a homogeneous Moon: (1) the surface of the Moon is stress-free, (2) the gravitational potential is continuous across the surface of the Moon, and (3) the displacement and potential are regular at the center of the Moon.

The solution vector $\mathbf{y}$ can be represented generally as a linear combination of six independent solutions $\mathbf{y} = \mathbf{Y} \cdot \mathbf{c}$, where $\mathbf{Y}$ is called the fundamental matrix and $\mathbf{c}$ is a 6-component vector of coefficients (Sabadini and Vermeersen, 2004). The fundamental matrix $\mathbf{Y}$ consists of two parts such that $\mathbf{Y} = [\mathbf{Y}_1 \ \mathbf{Y}_2]$. In this formulation, $\mathbf{Y}_1$ is the set of three regular solution vectors (positive powers of r):

$$\begin{bmatrix} n r^{1+n} & n r^{-1+n} & 0 \\ \frac{(3+n) r^{1+n}}{1+n} & r^{-1+n} & 0 \\ r^n (2(-3 + (n-1)n) \mu + g n r \rho) & n r^{-2+n} (2(n-1) \mu + g r \rho) & r^n \rho \\ \frac{2n(2+n) r^n \mu}{1+n} & 2(n-1) r^{-2+n} \mu & 0 \\ 0 & 0 & r^n \\ 4 G n \pi r^{1+n} \rho & 4 G n \pi r^{-1+n} \rho & (1+2n) r^{-1+n} \end{bmatrix} \quad (5.13)$$

where g , ρ , and μ are the gravity, density, and rigidity of the Moon model and $n = 2$ for tides. The corresponding irregular solution vectors (negative powers of r) are in $\mathbf{Y}_2$:

$$\begin{bmatrix} n(1+n) r^{-n} & (1+n) r^{-2-n} & 0 \\ (2-n) r^{-n} & -r^{-2-n} & 0 \\ n r^{-1-n} (-2(-1+n(3+n)) \mu + g(1+n) r \rho) & (1+n) r^{-3-n} (-2(2+n) \mu + g r \rho) & r^{-1-n} \rho \\ 2(-1+n^2) r^{-1-n} \mu & 2(2+n) r^{-3-n} \mu & 0 \\ 0 & 0 & r^{-1-n} \\ 4 G n (1+n) \pi \rho r^{-n} & 4 G (1+n) \pi r^{-2-n} \rho & 0 \end{bmatrix} \quad (5.14)$$

Each column of the fundamental matrix represents an independent solution of Equation 5.12. The coefficients c_i are determined by the boundary conditions, now expressed as (1) $y_3(R) = y_4(R) = 0$ where R is the radius of the Moon, (2) $y_6(R) = -\frac{(2n+1)}{R}$, and (3) $y_1(0) = y_2(0) = y_5(0) = 0$. The requirement that the solutions be regular at the origin reduces the number of independent solutions from six to three, since $\mathbf{Y}_2$ is undefined at the origin. The three coefficients are determined by forming the linear combination of solution vectors that satisfies the remaining boundary conditions $(y_3(R), y_4(R), y_6(R)) = (0, 0, -\frac{(2n+1)}{R}) = \mathbf{b}$.

This is accomplished using the projection matrix

$$\mathbf{P} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5.15)$$

The projection matrix selects out the y_3 , y_4 , and y_6 terms from each regular solution vector, which must satisfy the boundary conditions at the surface, discussed above. The three coefficients necessary to compute the correct linear combination of the regular solution vectors can be found from:

$$\mathbf{c} = (\mathbf{P}^T \cdot \mathbf{Y})^{-1} \mathbf{b} \quad (5.16)$$

Once the correct linear combination of regular solutions $\mathbf{y} = \mathbf{Y}_1 \cdot \mathbf{c}$ has been obtained, the desired harmonic degree ($n = 2$ for tides) can be substituted into $\mathbf{Y}_1$ to obtain the solution 6-vector $\mathbf{y}(r)$ in terms of the density, rigidity, gravitational constant, outer radius of the Moon, and desired inner radius at which the stress is to be computed. Of these, y_1 through y_4 are used in our formulation of the stress tensor, as discussed in the next section.

5.2.1 Tidal stress and strain from the solution vector

In this step, we include the time-varying gravitational tidal potential when computing the vector displacement. As discussed earlier, the components of the displacement vector $\mathbf{u} = (u_r, u_\theta, u_\phi)$ are products of radial and angular terms, with (r_s, θ_s, ϕ_s) describing the time-varying position of the Earth, and (r, θ, ϕ) describing the position within the Moon at which stresses are computed.

The elastic strain tensor ϵ_{ij} is formed by taking the vector gradient of the tidal displacement and symmetrizing the resulting tensor.

$$\nabla \mathbf{u} = \begin{bmatrix} \frac{\partial u_r}{\partial r} & \frac{1}{r} \left(\frac{\partial u_r}{\partial \theta} - u_\theta \right) & \frac{1}{r \sin \theta} \left(\frac{\partial u_r}{\partial \phi} - u_\phi \sin \theta \right) \\ \frac{\partial u_\theta}{\partial r} & \frac{1}{r} \left(\frac{\partial u_\theta}{\partial \theta} + u_r \right) & \frac{1}{r \sin \theta} \left(\frac{\partial u_\theta}{\partial \phi} - u_\phi \cos \theta \right) \\ \frac{\partial u_\phi}{\partial r} & \frac{1}{r} \frac{\partial u_\phi}{\partial \theta} & \frac{1}{r \sin \theta} \frac{\partial u_\phi}{\partial \phi} + \frac{u_r}{r} + \frac{u_\theta \cot \theta}{r} \end{bmatrix} \quad (5.17)$$

$$\epsilon_{ij} = \frac{\nabla \mathbf{u} + (\nabla \mathbf{u})^T}{2} \quad (5.18)$$

Tangential stresses ($\sigma_{\theta\theta}$, $\sigma_{\theta\phi}$, and $\sigma_{\phi\phi}$) are related to tangential strains through Equation 5.3. The elastic strain tensor ϵ_{ij} , however, does not account for the effect of self-gravitation, which affects all radial components of stress (σ_{rr} , $\sigma_{r\theta}$, and $\sigma_{r\phi}$). In the same manner in which we computed the displacement vector terms, the radial components of stress are products of radial and angular terms. Time variation is introduced to the stress tensor σ_{ij} through the changing coordinates (distance $r_s(t)$, co-latitude $\theta_s(t)$, and longitude $\phi_s(t)$) of the tide-raising source body (the Earth) as computed from MICA, the Multi-Year Interactive Computer Almanac (Chapter 4 Appendix A).

5.2.2 Propagating the solution vector through a layered model

This process of computing the stress tensor can be extended to a many-layered model with appropriate modifications. First, since the model is no longer homogeneous, we must calculate gravity appropriate to each layer. In the homogeneous model, $g = \frac{4\pi G\rho r}{3}$. In the layered model, $g_{layer} = g_s(\frac{s}{r})^2 + \frac{4\pi G\rho_{layer}}{3}(\frac{r^3-s^3}{r^2})$, where g_s is the gravity below the current layer, s is the radius of the layer below the current layer, and r is the current radius (measured from the center of the Moon, within the desired layer).

Starting with the three regular solutions within the inner-most layer, the propagator matrix $\mathbf{Z}(s, r) = \mathbf{Y}(s_i) \cdot \mathbf{Y}(r_{i+1})^{-1}$ can be used to construct solutions within each layer. In a layered model, there is an additional boundary condition: continuity of the solution vector across layer boundaries. This requires that the solution vector in layer i can be linked to the solution in layer $i + 1$ above it:

$$\mathbf{y}(r_{i+1}) = \mathbf{Z}(s, r) \cdot \mathbf{y}(s_i) \quad (5.19)$$

With a desired model specifying the density ρ , rigidity μ , and radius s

of each layer, from the degree-2 tidal potential the gravity and regular solution vectors can be computed in each layer. From these, the coefficients necessary to form the linear combination of solution vectors that matches boundary conditions can be computed in each layer. The stress tensor can then be built following the same steps as for the homogeneous case.

Since each element in the stress tensor can be written as a product of terms dependent on source coordinates (r_s, θ_s, ϕ_s) and position within the Moon (r, θ, ϕ) , the phase of the temporal variation of the tidal stress (i.e. the timing of stress peaks) is independent of the internal structure model (also noted in Minshull and Goulet (1988)). This means that any investigation of the relationship between tidal stress and moonquake occurrence times does not require a precise knowledge of the lunar interior. The variation of density and elastic moduli with radius affects only the magnitude of the elements of the stress tensor at a given depth. Therefore in the remainder of our calculations, we use a homogeneous elastic model of the lunar interior, with density $\rho = 3000 \text{ kg/m}^3$ and rigidity $\mu = 10^{10} \text{ Pa}$.

5.3 Stress tensor exploration

As with any real symmetric matrix, the stress tensor has real eigenvalues and orthogonal eigenvectors. Physically, the eigenvectors represent those directions in which the traction is parallel to the associated unit normal (the unit normal being perpendicular to a plane in which the shear stress is zero). A logical first step in our stress analysis is to examine the principal stress directions and magnitudes by computing the eigenvectors and eigenvalues of the stress tensor.

Since the gravitational interaction between the Earth and Moon is the largest contributor to tidal stress within the Moon, we expect the maximum principal stress direction to always point toward the Earth. Because the self-gravitation of the Moon tries to keep the Moon spherical, the maximum principal stress may not always point directly toward the Earth, but the deviation is small. To il-

lustrate, we compute the tidal stress tensor due to the Earth's influence as a function of geographical position within the Moon, at a constant depth within the moonquake source region. Initially we assume the Earth is at its mean position (distance $r = 384,400$ km, co-latitude $\theta = 90^\circ$, longitude $\phi = 0^\circ$), and plot the maximum principal stress directions (Figure 5.1a). As expected, at all locations on our spherical surface within the Moon, the maximum principal stress points towards the Earth.

Rather than investigating the stresses at a single point in time as a function of geographical position at constant depth within the Moon, we are interested in exploring how the maximum principal stress directions at a given source location change as the Moon moves through its orbit. In Figure 5.1b, we show the principal stress directions computed at the A1 source location, according to the position of the Earth at each of the 441 A1 moonquakes.

Because visualization of all three principal stress directions as a function of time at a single source location in the three-dimensional manner shown in 5.1b can be difficult, we instead switch to a two-dimensional formulation in which the eigenvectors are defined by the angles γ and α with respect to a local coordinate system at each point within the Moon. At each location within the Moon, $\gamma = 0^\circ$ corresponds to a vector pointing locally outward and γ increases to the South; α increases counter-clockwise about the local vertical from local South, as seen from above. Principal stress directions plotted in this coordinate system are shown in Figure 5.2 with γ ranging from 0 to 180° and α ranging from 0 to 360° (a full sphere). In order to visualize the coordinate axes formed by the principal stress directions, both positive and negative eigenvectors are plotted.

We next explore the principal stress directions at moonquake times and compare them to those at uniform (1-day) time steps. In Figure 5.3, we show the results at the A1 source location. For the most part, the eigenvectors at A1 moonquake times span the same (γ, α) range as eigenvectors at 1-day time steps. For comparison, in Figure 5.4 we show the sub-Earth longitude plotted against the

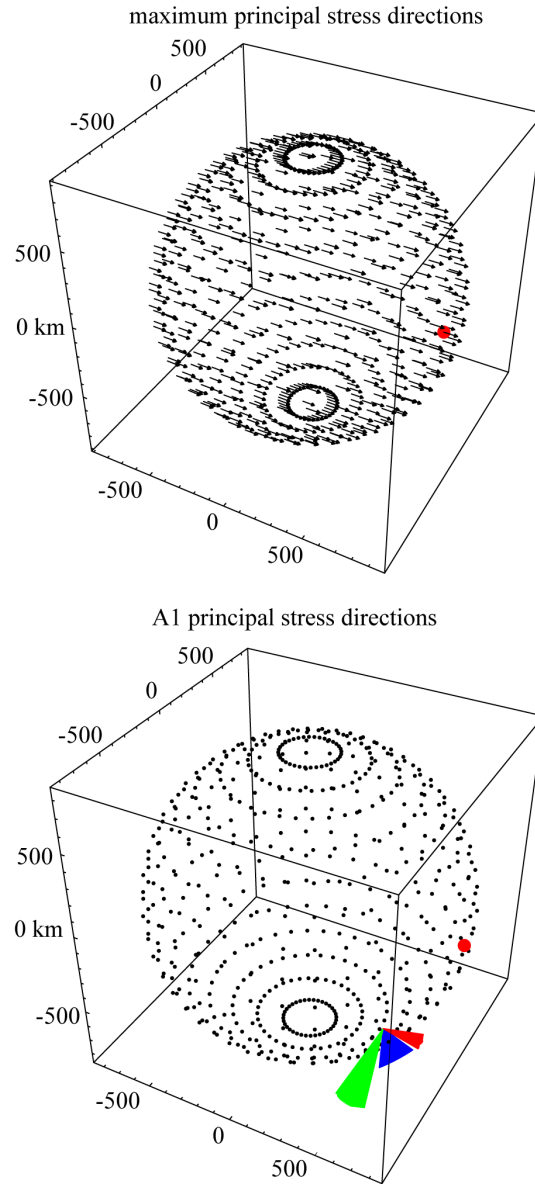


Figure 5.1 Principal stress directions. (a) Maximum principal stress directions (eigenvectors corresponding to the largest absolute value eigenvalues) computed every 10° in latitude and longitude at 869 km depth, due to the Earth at its mean position. The red dot marks the intersection of the line connecting the centers of the Earth and Moon with the imaginary interface at 869 km depth, within the commonly accepted deep moonquake generation zone of 750-1000 km. (b) Principal stress directions at the A1 source due to Earth's position at the times of A1 events. Red, green, and blue correspond to maximum, intermediate, and minimum principal stress directions, respectively.

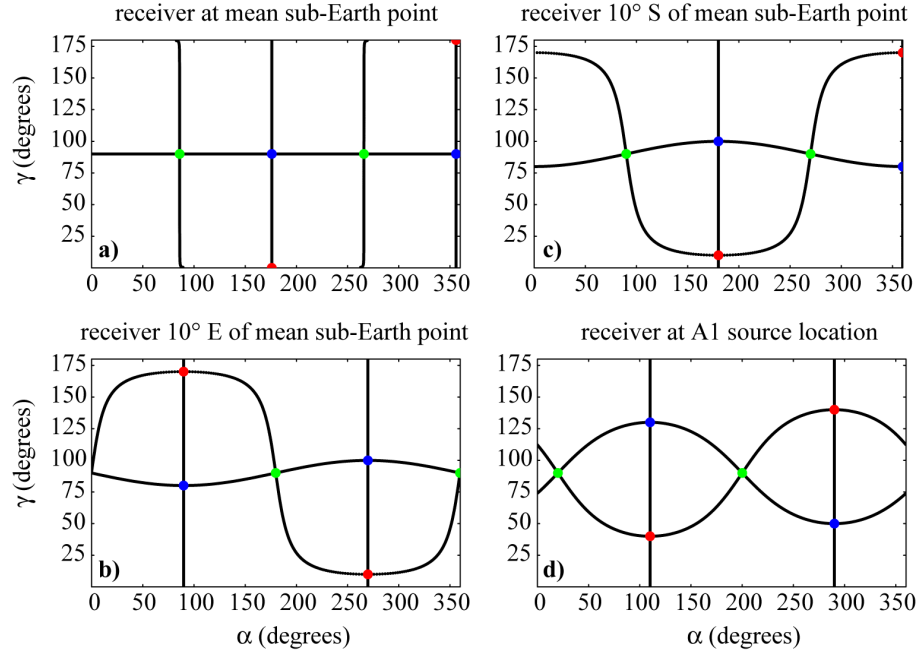


Figure 5.2 Principal stress directions at various locations. Maximum, intermediate, and minimum (red, green, blue) principal stress directions due to the Earth in its mean position plotted as (γ, α) pairs. The black lines define the planes formed by each pair of principal stress directions. (a) Principal stress directions computed at the mean sub-Earth point. As expected, the maximum principal stress direction (red dot) points towards Earth, in this case local vertical ($\gamma = 0^\circ$) (b) Principal stress directions computed 10° East of the mean sub-Earth point. (c) Principal stress directions computed 10° South of the mean sub-Earth point. (d) Principal stress directions at the A1 source location (latitude -15.7° N, longitude -36.6° E).

sub-Earth latitude at A1 moonquake times and at 1-day time steps. The behavior of the maximum principal stress directions at the times of A1 moonquakes is similar to that of the sub-Earth point at the same times: as the sub-Earth point moves through its trajectory with respect to the Moon, the principal stress directions move through a constrained region of similar shape.

At the A1 source location, there does not seem to be a strongly preferred geometry at the times of A1 events, since the principal stress directions at quake times are distributed similarly to those at 1-day time steps. As we saw in the last chapter, however, for some other clusters this is not always the case. In Figure 5.5

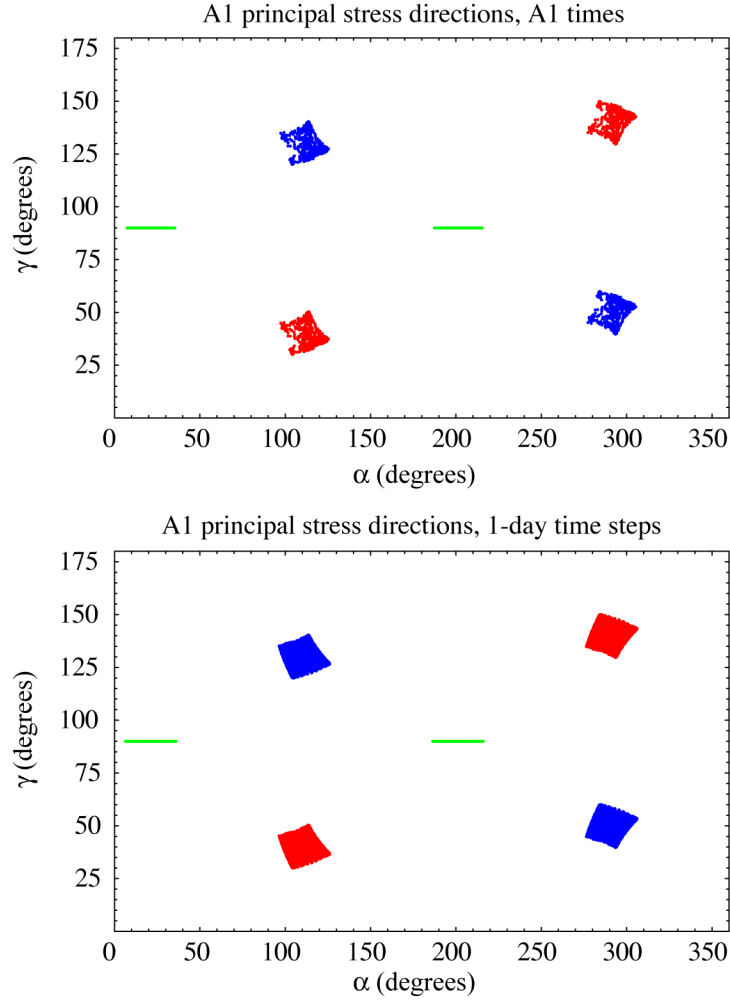


Figure 5.3 A1 principal stress directions. Maximum, intermediate, and minimum (red, green, blue) principal stress directions at the A1 source due to the Earth at the times of A1 moonquakes (top) and at uniform 1-day time steps (bottom).

we show the principal stress directions at the A22 source location, due to position of the Earth at the times of A22 events. This plot shows that the principal stress directions at the times of A22 events are constrained to a small region compared to the angular distance spanned by the principal stress directions at 1-day time steps.

In general, from cluster to cluster, the distribution of principal stress directions at moonquake times compared to the distribution at uniform 1-day time steps is not the same. This variability was also observed in our geometry analysis

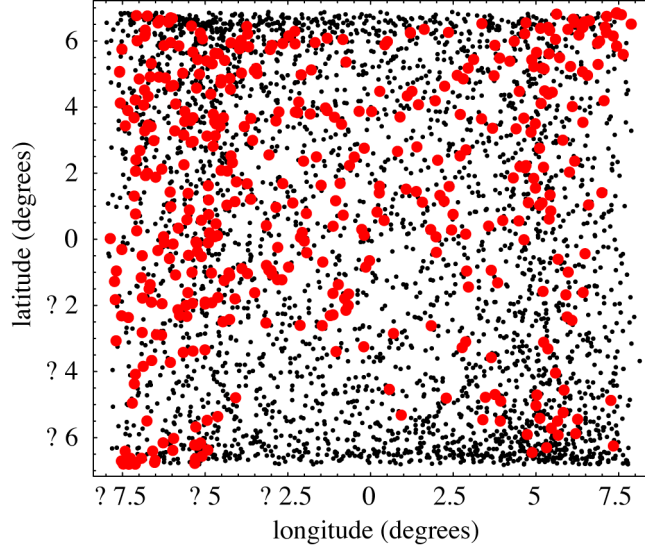


Figure 5.4 A1 sub-Earth point geometry. Position of the sub-Earth point (longitude, latitude) at the times of A1 moonquakes (red dots) and at uniform 1-day time steps (black dots). Like the maximum principal stress directions (Figure 5.3), the two span close to the same angular range.

(Chapter 4). Just as nearby clusters respond in different ways to the parameters describing the position of the Earth, some clusters produce moonquakes at certain times in the stress cycle, and some produce moonquakes at other times.

Note that, in Figures 5.3 and 5.5, the intermediate principal stress direction is always horizontal ($\gamma = 90^\circ$). This is a natural consequence of the local coordinate system. Since the maximum principal stress always points towards the Earth, and the remaining two principal stress directions must form right-handed coordinate axes, one will always lie in the plane tangent to the spherical shell at the depth in the Moon at which the stress is evaluated, corresponding to $\gamma = 90^\circ$.

5.4 Shear and normal stresses and rates

A general stress tensor $\mathbf{T}$, in the coordinate system (1,2,3) can be written in the form of a symmetric 3x3 matrix:

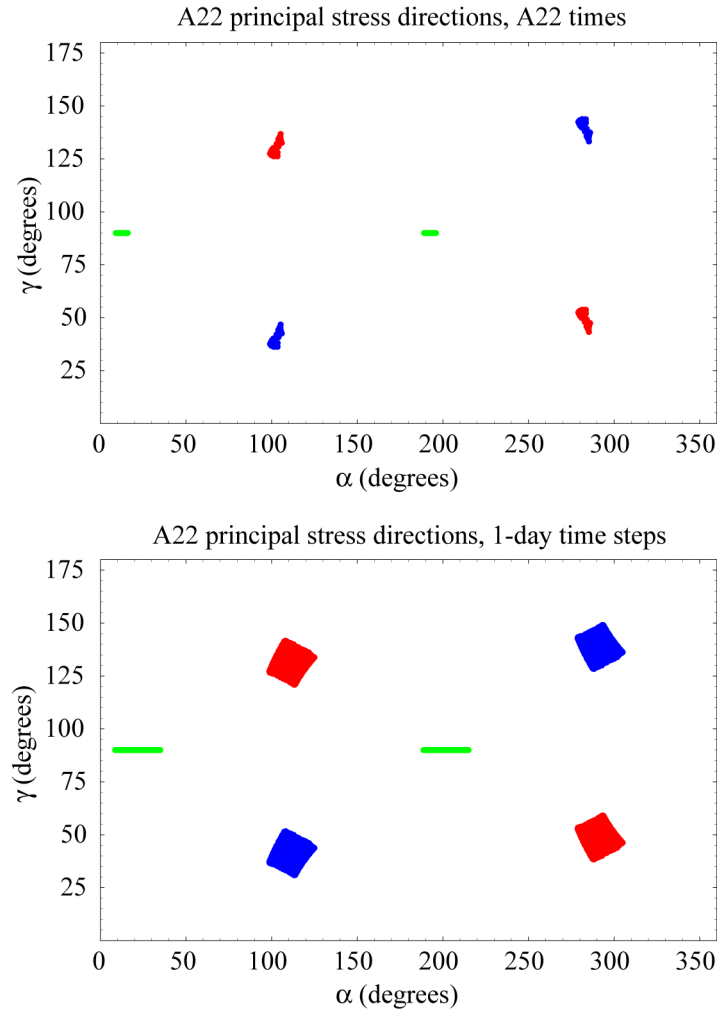


Figure 5.5 A22 principal stress directions. Maximum, intermediate, and minimum (red, green, blue) principal stress directions at the A22 source due to the Earth at the times of the 48 A22 moonquakes (top) and at uniform 1-day time steps (bottom).

$$\mathbf{T} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix} \quad (5.20)$$

It has the defining property that, for a plane specified by unit normal vector $\hat{\mathbf{u}}$, the force per unit area acting across that plane (the traction) is given by

$$\mathbf{t} = \mathbf{T} \cdot \hat{\mathbf{u}} \quad (5.21)$$

The traction can be written as the sum of two components, one of them (the normal stress vector $\mathbf{n}$) perpendicular to the plane, and the other (the shear stress vector $\mathbf{s}$) in the plane. The normal component of the traction vector (the normal stress) is

$$n = \hat{\mathbf{u}} \cdot \mathbf{t} = \hat{\mathbf{u}} \cdot \mathbf{T} \cdot \hat{\mathbf{u}} \quad (5.22)$$

and the normal stress vector is $\mathbf{n} = n\hat{\mathbf{u}}$. The shear stress vector is $\mathbf{s} = \mathbf{t} - \mathbf{n}$ and the magnitude of this vector (the shear stress) is

$$s = \sqrt{\mathbf{s} \cdot \mathbf{s}} \quad (5.23)$$

Before we can compute shear and normal stress at the deep moonquake hypocenters, however, we must specify a failure plane orientation. The plane is defined by a local unit normal vector $\hat{\mathbf{u}}$ with a dip γ and strike α . Note that a vertical unit normal vector ($\gamma = 0^\circ$) corresponds to a horizontal failure plane. The dip of the plane increases to the South from horizontal and the strike increases counter-clockwise from South, when viewed from above. The entire suite of possible plane orientations can be described with γ ranging from 0 to 90° and α from 0 to 360° . In this case it is not necessary to extend γ to 180° as we did in the principal stress analysis, since a plane defined by a given unit normal is the same plane as defined by the negative of that unit normal. However, for now the plotting convention of γ ranging from 0 to 180° is left as in Figure 5.2, for comparison.

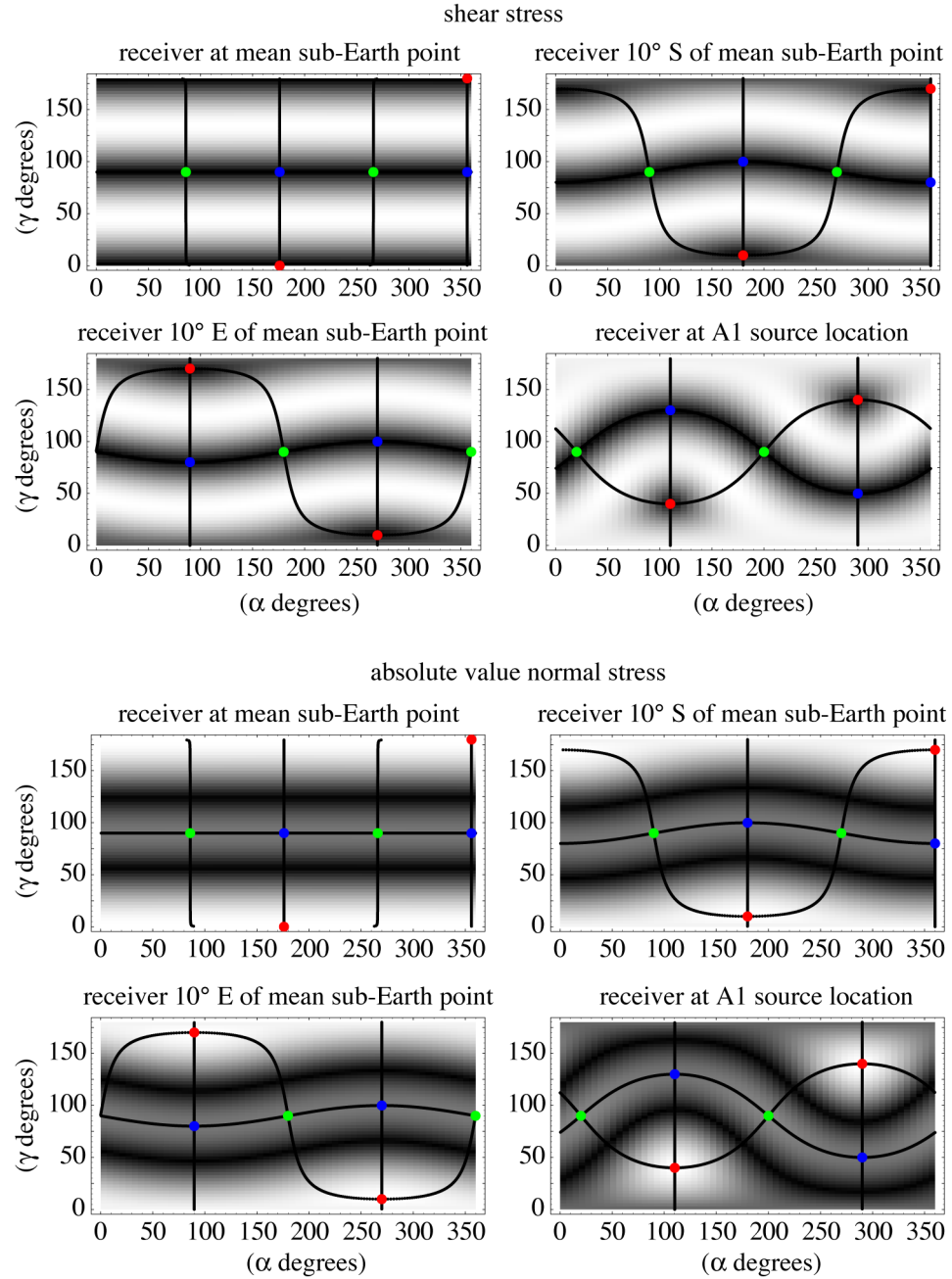


Figure 5.6 Shear and normal stress at test locations. Shear (upper) and normal (lower) stress computed on all possible plane orientations, at the four receiver positions (as in Figure 5.2), due to the Earth at its mean position. Black corresponds to zero stress and white to positive stress. The absolute value of the normal stress is shown, so that dark corresponds to low (not negative) absolute values of stress. The maximum, intermediate, and minimum (red, green, blue) principal stress directions are shown for comparison.

To begin, we first compute the shear and normal stress over all possible plane orientations at the four receiver locations shown in Figure 5.2, due to the Earth in its mean position (Figure 5.6). Also shown are the principal stress directions from Figure 5.2. As defined, the principal stress directions represent the normal vectors to those planes in which the shear stress is zero. For plotting purposes, the absolute value of the normal stress is shown, so that dark regions of the plot correspond to low values (not negative values) of normal stress. This plotting convention is not necessary for the shear stress, since (as defined) it is always positive.

We are interested in determining whether temporal variations in shear and normal stress can be linked to moonquake occurrence times. For example, the shear and normal stresses on a locally horizontal plane at the A1 source location over the course of the Apollo experiment are shown in Figure 5.7.

As mentioned previously, we also have reason to believe that moonquakes might be sensitive to stress rates. To compute stress rates, we first compute the shear and normal stress on a given plane at uniform time steps. These time series are then interpolated with cubic splines (piece-wise cubic polynomials) of the dependent variable (time), so their derivatives can be computed analytically. The resulting functions can then be evaluated at both uniform time steps and at moonquake times. This procedure is less computationally expensive than keeping the explicit time dependence of the stress tensor and computing the derivative directly, since doing so would require the repeated derivation of the many trigonometric terms by which the source position is expressed. Shear and normal stress rates on a locally horizontal plane at the A1 source location over the course of the Apollo experiment are shown in Figure 5.8.

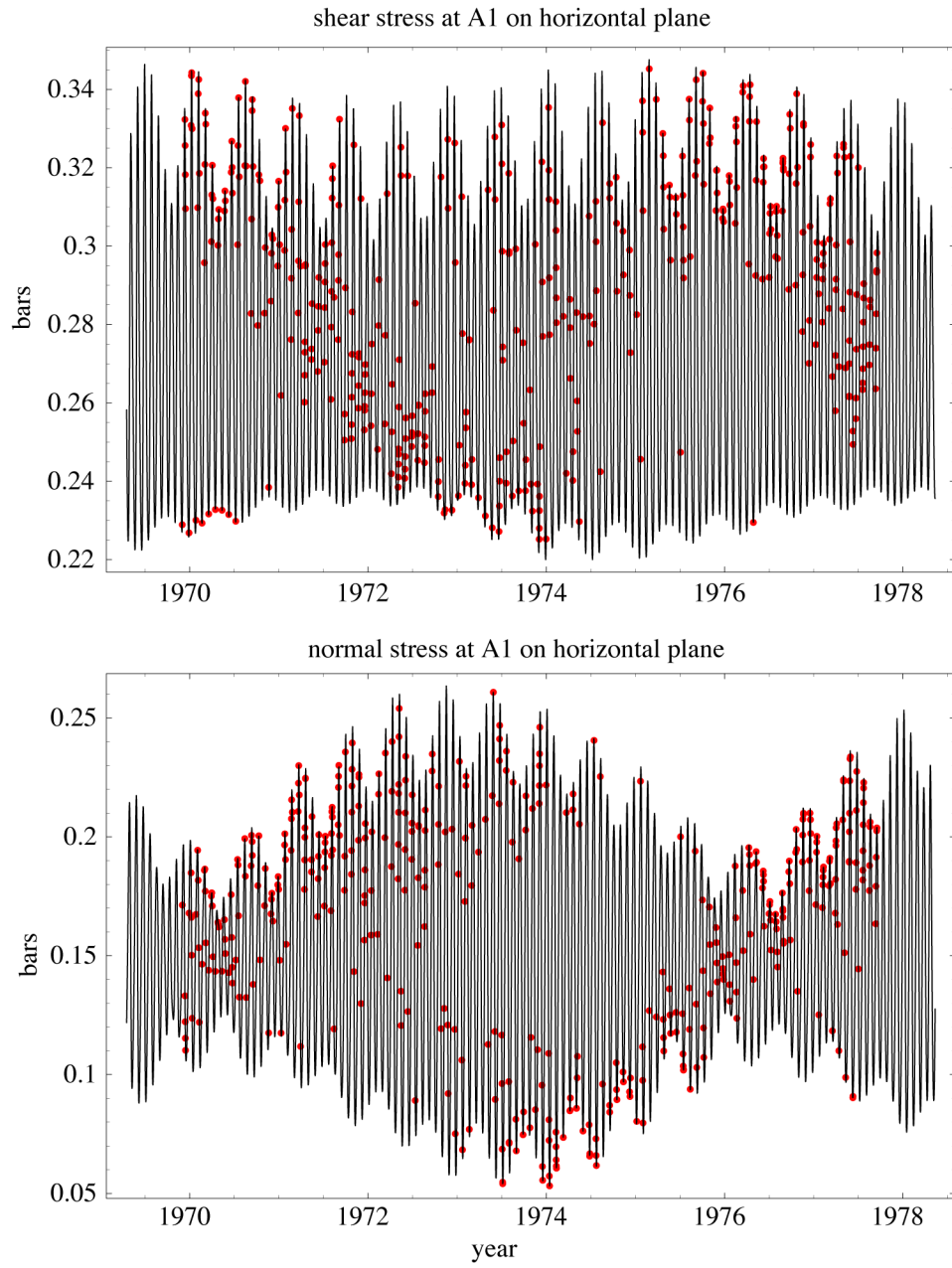


Figure 5.7 A1 shear and normal stresses. Shear and normal stresses (in bars) evaluated at the A1 location (latitude -16.6°N , longitude -39.8°E) on a horizontal plane ($\gamma, \alpha = 0^{\circ}, 0^{\circ}$). The black line shows stresses evaluated on uniform 1-day time steps. The red dots show stresses at the times of A1 moonquakes.

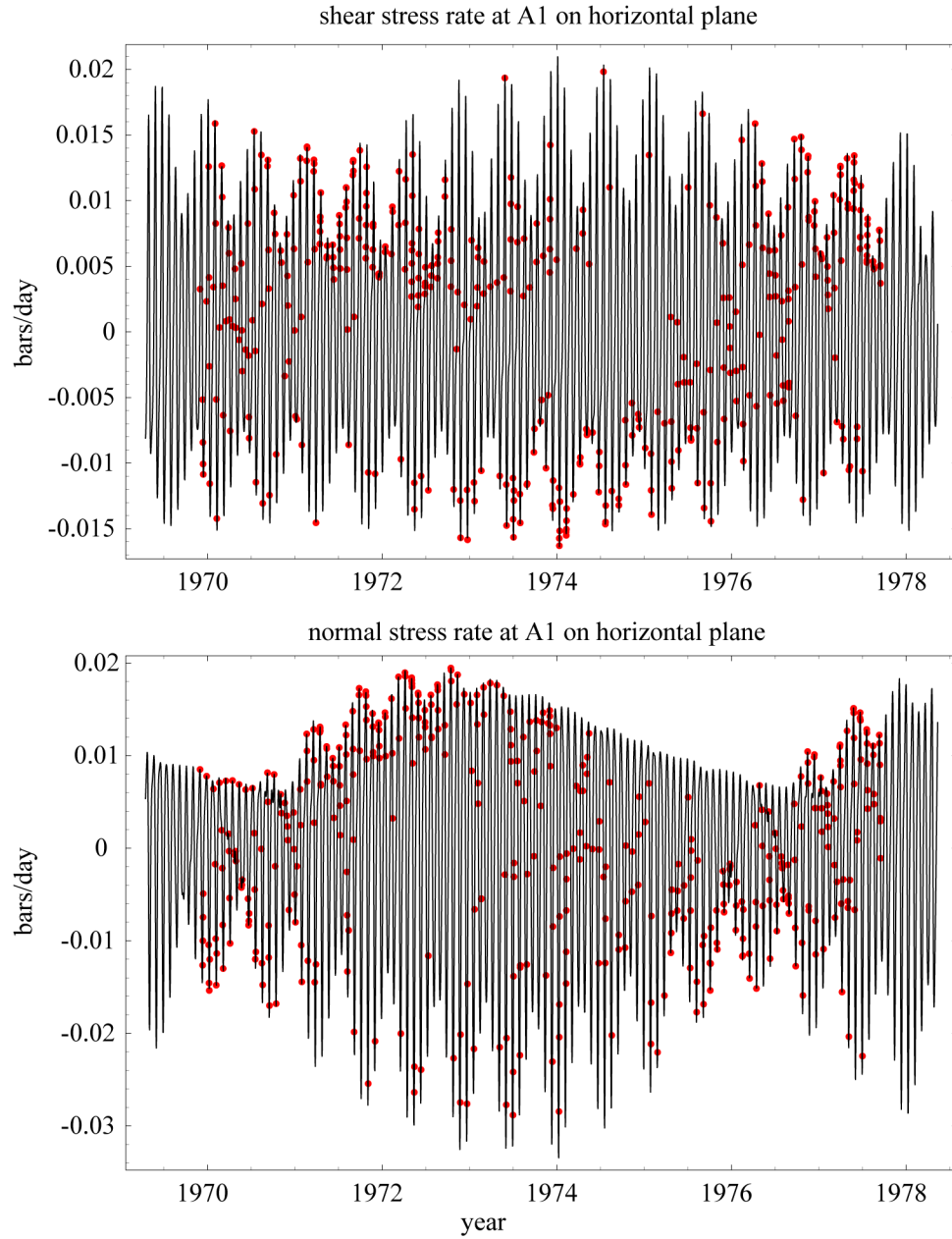


Figure 5.8 A1 shear and normal stress rates. Shear and normal stress rates (in bars per day) evaluated at the A1 location (latitude -16.6°N , longitude -39.8°E) on a horizontal plane ($\gamma, \alpha = 0^{\circ}, 0^{\circ}$). The black line shows stress rates evaluated on uniform 1-day time steps. The red dots show stress rates at the times of A1 moonquakes.

5.5 Grid search

It is not immediately obvious what plane orientation (γ, α) can be expected to produce a favorable stress state for moonquake occurrence. In Figures 5.7 and 5.8, we see that on a horizontal plane, A1 moonquakes do not correlate in a consistent way with a particular stress or stress rate. Because of the high S- to P-wave arrival amplitudes, deep moonquakes have traditionally been assumed to represent shear failure (Lammlein et al., 1974). Thus we could begin by searching for the plane that maximizes shear stress at moonquake times. Previous studies have attempted such searches (Goultly, 1979; Minshull and Goultly, 1988) for the A1 cluster. However, while A1 occurrence times were found to correlate well with shear stress peaks over short periods, no such correlation was found to extend throughout the entire duration of the seismic experiment. In addition, these and other studies presented varying conclusions regarding fault geometry and, in the cases where individual tensor components were analyzed, relevant stress tensor terms.

To better understand which stress factors more highly influence moonquake occurrence, we perform a search for *some* stress state, over the range of all possible plane orientations, which best approximates a constant value at the times of moonquakes. This method is more objective because it allows us to explore the factors to which deep moonquakes respond, rather than imposing an *a priori* failure criterion such as maximum shear stress.

For example, consider searching for the plane orientation (γ_1, α_1) that produces an approximately constant value of normal stress (only) at the times of moonquakes. If we searched again using the shear stress as a criteria, we might recover the plane orientation (γ_2, α_2) . But if the fits obtained to the shear and normal stresses are similar, we might ask ourselves which plane orientation is “correct.” It may very well be possible to get a better fit by examining a failure criterion that combines the effect of both shear (σ_S) and normal (σ_N) stress. An

example of this would be the Coulomb stress criterion:

$$\sigma_C = \sigma_S + \mu_f(\sigma_N + P) \quad (5.24)$$

where μ_f is the coefficient of friction and P is the pore pressure. Coulomb stress has been suggested to be important in terrestrial earthquake occurrence (Stein and Lisowski, 1983; Oppenheimer et al., 1988). The pore pressure in the Moon is negligible, since there is likely no water at the depths of deep moonquakes. However, to compute Coulomb stress, we must assume a value for the coefficient of friction, a physical parameter which is not well constrained for the Moon, especially at the depth of deep moonquakes. Instead, we define a more general criterion as follows.

We examine the sensitivity of moonquake occurrence to four factors: normal stress, shear stress, normal stress rate, and shear stress rate, computed over all possible plane orientations. Our goal is to identify the plane that produces a linear combination of these factors resulting in the most nearly constant values at the times of moonquakes. This allows us to analyze the dependence of moonquake occurrence on a variety of influences, based only on the times of the events. The problem is formulated as follows: we seek the stress coefficients w_N and w_S , and the stress rate coefficients $w_{\dot{N}}$ and $w_{\dot{S}}$, necessary to minimize

$$C - (w_N\sigma_N + w_S\sigma_S + w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S) \quad (5.25)$$

in a least-squares sense, where C is a constant stress, w_N and w_S are unit-less, and $w_{\dot{N}}$ and $w_{\dot{S}}$ have units of days. Any constant stress C can be chosen, since the resulting linear combination can be changed with a scale factor. We use $C = 1$ bar. We also separately minimize $C - (w_N\sigma_N + w_S\sigma_S)$ (just stresses) and $C - (w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S)$ (just stress rates) in order to gauge the relative importance of stresses and stress rates at the times of moonquakes.

On a grid of all possible plane orientations, with 10° intervals of dip γ and strike α , we search for the linear combination of stresses (and/or rates)

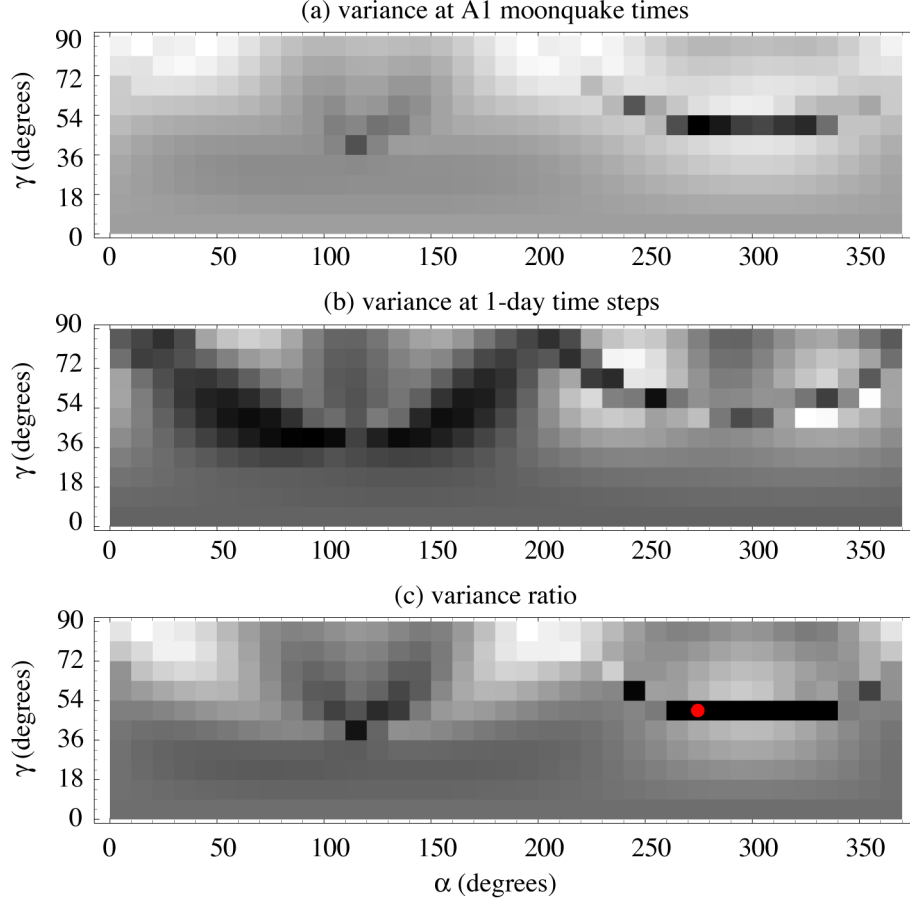


Figure 5.9 A1 variance. Variance of the linear combination of stresses and weights at each (γ, α) point that minimizes $1 - w_N \sigma_N + w_S \sigma_S$. Black is low and white is high. (a) Variance at A1 moonquake times. (b) Variance at uniform 1-day time steps. (c) Variance ratio. The grid point where the variance ratio is minimum (0.4386) is marked with a red dot.

such that the ratio of variances computed at quake times and at 1-day time steps is minimized. At each (γ, α) grid point, we solve for the coefficients necessary to minimize Equation 5.25. Using those coefficients, at each grid point we then compute the linear combination of stresses and rates. We define the best-fit plane orientation as the one which minimizes the ratio of the variance of the best-fitting linear combination at quake times to the variance of said linear combination at 1-day time steps. Using the variance ratio as the test statistic removes the bias associated with the uneven sampling of moonquakes.

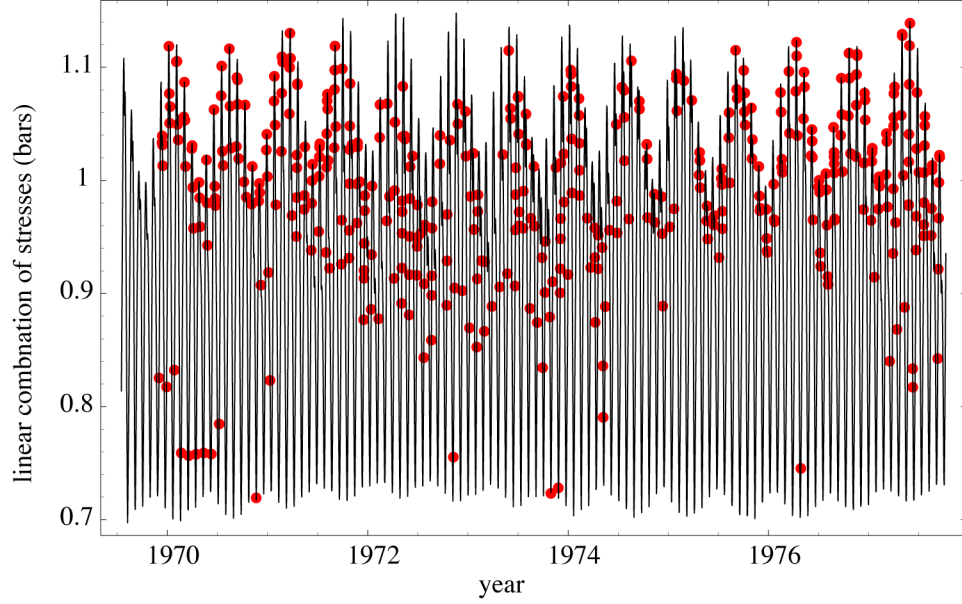


Figure 5.10 A1 linear combination of normal and shear stress. Linear combination of normal and shear stresses such that $-4.6626\sigma_N + 2.6460\sigma_S \simeq 1$ computed on the plane with $\gamma = 50^\circ$ and $\alpha = 270^\circ$ at the A1 source. The black line is the linear combination computed at 1-day time steps. The red dots are the linear combination at A1 moonquake times, and group close to 1 bar as computed.

The variance at A1 moonquake times, 1-day time steps, and the variance ratio as a function of γ and α are shown in Figure 5.9 for the best-fit linear combination of normal and shear stresses (no rates) computed at the A1 source location. Because we evaluate a different linear combination at every plane orientation (γ, α) , and we compute a variance of each linear combination evaluated at many times, the plots in Figure 5.9 do not vary smoothly as do the plots of shear and normal stress due to a stress tensor at a single point in time (Figure 5.6).

In Figure 5.9c, the minimum variance ratio is marked with a red dot. In this case, the minimum variance ratio is 0.4386, the weights w_N and w_S are -4.6626 and 2.6460 respectively, and $(\gamma, \alpha) = (50^\circ, 270^\circ)$. The resulting linear combination is shown in Figure 5.10.

The best-fitting linear combination of normal and shear stress shown in Figure 5.10 for A1 is an improvement over the behavior of the individual stresses computed on a horizontal plane (Figure 5.7). However, we are also interested

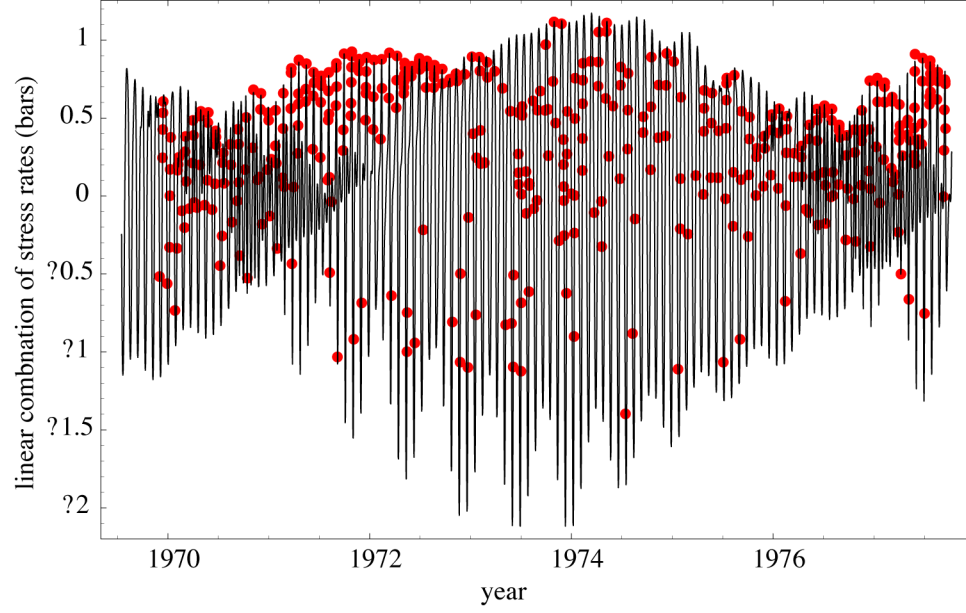


Figure 5.11 A1 linear combination of normal and shear stress rates. Linear combination of normal and shear stress rates such that $w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_{\dot{N}} = 2.3977$ days and $w_{\dot{S}} = -67.9453$ days, computed on the plane with $\gamma = 30^\circ$ and $\alpha = 100^\circ$ at the A1 source. The black line is the linear combination computed at 1-day time steps. The red dots are the linear combination at A1 moonquake times.

in determining how strongly moonquakes respond to stress rates. As discussed earlier, the fact that some moonquake times are coincident with monthly stress peaks suggests that some clusters are sensitive to stress rates. In addition, we have observed that moonquake occurrence at some clusters is heavily influenced by the rate of change of the Earth's position (Chapter 4).

For A1, the linear combination of normal and shear stress rates such that $w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$ is shown in Figure 5.11. Again, the linear combination of stress rates fits moonquake occurrence better than the individual stress rates computed on a horizontal plane (Figure 5.8). In this case, the fit has a slightly higher minimum variance ratio (0.4586) than that obtained using only shear and normal stresses, suggesting that A1 moonquakes respond more strongly to stresses than they do to stress rates.

Lastly, we compute the linear combination of both stresses and rates

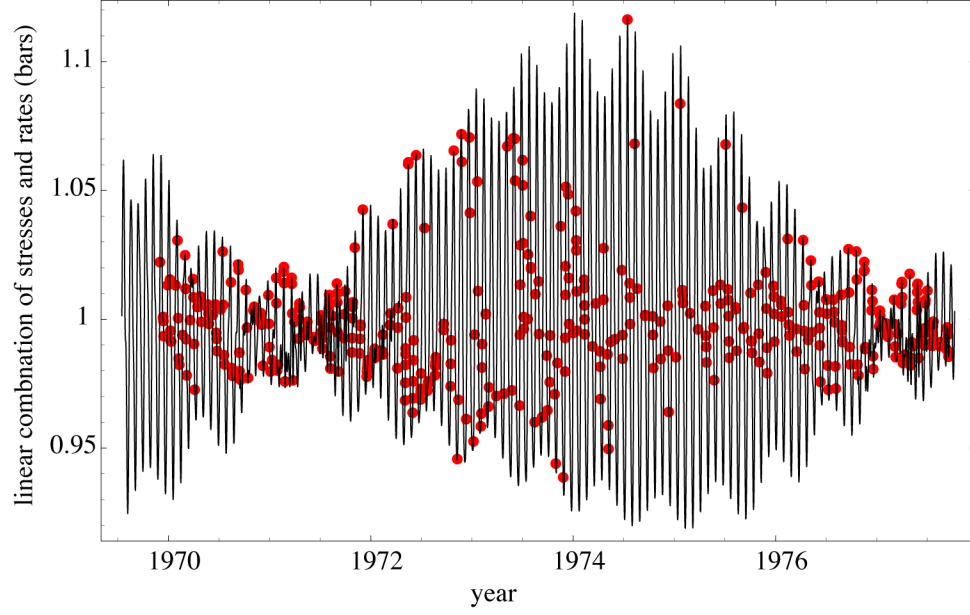


Figure 5.12 A1 linear combination of normal and shear stresses and rates. Linear combination of normal and shear stresses and rates such that $w_N\sigma_N + w_S\sigma_S + w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_N = -0.3505$, $w_S = 3.6709$, $w_{\dot{N}} = 9.3921$ days, and $w_{\dot{S}} = -1.0386$ days, computed on the plane with $\gamma = 30^\circ$ and $\alpha = 200^\circ$ at the A1 source. The black line is the linear combination computed at 1-day time steps. The red dots are the linear combination at A1 moonquake times.

which minimizes Equation 5.25 with $C = 1$ bar. The fit for A1 is better than that obtained using stresses or rates alone (minimum variance ratio = 0.3348, Figure 5.12); this is to be expected since in this case we have used four parameters in the fit instead of two.

Grid search results for the 51 clusters shown in Figure 4.1 are listed in Table 5.1 for stresses (method 1), Table 5.2 for stress rates (method 2), and Table 5.3 for stresses and rates (method 3). In Figure 5.13, we show a comparison of the minimum variance ratio achieved using each of the three fit methods for each cluster.

From this comparison it is clear that A1 is not a cluster for which typically “good” results were achieved (i.e. the minimum variance ratio achieved for A1 is higher than that achieved for many other clusters). In Figures 5.14 and 5.15, we show the best-fitting linear combination using each fit method for cluster A16, a

particularly good example of how lower-variance fits differ from those for A1.

Table 5.1 Grid search results, normal and shear stress.

cluster	min. var. ratio	γ (degrees)	α (degrees)	w_N	w_S	f-probability [†] (%)
A1	0.4385	50	270	-4.6626	2.6460	0.00
A3	0.3053	60	90	1.3764	3.7073	0.00
A5	0.2637	50	310	-4.2102	2.7602	0.00
A6	0.5983	60	40	-4.0011	2.2765	0.00
A7	0.2135	40	280	1.0076	3.2337	0.00
A8	0.5192	80	220	-5.1246	-0.8629	0.00
A9	0.2573	70	290	-5.6457	-1.2638	0.00
A10	0.5167	60	240	-5.4529	-1.0347	0.00
A13	0.2034	60	240	-5.7362	-1.2324	0.00
A14	0.3146	60	340	-4.7759	1.1663	0.00
A15	0.3676	80	220	-5.3264	1.0569	0.00
A16	0.1933	80	110	-6.2544	-1.8575	0.00
A17	0.0217	60	240	-7.2688	-1.8547	0.00
A18	0.2534	60	70	-5.8276	-1.2664	0.00
A19	0.0190	70	340	1.4358	2.1973	0.00
A20	0.6159	80	150	-3.9654	3.1736	0.01
A21	0.2500	70	210	-5.1332	-1.5643	0.00
A22	0.0188	80	20	-5.2908	-5.7133	0.00
A25	0.0942	30	70	-5.6949	-0.7013	0.00
A26	0.6154	10	320	2.4305	-0.4354	1.83
A28	0.0087	80	80	-6.2657	-0.2599	0.00
A30	0.1952	60	210	-4.3279	2.3006	0.00
A32	0.1534	70	40	-5.6844	-0.4799	0.00
A33	0.0987	30	230	-6.5043	-3.6878	0.00
A34	0.1065	20	310	3.5586	0.2922	0.00
A35	0.6554	80	170	-5.3834	-1.6749	2.50
A36	0.2818	20	20	2.5199	-0.4511	0.00
A37	0.0575	30	280	0.5716	4.0723	0.00
A38	0.5095	60	150	-4.8598	-0.5108	0.96
A39	0.0811	80	250	-6.3043	-3.7497	0.00
A40	0.1362	20	120	2.6818	-0.3436	0.00
A41	0.0639	40	100	2.8235	0.3387	0.00
A42	0.3161	80	50	-1.0124	4.8148	0.00
A44	0.4544	30	170	-5.2018	-1.0130	0.00
A51	0.1430	50	90	-5.5941	-1.8438	0.00
A65	0.0808	80	40	-3.9073	2.7970	0.00
A73	0.2302	30	80	3.6473	-0.6827	0.00
A86	0.6708	80	230	-4.0174	2.4141	9.02
A96	0.0677	30	240	4.8452	-1.8129	0.00
A97	0.0864	10	290	0.5873	5.0516	0.00
A100	0.5518	60	110	-5.9937	-1.2250	1.97
A201	0.5221	70	290	-5.3664	-0.5876	0.09
A202	0.2202	10	290	1.8601	2.2113	0.00
A204	0.1382	60	110	2.1851	2.0922	0.00
A218	0.2076	40	210	-5.5999	-2.1317	0.00
A223	0.1397	70	110	-4.3392	2.5427	0.00
A224	0.2675	90	70	-4.7992	-0.8502	0.00
A234	0.2278	70	210	-5.5699	-2.3546	0.00
A238	0.0623	30	300	1.8600	3.7609	0.00
A257	0.6554	80	220	-4.1460	2.4619	8.05
A271	0.5440	50	320	2.9098	-0.3602	2.87

[†] rounded to the nearest hundredth of a percent

Table 5.2 Grid search results, normal and shear stress rates.

cluster	min. var. ratio	γ (degrees)	α (degrees)	$w_{\dot{N}}$	$w_{\dot{S}}$	f-probability [†] (%)
A1	0.4585	30	100	2.3977	-67.9453	0.00
A3	0.2463	40	350	87.1434	-29.0889	0.00
A5	0.1553	40	80	-64.8552	-97.5951	0.00
A6	0.5242	40	50	-98.7142	63.7391	0.00
A7	0.1404	50	40	-130.9530	55.0867	0.00
A8	0.2709	90	230	-117.8060	8.0022	0.00
A9	0.0684	70	180	59.4420	42.4894	0.00
A10	0.2124	60	30	-117.2510	-8.1371	0.00
A13	0.2294	40	280	-64.3928	90.3603	0.00
A14	0.1759	60	240	-142.7730	40.2624	0.00
A15	0.1167	90	0	-289.3340	-35.7144	0.00
A16	0.0608	50	300	99.3570	-103.9750	0.00
A17	0.0208	60	140	-98.0702	-19.5615	0.00
A18	0.1963	60	30	-109.9140	61.5077	0.00
A19	0.0410	80	290	-71.7595	100.3510	0.00
A20	0.4946	20	60	19.3861	-4.0551	0.00
A21	0.1486	80	210	-142.6890	24.6718	0.00
A22	0.0959	70	180	-58.1275	-77.0705	0.00
A25	0.0797	20	80	46.5406	-176.2790	0.00
A26	0.6767	90	80	-63.5177	42.6341	5.55
A28	0.0048	90	90	78.7522	62.7600	0.00
A30	0.1230	70	200	-38.8703	-63.1301	0.00
A32	0.0470	60	270	83.2541	-33.8727	0.00
A33	0.0452	30	270	-231.7090	-47.0746	0.00
A34	0.0386	70	270	138.4670	7.5566	0.00
A35	0.3524	80	30	-37.2287	-55.9103	0.00
A36	0.1317	80	270	-101.7770	65.9749	0.00
A37	0.0368	70	320	49.6215	-57.8189	0.00
A38	0.5398	50	280	20.2309	-55.0048	1.73
A39	0.0548	70	310	115.6580	-199.5570	0.00
A40	0.2002	90	60	-28.6249	91.7055	0.00
A41	0.1795	20	60	-18.2275	108.4770	0.00
A42	0.3183	50	200	-100.5640	-42.0346	0.00
A44	0.4648	50	190	-84.5658	-36.2556	0.00
A51	0.1443	30	300	11.3726	81.8425	0.00
A65	0.1290	50	310	53.8736	-27.2694	0.00
A73	0.3617	60	180	-25.7453	-71.3450	0.04
A86	0.3036	20	320	-120.5560	50.5874	0.00
A96	0.1327	20	260	-26.6411	-112.3360	0.00
A97	0.0669	30	180	-47.8452	197.6460	0.00
A100	0.4375	50	50	-101.4390	-4.6009	0.16
A201	0.1895	80	40	126.8000	-33.6809	0.00
A202	0.2261	10	40	9.9762	-59.1912	0.00
A204	0.0493	40	230	-148.1890	-45.4449	0.00
A218	0.2745	30	210	-110.0010	78.1066	0.00
A223	0.2083	90	280	-43.6099	-59.5176	0.00
A224	0.2816	80	60	-52.9495	67.4996	0.00
A234	0.1775	80	220	-151.0660	62.9861	0.00
A238	0.0096	80	340	75.6445	-20.2688	0.00
A257	0.1138	20	170	-70.0140	31.7037	0.00
A271	0.2626	90	50	-86.8554	61.1863	0.00

[†] rounded to the nearest hundredth of a percent

Table 5.3 Grid search results, normal and shear stresses and rates.

cluster	min. var. ratio	γ (degrees)	α (degrees)	w_N	w_S	$w_{\hat{N}}$	$w_{\hat{S}}$	f-probability [†] (%)
A1	0.3348	30	200	-0.3505	3.6709	9.3921	-1.0386	0.00
A3	0.2394	40	230	-4.0588	3.3281	9.3042	4.9826	0.00
A5	0.0690	50	270	-5.4602	0.4292	0.0268	-9.9447	0.00
A6	0.3448	70	40	-4.4454	1.6020	4.9077	6.9357	0.00
A7	0.0368	60	40	-4.6408	1.3258	1.9023	6.9807	0.00
A8	0.2365	50	120	2.3034	1.3402	-8.3245	5.3351	0.00
A9	0.0448	60	330	-4.2561	2.9613	12.2548	9.2698	0.00
A10	0.2474	70	120	1.9656	2.0903	-9.2416	6.5383	0.00
A13	0.0721	50	240	-5.1933	0.7817	0.4602	9.4555	0.00
A14	0.0735	60	230	-4.7110	2.0730	9.5339	7.8988	0.00
A15	0.0676	80	270	-6.4700	0.1792	-3.3245	11.6362	0.00
A16	0.0042	80	90	-5.1173	0.5406	-5.6555	-9.6449	0.00
A17	0.0031	80	210	-2.1023	6.5055	-32.1006	-11.4233	0.00
A18	0.0934	60	80	-5.3203	-0.3583	-7.3762	12.1487	0.00
A19	0.0042	70	60	-4.6506	0.2544	-0.6902	5.1841	0.00
A20	0.3123	40	70	2.5300	0.2702	-1.1895	6.6074	0.00
A21	0.0116	40	240	-4.7856	1.1014	6.1392	9.2195	0.00
A22	0.0021	80	350	4.5148	7.6783	-29.3387	0.1316	0.00
A25	0.0648	30	90	-5.8243	-0.0330	-7.7634	-4.9223	0.00
A26	0.3829	70	220	-3.3896	2.9149	6.9731	3.5266	0.00
A28	0.0018	80	90	-6.1927	0.0367	-13.6388	-1.4796	0.00
A30	0.0363	80	280	-2.8520	3.4076	-8.6291	-3.5362	0.00
A32	0.0325	40	150	-5.7223	1.0170	14.1099	-14.5363	0.00
A33	0.0335	30	310	-5.9387	0.2088	23.1622	3.3248	0.00
A34	0.0159	80	270	-5.8164	1.3940	-23.0292	-4.5424	0.00
A35	0.2812	20	40	-1.4284	3.8479	-11.1082	-2.0379	0.00
A36	0.0255	90	60	-4.6637	1.8494	-3.4076	-9.5767	0.00
A37	0.0092	90	40	-4.6433	0.7717	2.5786	9.7424	0.00
A38	0.2328	40	270	2.2006	0.9245	-1.5713	7.5277	0.00
A39	0.0473	90	70	-4.9533	1.4184	-4.3565	-7.6196	0.00
A40	0.0381	20	100	2.9600	-0.6240	0.8288	9.6334	0.00
A41	0.0167	40	80	3.3202	-1.5393	2.4669	7.5228	0.00
A42	0.1212	40	230	-5.9037	-1.9762	15.8544	-11.7084	0.00
A44	0.1364	70	300	2.4656	0.7607	-4.5151	8.8947	0.00
A51	0.0317	60	80	-4.5690	1.0923	5.3040	9.2129	0.00
A65	0.0185	70	50	-3.8794	4.6008	15.8984	-0.2634	0.00
A73	0.2043	40	80	3.3367	-1.3236	4.1519	0.2911	0.00
A86	0.0253	30	180	-1.5689	4.0513	11.9393	-4.3219	0.00
A96	0.0237	20	270	2.4387	0.3819	-10.1107	-25.7693	0.00
A97	0.0437	80	140	-3.8576	5.2873	-32.3283	17.3960	0.00
A100	0.1271	20	260	2.1379	1.9041	-6.8292	8.2404	0.00
A201	0.0720	40	210	1.1155	3.2385	9.0146	-3.7970	0.00
A202	0.0725	80	90	-4.8502	1.9001	-7.7076	-8.0062	0.00
A204	0.0266	30	220	-4.9039	0.7300	3.2557	11.7166	0.00
A218	0.0602	10	260	-5.0278	1.5403	6.8810	10.0190	0.00
A223	0.0732	80	260	-4.3303	3.2888	13.5260	-3.1689	0.00
A224	0.2066	60	270	-3.9599	2.3245	-12.8937	4.7565	0.00
A234	0.0088	80	70	-4.7846	0.6484	2.8107	10.8956	0.00
A238	0.0022	80	220	-6.1453	2.0646	12.7571	15.3540	0.00
A257	0.0204	90	60	-4.9643	0.5615	5.0110	9.5398	0.00
A271	0.1741	60	320	2.7659	-1.7131	4.0067	11.9206	0.00

[†] rounded to the nearest hundredth of a percent

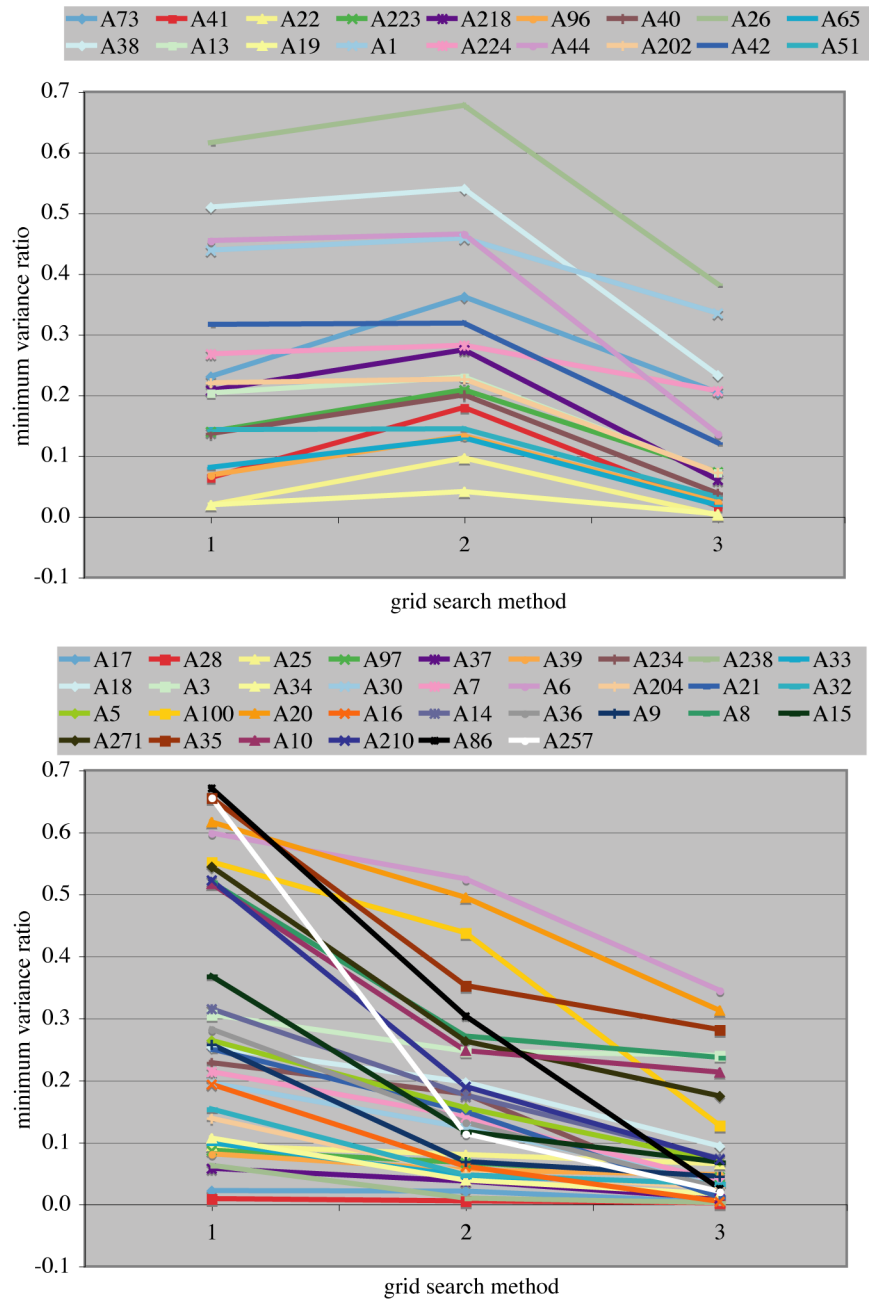


Figure 5.13 Minimum variance ratio comparison. A comparison among 51 moonquake clusters of the minimum variance ratio achieved using each of the three fit methods: (1) shear and normal stresses, (2) shear and normal stress rates, (3) shear and normal stresses and rates. Note for 33 of the 51 clusters analyzed (lower plot), forming the fit using stress rates (method 2) results in lower minimum variance ratios than stresses alone (method 1).

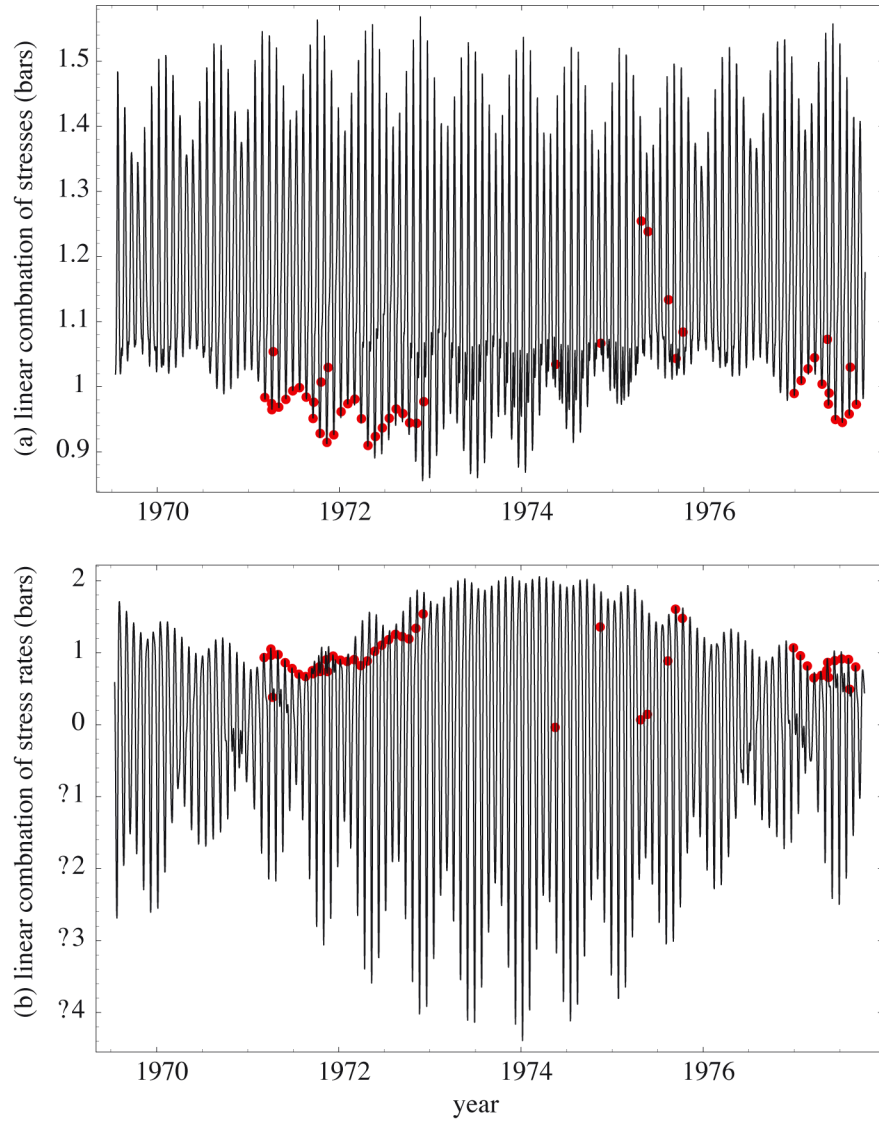


Figure 5.14 A16 linear combinations, methods 1 and 2. (a) Linear combination of normal and shear stresses such that $-6.2544\sigma_N - 1.8575\sigma_S \simeq 1$ computed on the plane with $\gamma = 80^\circ$ and $\alpha = 110^\circ$ at the A16 source. The minimum variance ratio is 0.1933 in this case. (b) Linear combination of normal and shear stress rates such that $w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_{\dot{N}} = 99.3570$ days and $w_{\dot{S}} = -103.9750$ days, computed on the plane with $\gamma = 50^\circ$ and $\alpha = 300^\circ$ at the A16 source. The minimum variance ratio is 0.0608 in this case. In both cases, the black line is the linear combinations computed at 1-day time steps, and the red dots are the linear combinations at A16 moonquake times.

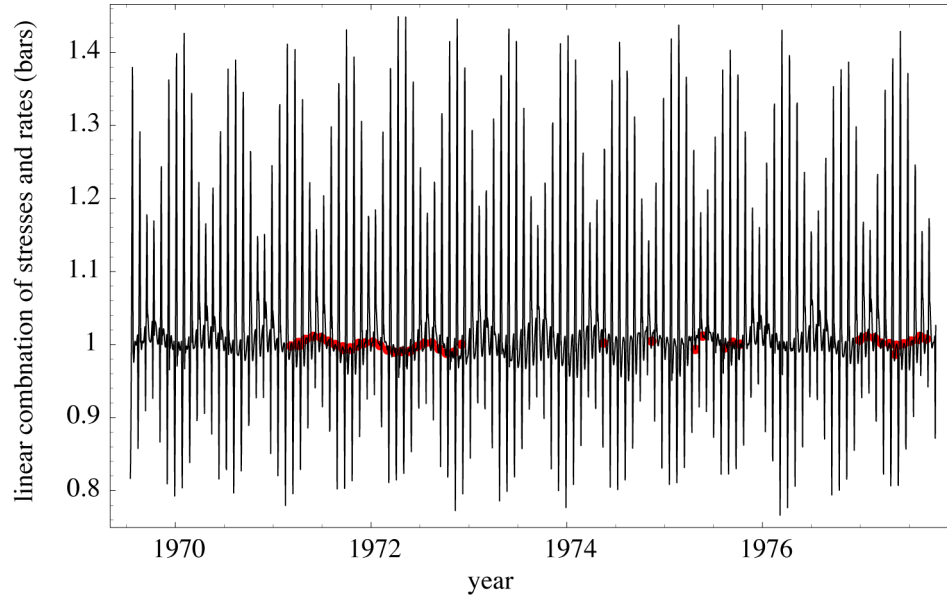


Figure 5.15 A16 linear combinations, method 3. Linear combination of normal and shear stresses and rates such that $w_N\sigma_N + w_S\sigma_S + w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_N = -5.1173$, $w_S = 0.5406$, $w_{\dot{N}} = -5.6555$ days, and $w_{\dot{S}} = -9.6449$ days, computed on the plane with $\gamma = 80^\circ$ and $\alpha = 90^\circ$ at the A16 source. The minimum variance ratio is 0.0042 in this case. The black line is the linear combination computed at 1-day time steps. The red dots are the linear combination at A16 moonquake times.

5.6 Results and discussion

We are interested in determining the significance of the stress fits we obtained using our grid search method. We measure the statistical significance of each fit using the Fisher-Snedecor f -test. The null hypothesis is that the samples whose variances are being compared were taken from normally distributed populations with equal standard deviations. The statistic f , as we have already computed, is the ratio of the variances of the samples being compared. As a result, f -values either much less or much greater than 1 will indicate very low probabilities that the samples come from the same population. In each case considered, the variance of the best-fitting linear combination of stresses at moonquake times is smaller than the variance of said linear combination at uniform 1-day time steps.

The probability P that the variances of the populations from which the two samples were taken are the same is computed from the test statistic f :

$$P(df_1, df_2, f) = I\left(\frac{df_2}{2}, \frac{df_1}{2}, \frac{df_2}{(df_2 + df_1 f)}\right) \quad (5.26)$$

where $I(a, b, z)$ is the incomplete beta function, df_1 is the number of degrees of freedom of sample 1, and df_2 is the number of degrees of freedom of sample 2 (Press et al., 1992). The last column of Tables 1 through 3 lists the probability based on the f -statistic that the variance of the best-fitting linear combination obtained at quake times is the same as the variance at uniform 1-day time steps. These results are also plotted in Figure 5.16. For a majority of the fits, the f -test predicts that the variance of the linear combination at quake times is significantly different than the variance at all times.

We observe that a significant number of our fits have minimum variance ratios of 0.1 or less: 26% of clusters for method 1 (just stresses), 29% of clusters for method 2 (just rates), and 71% of clusters for method 3 (stresses and rates). These clusters are listed in Table 5.4. In Figure 5.17, we show two examples (A19

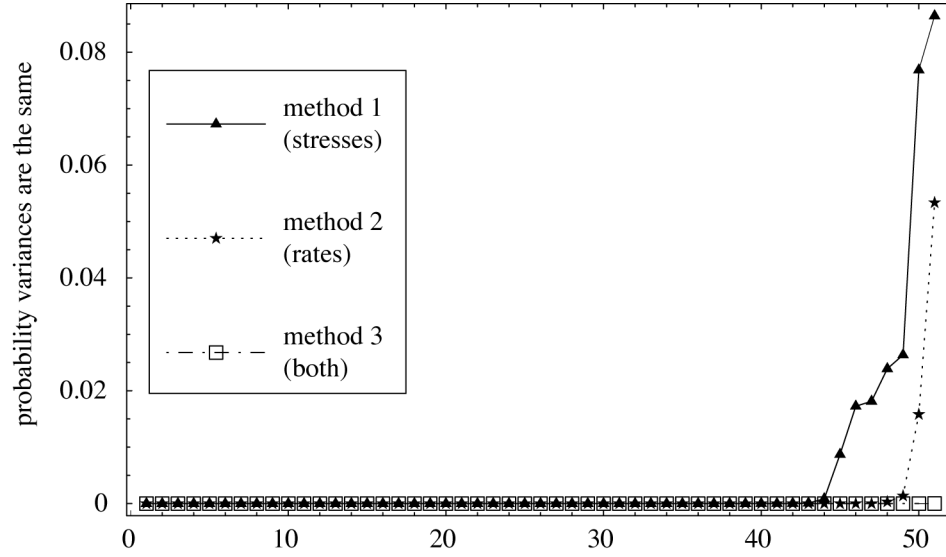


Figure 5.16 Significance based on f-test. Probability based on the f-statistic that the variance of the best-fitting linear combination obtained at quake times is the same as the variance at uniform 1-day time step, for each of the 51 moonquake clusters we have examined, using each of the three fitting methods.

and A22) of linear combinations for which, like A16 (Figure 5.15), the minimum variance ratio obtained using our grid search (method 3) was extremely low. That we were able to obtain stress functions with variance this low is an unexpected result, and indicates that our method of searching for linear combinations of stresses and/or rates can result in a reasonable failure criterion.

We also observe that fault plane orientations can be different for nearby clusters. For example, for clusters A18 and A37 (angular separation 2.9°), the best-fit plane orientations obtained using shear and normal stresses are $(\gamma, \alpha) = (60^\circ, 70^\circ)$ and $(30^\circ, 280^\circ)$ respectively, and are similarly variable for the other fit methods. There is no evident correlation between the proximity of clusters and the orientation of the best-fitting failure plane. This result is consistent with, but derived independently from, the conclusions of our geometry exploration, suggesting that moonquake failure geometry is a dominantly local phenomenon. This is also consistent with previous work which has, for the A1 cluster, constrained the A1 hypocenters to a region of ~ 1 km in diameter (Nakamura, 1978).

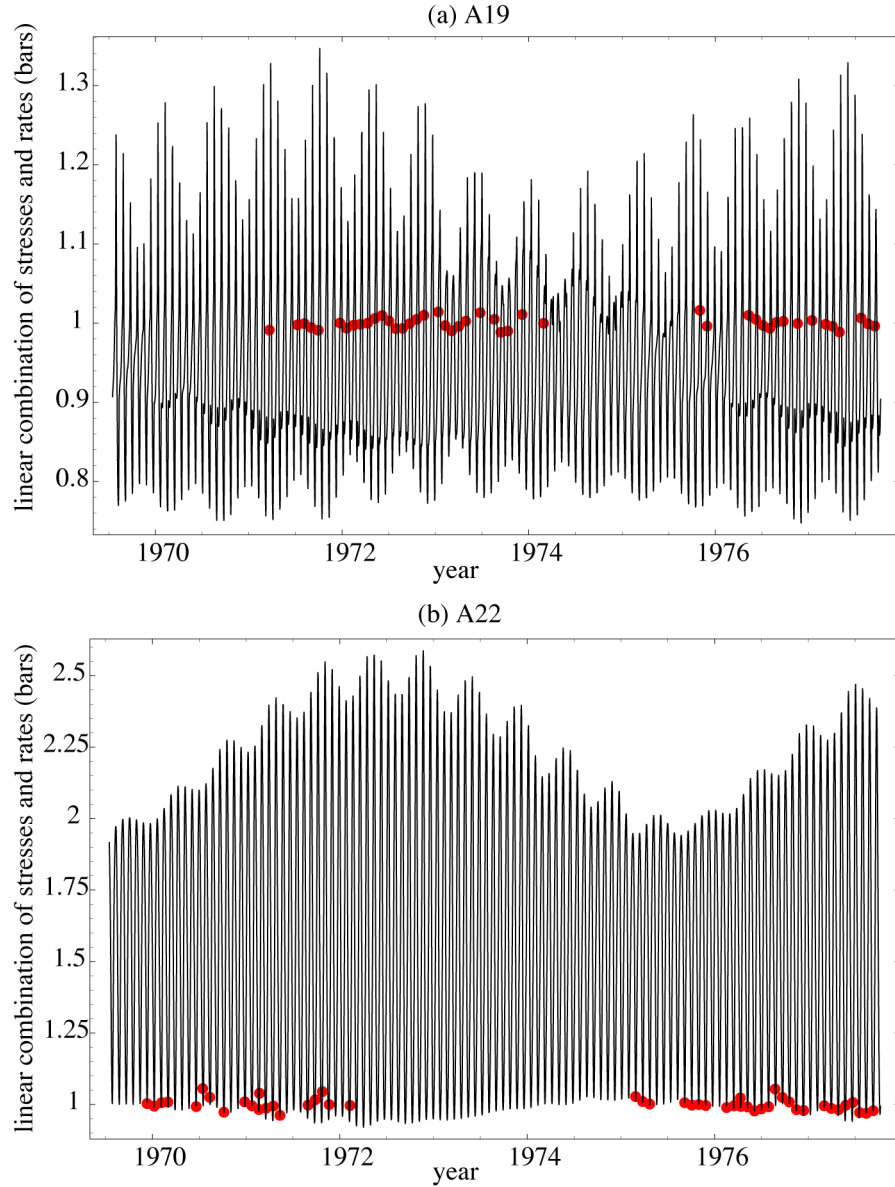


Figure 5.17 Additional low variance ratio examples. (a) Linear combination of normal and shear stresses and rates such that $w_N\sigma_N + w_S\sigma_S + w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_N = -4.6505$, $w_S = 0.2544$, $w_{\dot{N}} = -0.6902$ days, and $w_{\dot{S}} = 5.1841$ days, computed on the plane with $\gamma = 70^\circ$ and $\alpha = 60^\circ$ at the A19 source. The minimum variance ratio is 0.0042 in this case. (b) Linear combination of normal and shear stresses and rates such that $w_N\sigma_N + w_S\sigma_S + w_{\dot{N}}\dot{\sigma}_N + w_{\dot{S}}\dot{\sigma}_S \simeq 1$, where $w_N = 4.5148$, $w_S = 7.6783$, $w_{\dot{N}} = -29.3387$ days, and $w_{\dot{S}} = 0.1316$ days, computed on the plane with $\gamma = 80^\circ$ and $\alpha = 350^\circ$ at the A22 source. The minimum variance ratio is 0.0021 in this case. In both cases, the black line is the linear combinations computed at 1-day time steps, and the red dots are the linear combinations at (a) A19 and (b) A22 moonquake times.

Table 5.4 Clusters for which the minimum variance ratio is ≤ 0.1 . For each grid-search method, the number, percentage, and identification of clusters for which the minimum variance ratio obtained was ≤ 0.1 .

method	number of clusters (%)	clusters
1 (stresses)	13 (26%)	A17, A19, A22, A25, A28, A33, A37, A39, A41, A65, A96, A97, A238
2 (rates)	15 (29%)	A9, A16, A17, A19, A22, A25, A28, A32, A33, A34, A37, A39, A97, A204, A238
3 (both)	36 (70%)	A5, A7, A9, A13, A14, A15, A16, A17, A18, A19, A21, A22, A25, A28, A30, A32, A33, A34, A36, A37, A39, A40, A41, A51, A65, A86, A96, A97, A201, A202, A204, A218, A223, A234, A238, A257

Previous studies that investigated the relationship between tidal stress and moonquake occurrence have focused on finding shear stresses, resolved on fault planes, that were consistent with moonquake times (Toksöz et al., 1977; Cheng and Toksöz, 1978; Goult, 1979; Minshull and Goult, 1988). Our grid search suggests that this is an incomplete description of moonquake occurrence. For some clusters, the variance ratio is small regardless of the plane orientation on which the stresses are computed. This is the case for cluster A28, when considering shear and normal stresses and rates. In Figure 5.18, we show the variance ratio obtained at A28 using grid search method 3 on every plane orientation, sorted from lowest to highest. The maximum variance ratio obtained in this case is 0.05, which is still quite small compared to the range of values obtained for other clusters (Figure 5.13). This indicates that, to some extent, failure at the A28 source is not heavily dependent on plane orientation. Note, however, that the minimum variance value is still much smaller than the maximum variance. A possible explanation for this behavior is that the process responsible for generating moonquakes has two distinct components: one which is dependent on plane orientation, and another

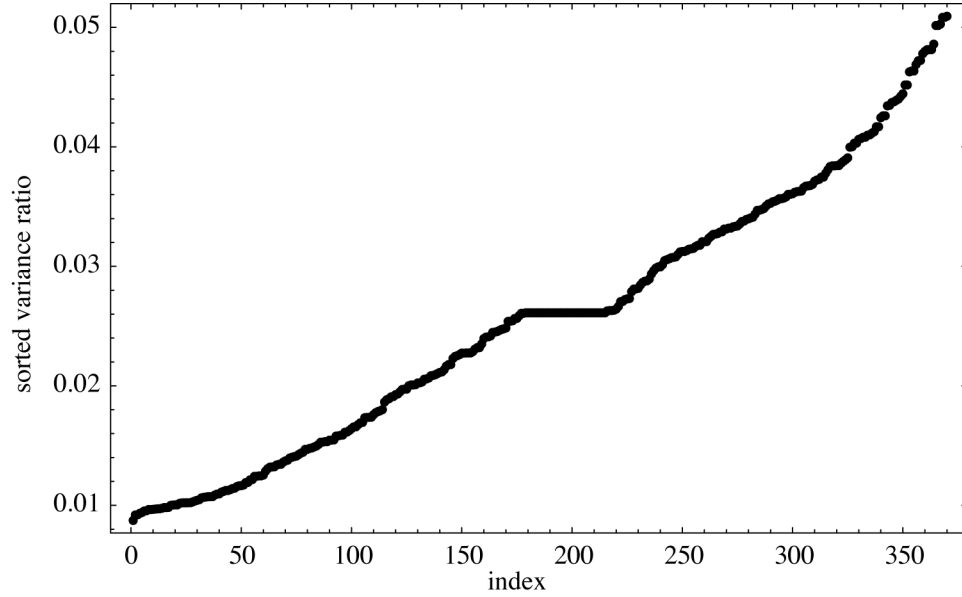


Figure 5.18 Variance ratio for A28. For the grid search performed at A28 using shear and normal stresses and rates (method 3), the variance ratio obtained at every plane orientation, sorted from lowest to highest.

which is independent of orientation.

Our grid search results also indicate that stress rates can be more important to moonquake failure than stresses themselves. Of the 51 clusters we analyzed, 33 of them (65%) get lower-variance results when considering stress rates alone (method 2) than when considering stresses alone (method 1). That moonquake occurrence is sensitive to the rate of shear and normal stress is a new result. Also, in some cases, the weights assigned to the normal stress are larger than those assigned to the shear stress, in apparent contradiction with previous work.

These aspects of our grid search, combined with the depth at which these moonquakes occur, (between 850-1000 km depth, where the temperature is $\sim 1000^{\circ}$ C) suggest that for some clusters, other avenues of investigation, which don't invoke only shear-stress-driven failure on a plane, might better describe moonquakes. A plausible analogy is provided by deep earthquakes, for which phase changes and dehydration embrittlement are thought to cause failure in a regime where brittle shear failure would otherwise not be expected (Frohlich, 2006). However, the

extent to which these analogies apply to deep moonquakes has not yet been fully explored.

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6

Summary

Deep moonquakes have proven to be an interesting phenomenon, with many characteristics that set them apart from their terrestrial counterparts. Many of these properties have been relatively well-constrained: that they are very deep, that they occur in highly localized “clusters,” that they produce repeatable waveforms and are periodic – all of these observations have inspired previous investigations of the actual mechanism that describes these unique events.

Due to the scattering of seismic signals within the Moon, and the small number and limited distribution of the seismic stations on the lunar surface, lunar seismograms are of poor quality compared to those of earthquakes. As a result, many of the seismological processing techniques typically employed in the analysis of earthquakes cannot be applied to moonquakes. Previous studies placed bounds on the magnitudes of deep moonquakes (Lammlein et al., 1974; Goins et al., 1981), but the uncertainties in these estimates are large due to the limited quality of the available data – estimated body wave magnitudes of the largest deep moonquakes range from 1.3 to 3.0. Likewise, only rough estimates of the stress drop associated with a typical deep moonquake have been made, with the largest deep moonquakes estimated to relieve approximately 0.1 bars. Magnitudes and stress drops were computed using the corner frequencies of deep moonquake dis-

placement spectra, which are not well-constrained, meaning these estimates could differ by an order of magnitude. In addition, efforts to characterize the details of deep moonquake ruptures (specifically focal mechanisms) have not been successful, since the direction of first motion cannot be determined from the seismograms.

The lunar seismic data set, however, is still extremely valuable, as it represents the only extraterrestrial seismic data in existence (the Viking landers on Mars did have seismometers, but since the instrument was not well-coupled to the ground, only wind events were detected; see Anderson et al., 1977). Due to the limitations of the Apollo network discussed above, those interested in gaining a better understanding of the process associated with the generation of deep moonquakes must try to work with these data using alternative means than those applied to earthquakes. Although Nakamura (1978) and Koyama and Nakamura (1980) did develop new techniques for estimating the mechanism for failure using seismograms from the A1 cluster, these were not widely applied since there are few clusters as well-characterized as A1, and no clusters with a larger number of events.

We have seen that it is possible to exploit some of the characteristics that make deep moonquakes unique, in order to learn more about them. The repeatability of waveforms from individual clusters allowed us to perform our new event search using a cross-correlation analysis. We used the new events obtained to reassess some spatial and temporal aspects of deep moonquake occurrence, including seismic phase arrival picks (and hence deep event locations) and tidal periodicity. In addition, we used both our new events and the previously catalogued events to perform a thorough investigation of the influence of Earth-Moon geometry and the resulting elastic tidal stress on moonquake occurrence times. We now discuss the implications of our findings, based on this work.

6.1 New events: Implications for locations, velocity models, and lunar seismicity

From the eight clusters for which we obtained new events (A1, A6, A8, A9, A10, A14, A18, and A20), we found an average 36% increase in the number of events. For the A33 moonquake cluster, we did not find any new events. Because A33 had a smaller number of initial events (64), the resulting target stack formed from those events likely did not have sufficient signal-to-noise to correlate with low-signal events in the continuous data. To test this, we performed additional event searches for deep clusters A7 (85 initial events) and A44 (94 initial events).

Following the same criteria outlined in Chapter 2, application of the event search to these two clusters produced spurious results. The number of new events was anomalously large, often due to multiple correlations found in short succession. Because of this, we did not report new events for those clusters, and did not continue our new event searches for clusters with lower numbers of initial events. A large amount of computing time and quality-control (approximately 5 days per event search) is required to validate potential new events for each cluster. We obtain diminishing returns as the number of initial events decreases to the point where, like A33, no correlations are found that match our criteria. For the eight clusters listed above, we have done the best we can to ensure that all events resolvable from the continuous data have been accounted for.

6.1.1 Cluster locations and velocity models

Deep moonquake cluster locations, as well as seismic velocity models, are constrained by the number of, and uncertainties in, seismic phase arrival picks derived from lunar seismograms. Because phase arrivals are often not clearly identifiable on individual traces, picks are typically made from waveform stacks that consider all events from a given cluster, taking advantage of waveform coherence

to enhance phase arrivals. We expected stacks that included our new event seismograms would possess further enhanced signal-to-noise, allowing for more precise and accurate arrival picks.

We found that our arrival picks, when present, are consistent with those of previous studies, within their errors (Nakamura, 1983; Lognonné et al., 2003). In addition, our pick estimates are generally more conservative than those of previous studies, meaning there are several instances among the nine clusters we analyzed where we felt reliable picks could not be made, despite the existence of those picks in other studies (care was taken to ensure our picks were not contaminated by knowledge of previous picks).

For event relocation, therefore, picks made from stacks that included our new events resulted in locations consistent with those of previous studies (Nakamura, 2005; Lognonné et al., 2003). The resulting 95% confidence contours (Figure 3.5), which have not been shown previously, emphasize the effect of the limited source-receiver geometry that occurs when picks are lacking at station 15. Locations for such clusters can be uncertain up to 30° approximately North/South of the line connecting the remaining three stations.

Although the uncertainties in existing 1-D velocity models may reflect the large uncertainties in arrival picks, our analysis likely indicates that these models could not be significantly improved using arrival picks that include our new events.

6.1.2 Lunar seismicity

Our new events are beneficial for any study of lunar seismicity based on the number and occurrence times of deep moonquakes. A complete catalog is desirable for such studies, which include periodicity and spectral estimates of moonquake occurrence times (Chapter 3; Lammlein et al., 1974; Lammlein, 1977), geometry and stress analyses which attempt to match occurrence times with certain geometry/stress states (Chapters 4 and 5; Lammlein, 1977; Toksöz et al., 1977;

Cheng and Toksöz, 1978; Nakamura, 1978; Goulty, 1979; Minshull and Goulty, 1988), studies based on inter-event intervals (see e.g. Koyama, 2005), and seismicity estimates. Because we were able to discern new moonquake signals in the continuous data all the way down to the noise level, it is likely that additional deep moonquakes occurred that the Apollo network was unable to detect. This is relevant to estimates of the total amount of the Moon’s seismicity and annual energy release.

6.2 Geometry and stress analyses: implications for mechanisms

Our investigation of the parameters describing the Earth’s position relative to the Moon (which are used to compute the stress within the Moon) at the times of moonquakes revealed that individual moonquake clusters tend to produce events preferentially at certain times in the lunar orbit. However, we found that nearby moonquake clusters can respond in different ways to the same parameters. This indicates that local structure at individual cluster locations is likely important to failure. We incorporate local structure by computing tidal stresses as resolved onto local failure planes.

Several previous studies have investigated the relationship between tidal stress and moonquake occurrence times (Toksöz et al., 1977; Cheng and Toksöz, 1978; Goulty, 1979; Minshull and Goulty, 1988). While their approaches were varied, most concluded that stress levels alone can’t fully account for moonquake occurrence (meaning moonquakes were not found to consistently align with stress peaks throughout the Apollo experiment). However, all but one of the four aforementioned studies limited their analyses to the A1 cluster (Toksöz et al., 1977 analyzed A1 and A18). Many of these suggest additional factors, apart from tidal stresses, that might contribute to failure. These include ambient stresses, such as

elastic stresses preserved in the interior due to early lunar events (e.g. bombardment or possible early tectonics) or from convection in the deep interior (Toksöz et al., 1977), or thermal stresses resulting from contraction as the lunar interior cools (Minshull and Goulety, 1988). However, no specific hypothesis testing was performed.

In our stress analysis, which incorporates many more deep event clusters and a more general stress criterion than those imposed previously, we have made two observations: (1) for some clusters, we can find a plane orientation that produces a fit with extremely low variance, meaning moonquake occurrence is well-explained by stresses resolved on a plane (Figures 5.13, 5.15, 5.17), and (2) at other clusters, the variance ratio is small regardless of the plane orientation on which stresses are resolved, meaning the best fit does not always depend heavily on plane orientation (Figure 5.18). Combined with our observations that better fits to moonquake occurrence are often obtained using comparatively large normal stress weights, and that deep moonquakes can be sensitive to stress rates, these results suggest a mechanism other than tidal stress-driven shear failure might be appropriate to some deep clusters.

Our grid search results do not directly address whether any of the above proposed sources for ambient stress might be important to moonquake failure. It is possible that deep moonquakes may be similar to deep earthquakes, which occur in a regime within the Earth where brittle shear failure on a plane is not expected. Laboratory experiments have shown that above a critical pressure and temperature, rocks fail by ductile flow rather than brittle rupture. In the Earth, this brittle-ductile transition occurs between 10 and 50 km depth (pressure 0.2 - 1.4 GPa) (Bott, 1982), and the corresponding temperature range is approximately 400 to 1000° C (Stacey, 1992). However, a significant number of earthquakes have been observed at much greater depths, between 60 and 700 km beneath the surface (Frohlich, 1989; International Seismological Centre catalog), where the pressures and temperatures range from 1.8 to 24.9 GPa and 500 to 1800°, respectively.

Temperature and pressure conditions in the Moon similar to those at Earth's brittle-ductile transition are reached near approximately 300 km depth in the lunar interior, so ductile flow should dominate in the active moonquake zone – between 700 and 1000 km depth, where the pressures and temperatures range from 3.2 to 3.9 GPa and 1000 to 1500° C (Hood and Zuber, 2000; Lognonné et al., 2003; Gagnepain-Beyneix et al., 2006), respectively. Yet for both deep moonquakes and deep earthquakes, we know from observations of seismograms that despite the conditions in the deep interior of both bodies, shear failure is still occurring there.

For deep earthquakes, several mechanisms have been proposed that might explain why shear failure at great depths can occur despite the inhibitive environment. For a thorough review, see Frohlich (2006). Of these, we present two hypotheses and discuss their relevance to deep moonquakes.

The first theory is known as *dehydration embrittlement*. This describes the process by which hydrated oceanic crustal materials release water when they are subducted and reach appropriate temperature and pressure conditions in the mantle. The released water fills pore spaces, increasing the pore pressure. This increases the effective hydrostatic stress and decreases the amount of shear stress necessary to cause failure (see equation 5.24), permitting brittle fracture to occur in the mantle at greater depths than under dry conditions. This mechanism is supported by rock mechanics experiments (e.g. Meade and Jeanloz, 1991), and is currently accepted as a possible explanation for intermediate-depth earthquakes (between 60 and 300 km depth, below which the dehydration process is largely complete).

Although it has been proposed that this behavior might occur in the lunar interior (Frohlich and Nakamura, 2007), dehydration embrittlement is not a plausible cause of failure for deep moonquakes. First, there is no direct evidence for sufficient quantities of water in the Moon. Samples returned from the lunar surface are ubiquitously dry (Papike et al., 1998), while the commonly accepted giant-impact formation model for the Moon predicts a loss of volatiles in the lunar interior

(Taylor, 2001). Second, plate tectonics are not active on the Moon, so there are no subducting slabs. While this does not rule out other means of transporting water to high pressure and temperature conditions, the lack of water (recent estimates of the water content in lunar materials are extremely low; see e.g. McCubbin et al., 2007) is the primary limitation of this mechanism.

A second hypothesis that has been proposed for deep earthquakes is *transformational faulting*, in which shear failure is induced by mineral phase changes in the Earth's interior. In response to an applied stress, a mineral with two stable forms can change from its low-pressure form to its high-pressure form. One such phase change in the Earth is the olivine-spinel transformation. Laboratory experiments designed to reproduce this transformation (Green and Burnley, 1989) show that in certain temperature/pressure environments consistent with deep earthquakes, the phase change initiates as lens-shaped “anti-cracks” of spinel, which produce stress concentrations at their tips. As anti-cracks form, they release heat, which increases their rate of formation. As the anti-cracks grow and their numbers increase, they link together, eventually reaching a critical density. When this occurs, the material can no longer support the applied stress, and catastrophic shear failure occurs along the growing anti-crack instability.

Assuming there is an appropriate phase transition in the lunar interior (pressures in the Moon are too low for the olivine-spinel transformation), this mechanism is plausible for deep moonquakes, and could explain our observations for those clusters that don't produce a clear best-fitting plane. These clusters may not have a preferred plane orientation because a phase change-induced mechanism does not require a pre-existing plane. As mentioned earlier, these observations are: (1) For some clusters, the best fitting stress state is independent of plane orientation. This suggests that failure may be occurring as a response to changes in pressure, which likewise trigger phase changes. (2) Some clusters have best-fitting linear combinations of shear and normal stress for which the relative contribution of normal stress is larger. This may be indicative of transformational faulting since

anti-cracks are observed to form perpendicular to the maximum compressive stress. (3) Some clusters have best-fitting linear combinations of stresses and stress rates for which the relative contribution of rates is larger. It is plausible that there be a delay between the stress state that marks the onset of anti-crack formation and the eventual coalescence of anti-cracks that leads to failure, so transformational faulting could also describe our observation that moonquakes often respond to stress rates. However, it is not clear whether phase changes exist in the Moon which could be possible candidates for anti-crack formation, since the composition of the lunar interior is not well-constrained.

6.3 The future of lunar seismology

A grid search for a best-fitting failure plane would be unnecessary if we were able to determine fault mechanisms from the lunar seismograms. This (and many other remaining questions about the Moon) could be addressed if future lunar missions included seismometers, since advances in instrumentation and a foreknowledge of the types of lunar signals would permit the design of a seismometer tailored to the Moon, and sensitive enough to detect first motions associated with moonquakes. Ideally such an instrument would be buried deep enough to avoid noise associated with the strong day/night temperature contrast at the surface (observed on the Apollo instruments), and sensitive enough at very low frequencies to observe surface waves and normal modes, which would provide greatly improved constraints on the lunar seismic velocity structure.

A future lunar seismology mission could also address the extent of the lunar core, the presence of which has been inferred from lunar laser-ranging data (Williams et al., 2001). Although some moonquakes have been found to occur on the far side (Nakamura, 2005), none were detected that originated from the far side antipode of the region spanned by the seismic stations on the near side. This could indicate either that the far side of the Moon is aseismic, or that signals originating

there can't penetrate a possibly attenuating core. A seismic network that included one or more stations on the far side could address this. Even one station on the far side would at least address whether that region is aseismic.

A single near side station could be useful as well, for any study based upon the occurrence times of deep moonquakes. Without a network, seismic sources can't be located, but events from known clusters could still be identified thanks to waveform similarity, hence extending the catalog of observed seismic signals on the Moon. Several missions specific to lunar seismology have been proposed recently, including LuSeN and LUNAR-A, but no plans for launch have been set. The continued interest of the planetary science community is critical for such missions to succeed.

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