Appendix C

Accompanying “Karachi tides during the 1945 Makran tsunami”

Potential explanations for an early anomaly in the Karachi tide-gauge record for November 28, 1945

SUMMARY

This appendix considers possible causes of a Karachi marigram anomaly that spans three hours in the early morning of November 28, 1945. The anomaly is centered on the time of a great earthquake sourced 300 km west of Karachi, and it ends at the previously accepted Karachi onset of an ensuing tsunami.

The anomaly may be an artifact of instrumental or human error. The Karachi tide station had a stilling well that was subject to blockage, and its temporary obstruction early on November 28 could explain the anomaly. Confirmation of this null hypothesis would likely require evidence from documents that may no longer exist. Clerical misdating of the anomaly, a further possibility, conflicts with clues on the marigram itself.

If instead genuine, the anomaly would require a cause that shortly precedes the great earthquake. No unusual weather is evident in contemporary reports. The possibility of a precursory tsunami could be tested by modeling submarine slides and slow earthquakes.

CONTENTS

BLOCKED CONNECTION BETWEEN HARBOUR AND STILLING WELL

Summary

An underwater obstruction might explain a two-part anomaly early on November 28 in the Karachi marigram for November 15 to December 1, 1945. The posited obstruction restricted communication between Karachi Harbour and the stilling well of the Karachi tide station, through a communication hole that had a history of blockage by mollusks and accreting sediment.

The two-part anomaly on November 28 is superimposed on the rising limb of a low neap tide. During the anomaly's first part, between 0145 and 0415 India Standard Time (IST), the graphed rise slows to a near standstill. This deceleration happens to extend across the origin time of the great 1945 Makran earthquake, 0327 IST. During the anomaly's second part, beginning at 0415 IST, the graphed water levels jump 15 cm almost instantaneously, and the slope of the tidal curve remains uncommonly steep until 0500 IST. The jump begins 45 minutes before the previously accepted onset for the 1945 Makran tsunami in Karachi Harbour.

We noticed one other anomaly of this shape on the same marigram. Smaller in duration and amplitude, it is superimposed on the rising limb of an extremely low spring tide on November 19. Perhaps related, as an indicator of repairs, is a nine-hour outage on November 20 that is not explained on the marigram.

If the deceleration on both days resulted from damming of the communication hole, the abrupt rise that follows may then be akin to a dam-break flood. Notes on the marigram are consistent with this hypothetical sequence but do not confirm it. The November 19 anomaly may have prompted repairs during the long, perhaps intentional outage on November 20. The November 28 anomaly is accompanied on the marigram by an ambiguous note about trouble with the gauge. This note, inked into an area at 0210 IST, says only "out of order," and it is not followed by a note about when the outage ended. Elsewhere on the marigram, the port's chief engineer says nothing about blockage and identifies a different, mainly mechanical cause for a gap in the Karachi marigram during the largest of the accepted tsunami waves on November 28.

This assorted evidence leaves the blockage hypothesis both viable and debatable. Confirming it would simplify the marigram's geophysical interpretation by obviating a precursor to the previously accepted waves of the 1945 Makran tsunami.

Introduction

A two-part anomaly appears early in the Karachi tide-gauge record of November 28, 1945, India Standard Time (IST). The anomaly, superimposed on a rising tide, consists of a steady deceleration that begins 0145 IST, and of an ensuing, abrupt acceleration. The deceleration, after rigorous detiding, becomes an apparent drawdown that begins before, and continues through, the 0327 IST origin time of the great 1945 Makran earthquake (Figs. 4 and 5). Accordingly, the anomaly may be important as evidence for precursory displacement of the ocean floor.

The anomaly might be explained more simply, however, by a problem with the gauge or by human error with the marigram. This section of Appendix C considers a known instrumental problem, and the next section examines the possibility of human error.

The possibility of an instrumental problem was noted in a journal article that excerpted the Karachi marigram for use in modeling the 1945 Makran tsunami. Neetu et al. (2011) presented, as a tracing, a nine-hour excerpt that begins at 0440 IST on November 28. The prior part of that day's marigram was excluded as unreliable: "The tide gauge at Karachi had malfunctioned before the tsunami struck there. The officer in charge of the tide gauge had marked on the chart that the gauge was out of order. Fortunately, the gauge had resumed recording just before the arrival of the initial wave" (Neetu et al. 2011:1612).

The specific instrumental problem considered here is temporary blockage of a communication hole in a stilling well. This orifice ordinarily enabled waters of Karachi Harbor to enter and exit the cylinder where the gauge detected changes in water level. The appendix begins with background on the tide station, particularly on a kind of stilling well that likely remained in operation in Karachi in 1945 (Fig. C1). Recounted next are reports of blockage in the several decades before 1945. Two possible instances of blockage in 1945—on November 19 and 28—are then illustrated with tracings of and excerpts from the marigram (Figs. C2 and C3). Considered also are ambiguities from explanatory notes on the marigram. We conclude that orifice blockage is a plausible but minimally corroborated explanation for the early anomaly on November 28.

Evidence

Karachi tide station

Tide levels in Karachi Harbour were recorded routinely at Manora between 1868 and 1948 (Hogarth 2014:7651, Permanent Service for Mean Sea Level 2016). The station was situated "alongside the end of a pier" that extended just beyond the lower limit of a tidal flat (Fig. 2b).

The equipment used in 1945 probably retained the old but standard design depicted in a monograph of the Great Trigonometrical Survey (Eccles 1901a:plate II). Waves and wake were damped by means of a stilling well, which at Karachi was an iron cylinder "about two feet four inches internal diameter and seventeen feet six inches long, driven about two feet into the ground" (Eccles 1901b:9). The well communicated with the harbour through a hole one inch (2.5 cm) in diameter that had been drilled through the cylinder "fifteen feet eight inches" below its top. In that case the communication hole at Karachi was nearly at the level of the harbour floor (Fig. C1a).

Vertical movement of a float in the stilling well allowed a copper band to rotate a wheel on the gauge. This rotation, through gears and a chain, governed a pencil that moved across a slowly turning drum 160 cm long. The pencil marked a gridded sheet nearly as long as the drum. The Karachi marigram for November 15 to December 1, 1945 (Fig. S1) fits this description. Its criss-crossing curves were inked for clarity after the sheet had been taken off the drum, as discussed below under "Clerical error in dating."

Published reports of blockage

The communication hole in the Karachi stilling well had a 19th-century history of fouling by marine organisms, and of further interference from sediment. According to a description published in 1901 (Fig. C1), "Occasionally the curves have slight imperfections due to shell fish blocking the communication; and in 1892 silt accumulated [in the stilling well] to such an extent that extreme high and low tides were not properly indicated, owing to the float at extreme low water and the counterpoise at extreme high water resting on the accumulation, which was removed in January, 1893" (Eccles 1901b, p. 9).

Observations in 1922 were twice interrupted "owing to the communication hole in the cylinder being blocked with mud. A diver was employed on the 14th January and again on the 15th and 16th March 1922, to remove the mud which had accumulated round the outside of the cylinder" (Survey of India 1924, p. 52).

Two-part anomalies on November 19 and 28, 1945

The Karachi marigram for November 15 to December 1, 1945, contains anomalies on November 19 and 28 that each might represent temporary blockage of the communication hole. Both are superimposed on the rising limbs of low tides (Fig. C1b).

A smaller two-part anomaly of this style begins about 20 minutes after an extreme low water of November 19. This low water had fallen 0.4 m below gauge datum (Table S3, extremum 18). The ensuing anomaly lasts about 20 minutes in all (Fig. C3a). Upon detiding, its maximum apparent drawdown is -0.09 m (Table S1, November 19, 1736 IST). An additional, positive anomaly of 0.19 m crests two hours later (1947 IST). This positive anomaly is the largest in the marigram detided in Figure 5a, outside the anomalies of November 28 and 29. Perhaps the November 19 anomalies prompted repairs that took place when the gauge was "out of order" on November 20, between 0845 IST and 1750 IST (Fig. S1).

The anomaly on November 28 begins nearly two hours after the a neap low water (Table S3, extremum 50) that was 1.4 m above the extreme low water of November 19. The ensuing rise in graphed water level on November 28 slows anomalously. Between 0330 IST and 0400 IST the water level reaches a standstill. Detided as in Figure 5, this end of this standstill coincides with a drawdown, relative to ambient tide, of 0.5 m. Soon thereafter the line turns a corner, and at 0415 the graphed water level rises 15 cm almost instantaneously (Fig. C3b). The graphed water level then continues to rise rapidly—more rapidly than on the rising limbs of other tides in the marigram (Fig. C2)—until 0500 IST (Fig. S2).

Explanatory notes on the marigram

A problem with the gauge early on November 28 is evidenced by an "out of order" note. This note, in purple ink (the day's color; App. C), was inserted into a gap in the purple trace of November 28 curve (Figs. C3b and C6a). This gap spans five minutes and is centered near 0210 IST. The hand is similar to that of the "out of order" note that marks the end of the November 20 outage (Fig. C3a). The marigram contains no such indicator of when the early November 28 outage ended.

A later outage on November 28 is explained in a note from D.B. Brow (Fig. C8c). Brow, who signed as Chief Engineer of Karachi Port Trust, would later become its Chairman, and would author a history of the port (Brow 1947). His note on the marigram begins by ascribing a gap in the marigram, soon after 0800 IST on November 28, to a mechanical problem caused by "a tidal wave." The note is silent about any earlier outage that day.

Interpretations and recommendations

A recognized problem with the Karachi tide station provides a plausible but unconfirmed explanation for marigram anomaly that spans the time of the great 1945 Makran earthquake.

Arguments for and against blockage

Blockage of the communication hole in the stilling well may explain the early anomaly on November 28 by providing a plausible mechanism for the early outage inferred by Neetu et al. (2011). First an obstruction constricts and finally seals off the orifice, producing inside the stilling well a drawdown with respect to the rising tide in the harbour outside. Second, the water levels inside catch up with the rising tide when harbour water rushes through a reopened hole. This explanation for the early anomaly is consistent with the known vulnerability of the Karachi tide station to blockage of the orifice. This vulnerability may even be expressed by the similar but smaller anomaly on November 19.

Alternatively, a genuine anomaly has been misinterpreted, beginning with the "out of order" note inserted into 0210 IST part of the November 28 record. This note, probably added on December 1 or later, may be the observatory staff's reasonable but debatable attempt to explain the apparent drawdown of 0145–0415 IST. Or even if there was an outage at 0210 IST, the "out of order" need not signify more than a five-minute interruption at that time. Orifice blockage does not uniquely explain the apparent drawdown, moreover, if that same effect may be produced by a tsunami, as speculated below under the heading "Precursory tsunami."

Additional clues that could be sought

The blockage hypothesis might be tested further with two kinds of old documents, if these documents happen to survive. First is the "separate chart" that was prepared to clarify the marigram for November 28 and 29 (Fig. C8c). Second and more basic would be daily tide-station logs like those prepared a half century before (example in Eccles 1901a:22). Entries there could include positions (in feet above gauge datum) of the pencil on the drum, correctness of the gauge clock, local weather, and waves at the tide gauge.

Further details about the tide station itself could be sought, to assess how the functioning diameter of communication hole may have affected well water levels inside the stilling well after the accepted 0500 IST onset of the 1945 Makran tsunami in Karachi Harbour. Procedures in Cross (1968) and Loomis (1984) suggest little damping or delay for amplitudes under 3 m and periods over 20 min, if the stilling well in 1945 communicated with the sea through a simple hole 2.5 cm in diameter, as it did in the design described by Eccles (1901b: 9-10). The possibility of greater damping, from communication through long or narrow pipes (Satake et al. 1988, Satake et al. 2010, Namegaya et al. 2009), might be checked if surviving records give details of the gauge design in 1945.

Acknowledgments

Peter Hogarth alerted us to the 1922 example of orifice blockage at the Karachi tide station. He and Philip Woodworth directed us to the monograph of Eccles (1901a, 1901b) for details about gauge design.

CLERICAL ERROR IN DATING

Summary

This part of Appendix C considers whether clerical error produced much of a puzzling anomaly in a Karachi tide-gauge record from November 1945. As noted above, the anomaly contains an apparent drawdown relative to a rising tide and an abrupt ensuing upturn in graphed water levels. The apparent drawdown begins almost two hours before the great Makran earthquake, which occurred early on November 28, 1945, local time, and the upturn begins 45 minutes too early to explain by coseismic deformation at the earthquake source.

These quandaries might be avoided if, by clerical error most of the anomaly took place instead the day after the great earthquake, as a continuation of the 1945 Makran tsunami. The posited error would have taken place during inking of a gridded paper sheet on which the gauge had penciled crisscrossing tidal curves. The curves cross one another because they span 17 days and were drawn mechanically on a drum that completed one rotation daily. The sheet was taken off the drum on the last of the 17 days, December 1. Sometime thereafter, probably before December 12, color ink that differs by day was applied by hand to the pencil lines to make each day's curve easier to follow. Hypothetically, during that step, observatory staff mistakenly inked an unremarkable segment of the November 28 curve in the November 29 color, while assigning in exchange an anomalous segment of the November 29 curve to November 28. Both these segments begin early in the apparent drawdown in the vicinity of a gap in the curve inked as November 28, and they end where they cross at low angle during the rapid upturn.

As appraised here, the posited clerical error conflicts with marigram evidence and further complicates interpretation of the anomaly. On the marigram, the curves for November 28 and 29 follow distinctly different paths, marks added to nearly all the curves attest to care in dating them, and marginal notes attest to official scrutiny that included approval by a curve examiner and commentary by the chief engineer of Karachi's port authority. The posited exchange leaves part of the anomaly in need of a cause on November 28, while requiring a separate explanation for the remainder reassigned to November 29.

These considerations leave little reason to second-guess a November 28 date for the puzzling anomaly. As a potential contributor to this anomaly, clerical error is difficult to identify on the marigram, and invoking it increases the number of anomalies to be explained.

Introduction

The paper "Karachi tides during the 1945 Makran tsunami" detides a Karachi marigram that includes an apparent drawdown, relative to rising tide, early on November 28, 1945, India Standard Time (IST; Figs. 4 and 5). The apparent drawdown, between 0145 IST and 0415 IST, is followed by an anomalous jump in graphed water level. Does this tandem anomaly mean that the 1945 Makran tsunami began before the great earthquake of 0327 IST that same morning?

No precursor would be required if the apparent drawdown can be discounted as an instrumental aritifact or human error. A plausible cause of an instrumental artifact—blockage of a hole through which a stilling well communicated with Karachi Harbour—is examined above. Considered below is the further possibility that a genuine drawdown of Karachi Harbour occurred the day after the great earthquake, on November 29, and was misdated to early hours of November 28 during inking of the marigram. This possibility was pointed out to us by an anonymous referee to whom we are much indebted.

The referee noted the potential for clerical error by studying the marigram scan (Fig. S1) and took the further step of differencing the reference tidal curve derived in Appendix A (the Accepted Tide; Table S2) from a version of the marigram (the referee's modified version of the

Digitized Marigram; Table S1) to derive a residual curve that highlights water-level changes from the tsunami (akin to the paper's Fig. 5). The considerable work involved included extracting, from the minute-by-minute list in Table S2, values of the Accepted Tide values at irregular times of the Digitized Marigram.

In a further appraisal, this appendix finds ample support for the dating that the marigram presents. The main findings appear in six illustrations that build on the referee's work. Figure C4, adapted from the referee's concluding graph, shows how the posited error affects the Digitized Marigram and its detided residual, with colors keyed to those inked on the marigram. Figures C5 and C6 put the posited error in context of the scanned marigram itself. The lines involved in the posited error are extracted, for ease of viewing, in Figure C7. Finally, potential causes of clerical error are partly evaluated in Figures C8 and C9, which present metadata from the marigram and indicators of earthquake intensity in Karachi, respectively.

Description of posited error

The clerical error appraised here would have arisen during inking of originally pencil curves on the marigram. At that point the marigram would have already been recorded in pencil on a gridded rectangular sheet that made one daily rotation on a cylindrical drum. Vertical movement of a float, in the stilling well illustrated in Figure C1, produced horizontal movement of the pencil that drew the tidal curves at a 1/3 of their actual amplitude (Eccles 1901a:11-13 and plate II, Eccles 1901b:9).

The need for inking is apparent in the marigram itself (Fig. S1) and in tracings made from it (Fig. C2). Customarily, a sheet would remain on the drum for half a month (Eccles 1901a:21). The marigram in Figure S1 contains a spaghetti of curves from 17 days, November 15 to December 1 (Fig. C8a). The curves are readable because, though first drawn mechanically in pencil, they have been overwritten manually in ink that color-codes each curve by date.

Eccles (1901a:21) prescribed a protocol for applying color to the marigram. The clerk in charge of the observatory was to visit two to four times daily, at set times. During each of these visits, the clerk was to identify and label the position of the graphing pencil by drawing and labeling, in color ink, a small circle around the pencil. This part of the protocol was still being followed during tidal observations at Karachi between November 15 to December 1, 1945. The marigram contains labeled ink circles that identify the pencil position twice daily, at 10 a.m. and 5 p.m. The sole exceptions are when the gauge was out of order, and during the tsunami on November 28.

The turn-of-the-century protocol further required the clerk to "ink in" the preceding day's curve. We do not understand how this tracing could have been accomplished accurately while the sheet was still wrapped around the drum, half facing downwards. We suppose that the inking was done instead with a pen held upright above on a fixed, flat surface onto which the sheet had been unrolled, after being taken off the drum. The color circles and their labels, having been applied during the days of observation, would be available as clues to the date of each curve and the color to be applied. In that scenario, the curves were inked in no earlier than December 1, the date when the sheet was taken off according to Abdul Malik, the clerk in charge (Fig. C8a). The inking was almost certainly complete by December 12, when an inspector examined the curves (Fig. C8b).

The ink color assigned to November 28 is purple, and that for November 29 is yellow. The clerical-error hypothesis calls for an error in inking that exchanges two curve segments. In the exchange, a segment of the November 28 curve is mistakenly inked in yellow, and a corresponding piece of the November 29 curve is mistakenly inked in purple (Fig. C7a–d). The curve segments hypothetically exchanged begin at 0210 IST (Fig. C6a) and end at 0445 IST, late in the steep upturn (Fig. C6c).

The hypothetically exchanged interval includes the origin time of the great 1945 Makran earthquake—0327 on November 28 IST (Fig. C6b), equivalent to 2157 on November 27 UTC (Byrne et al. 1992). The interval includes, in addition, most of the apparent drawdown relative to the rising tide (Figs. C4, C3b). This apparent drawdown, assigned in purple ink to November 28 (Fig. C6a), forms an anomalous shoulder in that day's marigram (Figs. 5 and C7c). According to the clerical-error hypothesis, most of this apparent drawdown took place instead on November 29, purple ink nothwithstanding (Fig. C7b).

Intersections, shapes, and patterns of the tidal curves

Intersections that define the exchanged line segments

The purple "out of order" gap for 0210 IST on November 28 provides the starting point for the posited exchange of line segments (Fig. C6a). The yellow line for November 29 meanders toward this gap. By the clerical-error hypothesis, the November 29 line emerges from the gap as the segment, between 0210 and 0445, that was inked mistakenly in purple. The posited mistake ends at 0445 at intersection of the yellow and purple lines (Fig. C6c).

A convincing exchange would involve curves that intersect in two places. The posited exchange. however, has but one clear intersection, at 0445 IST. Where the posited exchange begins, at 0210 IST, the line inked yellow as November 29 meanders past the "out of order" gap in the line inked purple as November 28. Near the gap the yellow line nowhere touches the purple line (Fig. C6a). Continuity of this part of the yellow line is evidenced by gray pencil that appears to show through the yellow ink.

Fluctuations that aid in assigning line segments to the correct day

The styles of the exchanged line segments provide no evidence that the curves were inked incorrectly. To the contrary, the styles instead accord with the applied ink colors. As inferred below, this congruence is evidenced by fluctuations in the curves: the curves for November 28 and 29, as inked, have more of the shape and abundance of these fluctuations (Figs. C7a and C7c) than of those from the posited exchange (Figs. C7b and C7d).

The purple line for the morning of November 28, as inked, shows two kinds of fluctuations between 0210 IST and 1200 IST. The fluctuations are few, short, and broad during the apparent drawdown, relative to rising tide, between 0210 IST and 0415 IST (Fig. C6a). Next, between 0500 IST and 1200 IST, they become larger, more numerous, and abrupt (Fig. C6c). The similarly numerous fluctuations inked in yellow for the morning of November 29 are of intermediate shape and amplitude.

Moved to November 29, the purple segment between 0210 and 0415 differs from adjoining parts of the November 29 curve in having fewer and broader low-amplitude fluctuations (Fig. C7b). Similarly, in its reciprocal move to November 28 (Fig. C7d), the yellow segment between 0210 and 0415 inserts, before the sharp peaks and troughs that follow, low-amplitude fluctuations typical of later parts of the tsunami (Fig. C7a). These problems with the posited exchange can be avoided by accepting the curves as inked.

Recession of tidal curves

The exchange illustrated in Figure C4 has the apparent benefit of removing an anomalous precession of morning rising tides. As inked, rising water levels on November 29, between 0100 IST and 0445 IST, are reached earlier in the day than are the same water levels the morning of November 28 (Fig. C6). This inked precession contrasts with the typical lunar-day recession of

Karachi's high waters and low waters. These tidal extrema group naturally in four sets—for the area's twice-daily low waters and the twice-daily high waters. The typical recession within each set is highlighted in Figure C5 by labeled extrema between November 25 and December 1. Those extrema are numbered, and are grouped into sets (S_0, S_1, S_2, and S_3), as in Appendix A. In tide-table predictions for Karachi (Hydrographic Department 1944:104-106), extrema within each set are separated by one lunar day—that is, by 24.8 hours (Pugh and Woodworth 2014)—with deviations of up to one hour (Fig. 3b). The additional length of the lunar day produces the typical recession of tides in solar time.

Lunar-day recession need not prevail, however, during a tsunami. The highest gauged part of the tsunami, near 0800 IST on November 28, places extremum 51 at a precessive time after that of extremum 55 (Fig. C5). Similarly, the apparent drawdown between 0145 IST and 0415 IST places part of the purple curve—whether as inked for November 28 (Fig. C7e) or shifted to November 29 (Fig. C7f)—after its counterpart on November 30.

The tsunami may further explain why, between 0100 IST and 0445 IST, the curve inked yellow for November 29 precedes the curve inked purple for November 28 (Fig. C6a). This precession in time might result from an anomaly in November 29 water levels. At 0100–0445 IST on November 29, the Digitized Marigram (black in Fig. C4a) is consistently higher than the Accepted Tide (light blue in Fig. C4a), and the residual is correspondingly positive (black, Fig. C4b). The additional height, at 0.1–0.2 m, is equivalent to a rightward shift of one to two gridded height units in the rotated coordinate system of the marigram sheet in Figures C5 and C6. Absent such a shift, water levels observed 0100–0445 IST on November 29 would have plotted one or two grid cells to the left in Figure C6a, such that the November 29 curve (as inked in yellow) would appear delayed with respect to the November 28 curve (as inked in purple)—as expected of tidal regression. The inked precession between 0100 and 0445 may thus represent a long-period tsunami component that persistently elevated water levels early on November 29.

Disruption by the earthquake and tsunami

It can be supposed that the earthquake of November 28 and the tsunami of November 28–29 disrupted work at the Karachi tidal observatory, and that the disruptions increased the chance of human error when the marigram was being inked and checked. However, as shown below, routine procedures and extra care in inking are instead suggested by notes on the marigram (Fig. C8). Furthermore, newspaper reports suggest that the earthquake caused little disruption in Karachi (Fig. C9), and evidence on the marigram suggests that the tsunami disrupted tidal observations for only a few tens of minutes, on soon after 0800 IST on November 28 (Fig. C8c).

Attention to the marigram

Except on November 28, the observatory staff followed protocol in circling and dating, twice daily, the position of the pencil on the drum of the operating gauge. This precaution minimized opportunities for later misdating of the tidal curves. Additional care with the curves is evidenced by their having been inspected on December 12, 1945, "by AWahid" (Fig. C8b).

Further review focused on the curves for November 28 and 29 is evidenced in a note from D.B. Brow (Fig. C8c). Brow, who signed as Chief Engineer of Karachi Port Trust, would later become its Chairman, and would author a history of the port (Brow 1947). His note on the marigram begins by ascribing a gap in the marigram, soon after 0800 IST on November 28, to a mechanical problem caused by "a tidal wave." The note concludes by calling attention to "a separate chart for the 28th and 29th." Preparation of this "separate chart" provided a further opportunity to detect errors in the curves for November 28 and 29. Brow implicitly endorses those curves as inked on the original marigram, because he does not describe the "separate chart" as containing corrections. Instead, the “separate chart,” like the graphs in Figure C7, may have served merely to isolate, from the maze of curves in Figure C2a, the complicated changes in water level that took place during the tsunami.

Damage to the tide gauge

According to the authoritative catalog of Ambraseys and Melville (1982, p. 90), the great 1945 Makran earthquake “was not felt very strongly” as far east as Karachi and “was not perceptible” farther east than Karachi. Similarly, little earthquake damage was reported in local newspapers, except for spillage of mercury in a lighthouse near the Karachi tide gauge, and stoppage of clocks in the city itself (Fig. C9).

The marigram note by D.B. Brow (Fig. C8c) describes but one mechanical problem from the tsunami, at “0810–0830 on the 28th Nov ’45.” The problem described was rapid movement of a copper belt that was connected to a float in the stilling well. Not mentioned by Brow is any blockage of a hole that admitted waters of Karachi Harbour into the stilling well of the Karachi tide gauge. In principle, blockage could produce an apparent drawdown with respect to a rising tide. But the apparent drawdown of 0145–0415 IST, on November 28, precedes any large tsunami waves of high frequency, or any other evident disturbance, to which blockage could be ascribed.

Occam’s razor

If the simpler solution is to be preferred, the apparent drawdown as inked is preferable to exchanging, between November 28 and 29, the tidal-curve segments for 0210–0445 IST:

1. The posited exchange removes only part of the apparent drawdown on November 28. The earliest part of this drawdown remains, in need of explanation other than clerical error (Figs. C4 and C7d).
2. The exchange further complicates its version of the apparent drawdown by adding two oscillations (from the yellow curve inked as November 29) that loosely bracket the time of the great earthquake (Figs. C4 and C6b). To explain these yellow-curve oscillations by unusual weather would mean invoking something that received no mention in local newspapers or in official weather summaries (details below, under “Unsual weather”).
3. The exchange adds, to the detided tsunami oscillations on November 29, a drawdown of uncommon depth and shape (Fig. C4b). As with the two oscillations added to November 28, this additional drawdown is difficult to explain by unusual weather.
4. Seiching could be invoked for the post-earthquake oscillation that is centered at 0400 along the yellow curve hypothetically redated as November 28. However, this yellow curve proceeds smoothly across the time of the earthquake and for 20 minutes thereafter (Fig. C6b).

NATURAL CAUSES

A natural explanation for the early anomaly on November 28 could help explain why it includes the 0327 IST origin time of the great 1945 Makran earthquake. However, if genuine and if not meterological in origin, the anomaly could then mean that the 1945 Makran tsunami began before the coseismic deformation conventionally viewed as the initial tsunami trigger.

Unusual weather

No unusual weather was reported for the Karachi area in the local dailies, *Daily Gazette* and *Sind Observer*, in their issues of November 28, 29, or 30. No Arabian Sea storms or other anomalies in that region were reported for that time in annual reviews by the national meteorological agency (Meteorological Department 1949a:C7, Meteorological Department

1949b:A3).

Precursory tsunami

It has been thought that the 1945 Makran tsunami combined more than one train of waves. The first wave train, in this view, was set off by tectonic displacement beginning 0327 IST on November 28, during the great earthquake; and a later wave train, set off by submarine slope failure, produced the largest waves at Pasni and Ormara, which are difficult to explain solely by offshore uplift from seismic slip on the subduction thrust (Byrne et al. 1992:458, Heidarzadeh et al. 2008:782-784, Rajendran et al. 2008). Recently the largest waves at Pasni and Ormara have been simulated by allowing slope failure offshore Pasni to follow the great earthquake (Rastgoftar and Soltanpour 2016, Heidarzadeh and Satake 2017).

The puzzling anomaly of 0145–0500, if not explained by observational error, provides grounds for evaluating whether still another wave train began before the great earthquake. Potential triggers include a submarine slope failure and rapid creep on a submarine fault. In tsunami modeling to test these hypothetical sources, successful simulations would produce no early effect on the tide-gauge record from Bombay. There, the 1945 Makran tsunami began as a positive wave at a time consistent with a trigger close to 0327 IST in the source area of the great earthquake (Neetu et al. 2011, Heidarzadeh and Satake 2015).

Slope failure

An initial drawdown lasting an hour or more can result from a long-lasting landslide that lowers the ocean floor as it elongates a scar in the downslope direction. This possibility is suggested by simulations of a Storegga landslide tsunami (Harbitz 1992:17, stations 4, 6, 7, and 8, Løvholt et al. 2017:X-1, Bjugn station).

Traces of youthful slides could be sought beneath the Arabian Sea near Karachi. To the south, offshore the Indus Delta, many slumps have been identified in Indus Canyon and on the adjoining continental slope, but most are probably of Pleistocene age (von Rad and Tahir 1997). To the west, sediment gravity flows on the continental slope are evidenced by turbidites there and on the abyssal plain (Bourget et al. 2010).

It is possible that a foreshock triggered a slide beneath the Arabian Sea in the last hours before the great Makran earthquake. In that case, however, the foreshock probably did not exceed magnitude 5.5—the approximate lower limit of 1945-era earthquakes in the Makran list of Quittmeyer (1979) and the global ISC-GEM catalog (Storchak et al. 2013, International Seismological Centre 2017).

Simulations of landslide-induced tsunamis might further assess their effects in the Indus Delta. Among 299 confirmed deaths from the 1945 earthquake and tsunami, 163 occurred in villages along the Delta's tidal creeks (Fig. 1).

Slow earthquake

A tectonic mechanism could be sought for lowering the floor of a deep part of the Arabian Sea near Karachi, during the last hours before the great Makran earthquake. The slip would need to be fast enough to trigger a tsunami but slow enough to avoid detection as an earthquake. In tsunami simulations it would need to produce, in Karachi Harbour, a progressive drawdown that lasts three hours and concludes with a water level 0.5 m below ambient tide, without extending to Bombay.

Tsunami models could be run for submarine faulting south of Karachi, on the deep-sea fan of the Indus Delta. Late Cenozoic turbidites of this fan have been displaced by an extensional plate boundary and by youthful growth faults (Edwards et al. 2000, Gaedicke et al. 2002).

Tsunami models could also evaluate precursory slip on the Makran subduction thrust. This possibility has the potential advantage of cause and effect, as in the giant slow earthquake that is thought to have both preceded and triggered the M 9.5 Chile mainshock of 1960 (Kanamori and Cipar 1974, Cifuentes and Silver 1989). A subduction thrust may partly unlock in the years before it fails abruptly in a great thrust earthquake (Hui and Lingsen 2018). The potential for slow Makran earthquakes is evidenced by estimates of present-day interplate coupling on the subduction thrust, where GPS evidence suggests that modern creep takes up one-third to two-thirds of the plate convergence (Frohling and Szeliga 2016).

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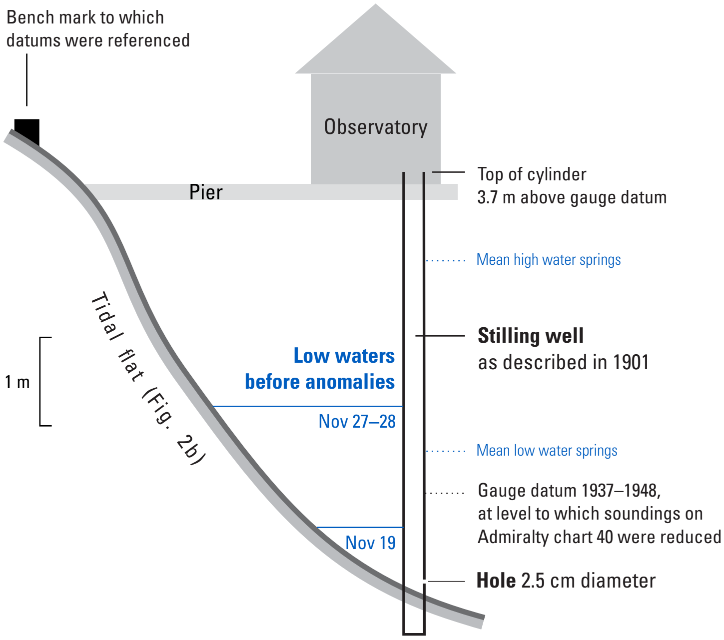
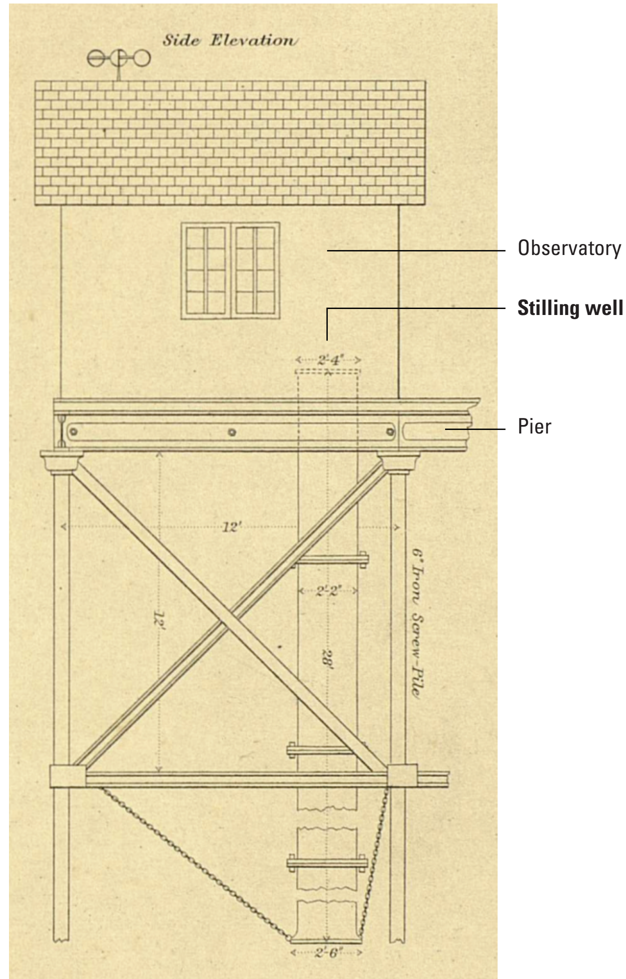
LIST OF FIGURES

Figure C1 Vulnerability of the Karachi tide station to blockage of its connection between harbour and stilling well

a Likely levels of stilling well and its orifice with respect to tides



b Tide station of the style probably in use in Karachi in 1945



"The tidal observatory at Kurrachee on the coast of Sind is one of the permanent observatories, and is situated alongside the end of the 'Tipping pier' on the Manora side of the Harbour. It is a substantial, isolated wooden structure, built on piles driven from eight to twelve feet into the ground.

"The cylinder is an iron screw pile of about two feet four inches internal diameter and seventeen feet six inches long, driven about two feet into the ground, and firmly braced to the observatory joists; the intention being that there should be about one foot of the cylinder above the highest tides, and about four feet of water within it at the lowest tides.

"The communication is by a hole one inch in diameter, drilled through the cylinder at a depth of fifteen feet eight inches below the top flange.

"Registrations were commenced on the 1st January, 1881, and have been highly satisfactory, though occasionally the curves have slight imperfections due to shell fish blocking the communication; and in 1892 silt accumulated to such an extent that extreme high and low tides were not properly indicated, owing to the float at extreme low water and the counterpoise at extreme high water resting on the accumulation, which was removed in January, 1893.

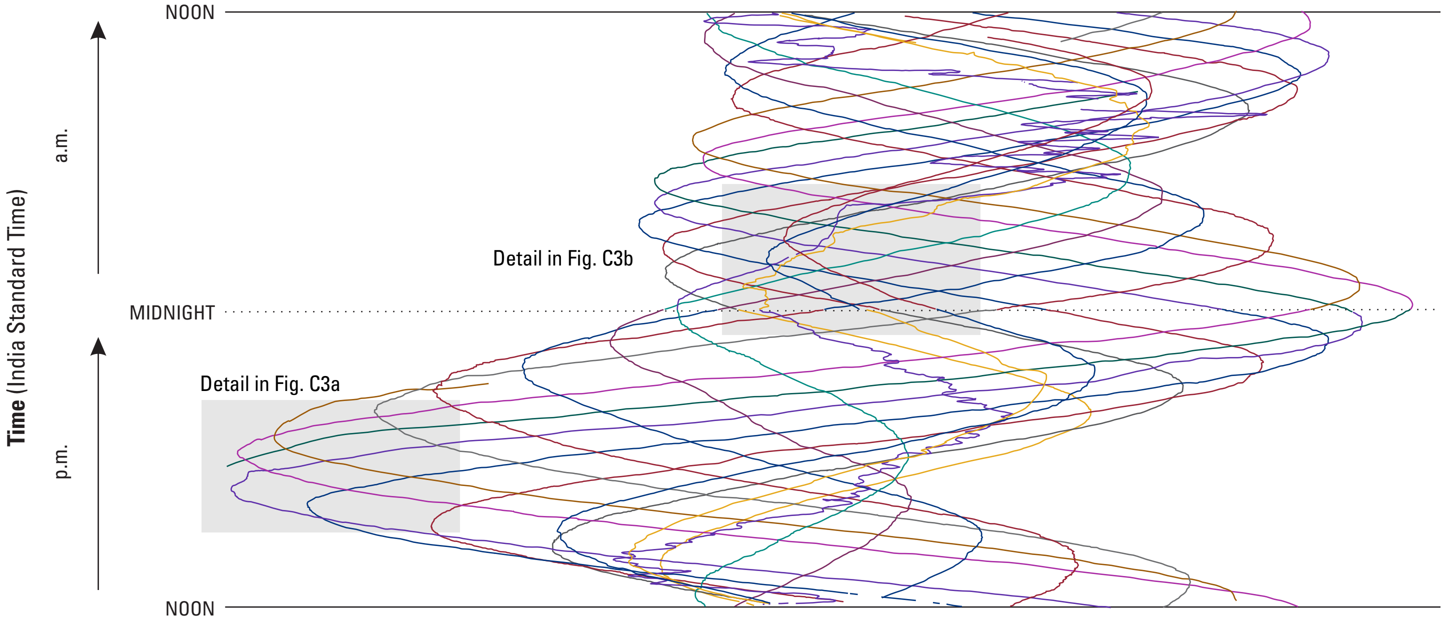
"The bench-mark of reference is a stone, about half a furlong S.W. of the observatory."

—Eccles (1901b, p. 9)

The datums are from Permanent Service for Mean ea Level (2016) and from Hydrographic Department (1944, p. 357). The anomalies of November 19 and 28 are illustrated in Figures C2 and C3. Low waters that preceded them are graphed on the marigram (Fig. S2) and listed in Table S3. The tide station in **b** was in Akyab, Burma (mechanical drawing in Eccles, 1901a, plate VII).

Figure C2 **Tracing of** Karachi marigram for November 15 to December 1, 1945

a **Tidal curves** color-coded by day as on scanned marigram (Fig. S1)



b **Anomalies** of similar shape, but of different size, during rising tides on November 19 and November 28

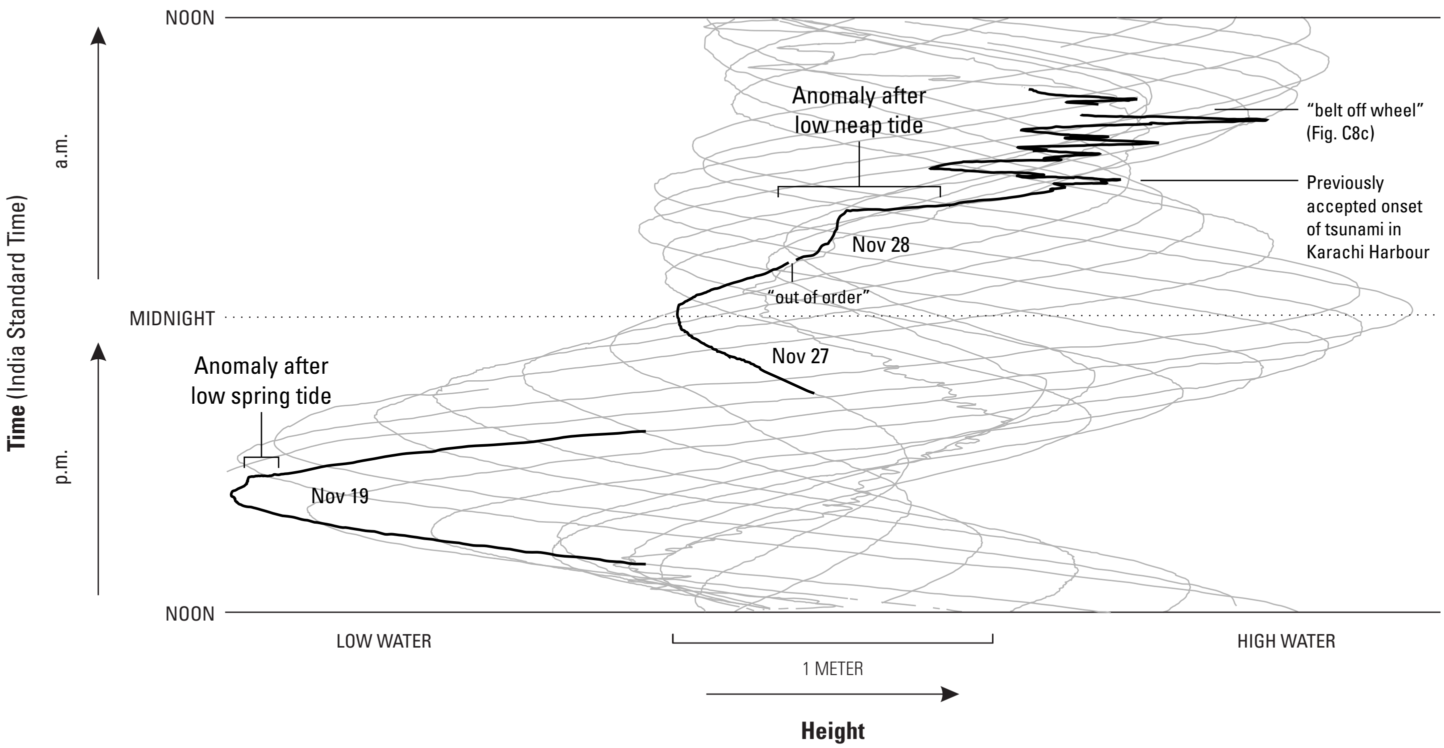
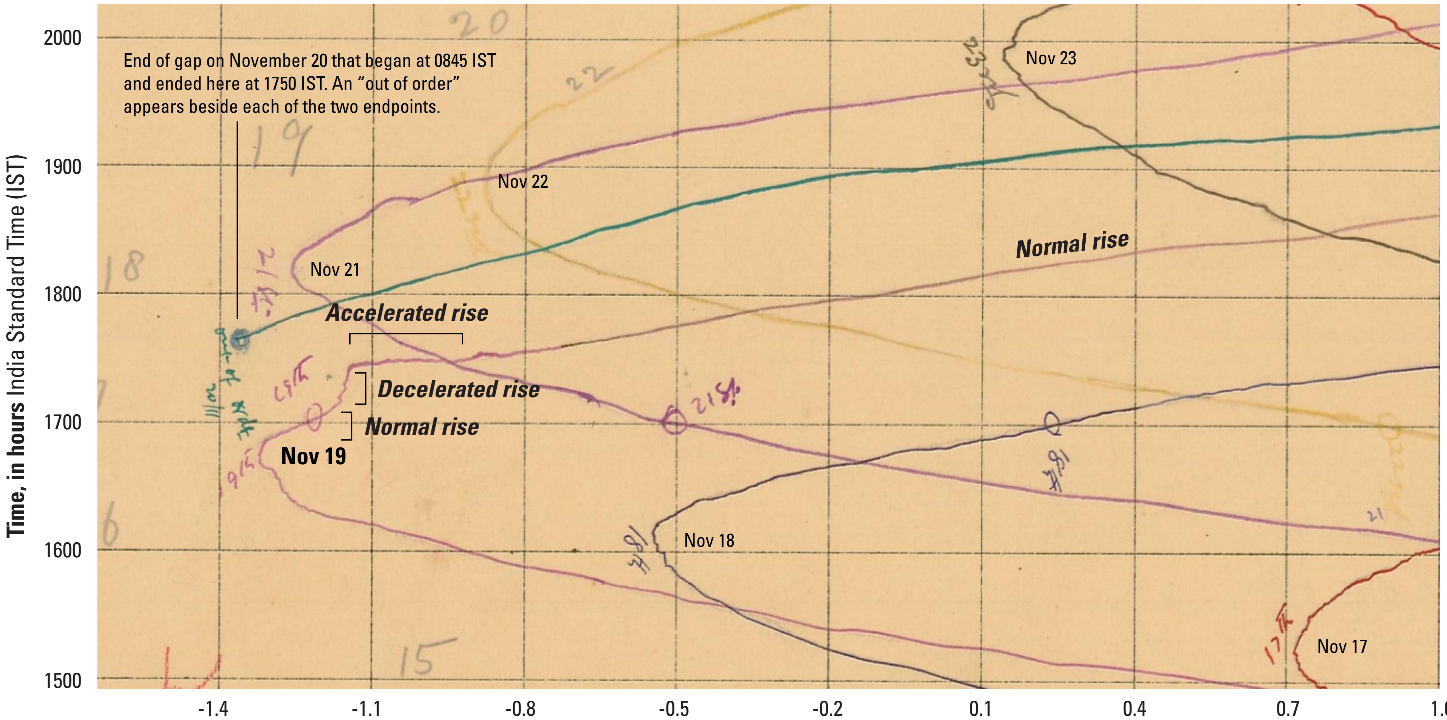
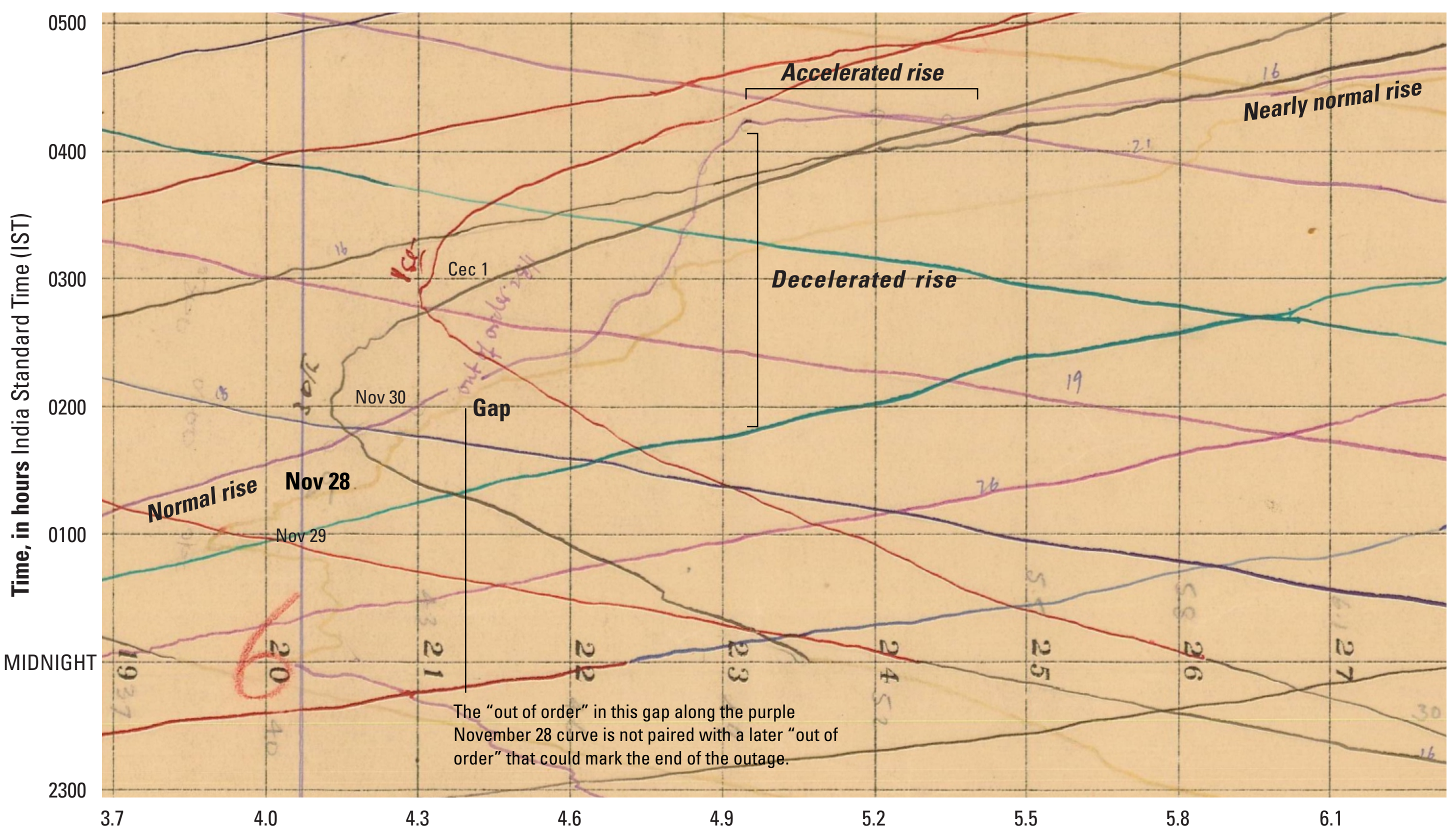


Figure C3 **Apparent drawdowns** decelerate rising tides of November 19 and 28, before the graphed water levels increase abruptly.

a **November 19**—Anomaly less than one-half hour long, in the first hour after a low spring tide



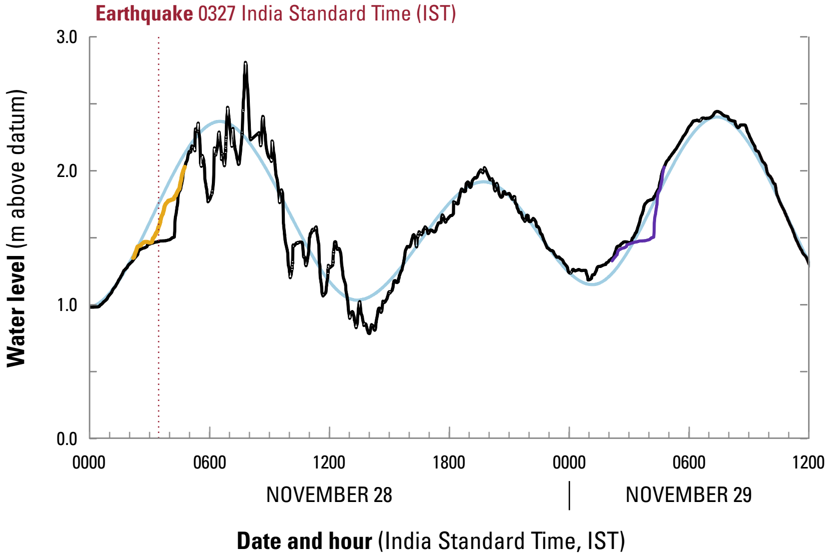
b **November 28**—Anomaly more than two hours long begins about nearly two hours after a low neap tide (shown in full in Fig. C2)



Height, in feet above datum of gauge and nautical chart

Figure C4 Clerical-error hypothesis

a Water levels



EXPLANATION for **a**

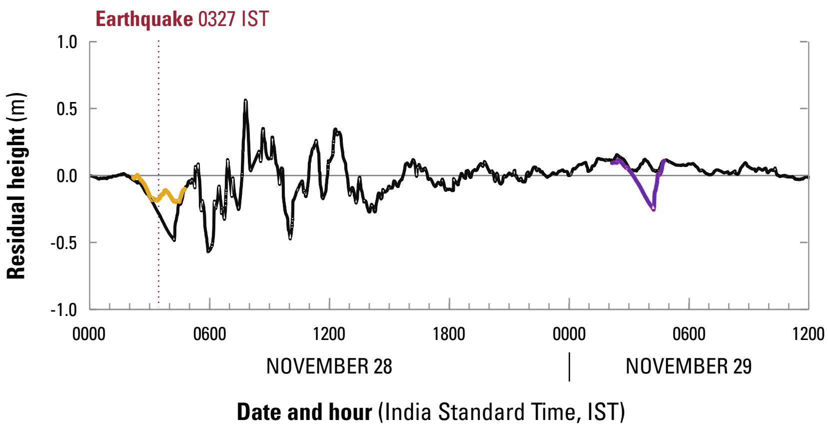
Observed water levels

Digitized Marigram—Adapted from marigram scan as traced in Figure C2. The digitized points, which mostly overlap in Figure 5, are linked here as a continuous line that neglects gaps at 0208–0213, 0806–0830, and 0910 IST. The black line accepts, in full, the dates assigned to the curves by means of color ink in the marigram (examples, Figs. C5 and C6).

Exchanged line segments—In the clerical-error hypothesis, the segment inked as November 29 (yellow) was actually recorded on November 28, and should replace the Digitized Marigram there; and in exchange, the segment inked as November 28 (purple) belongs on November 29.

Computed tide—The Accepted Tide derived in Appendix A

b Residuals



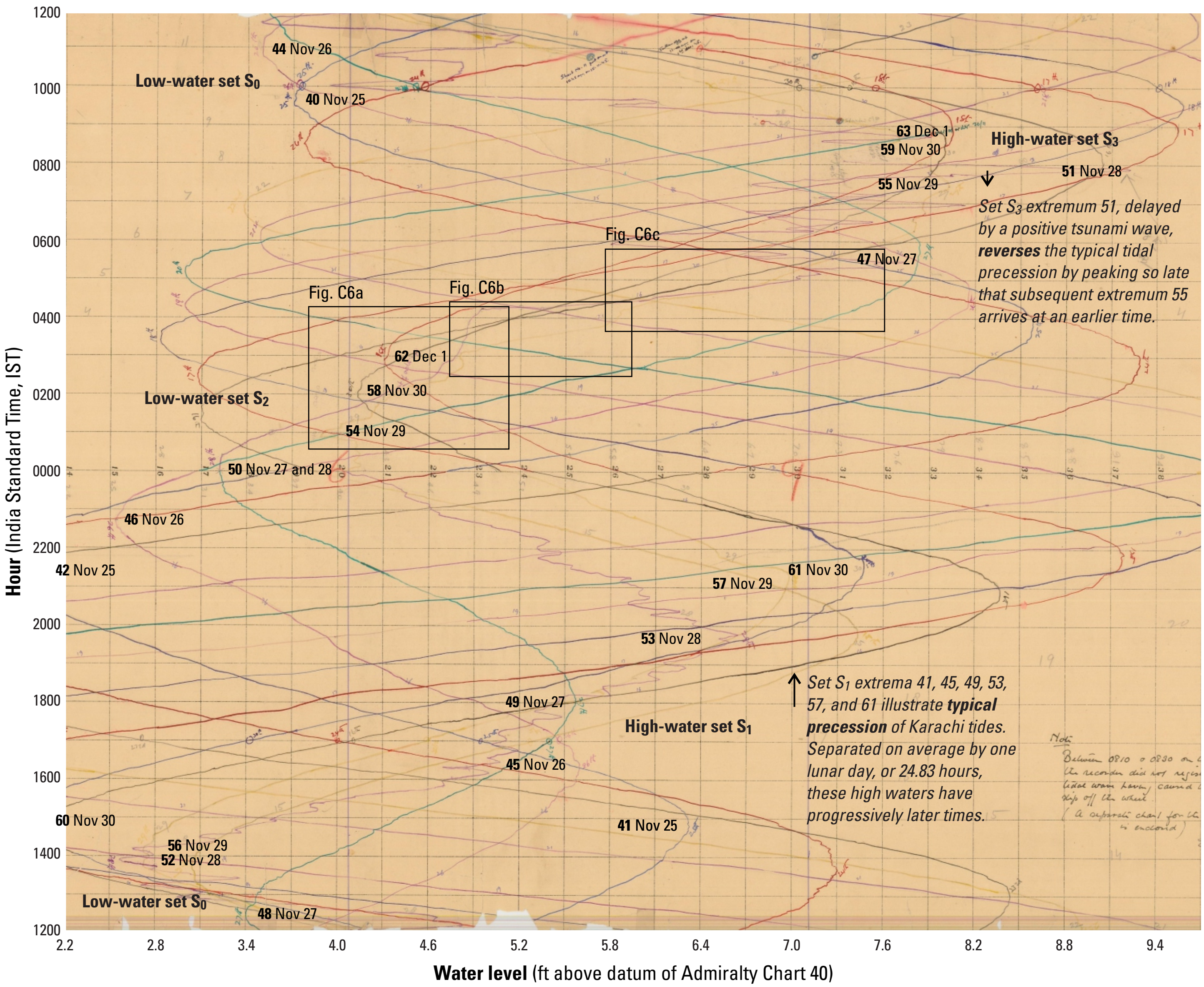
EXPLANATION for **b**

Residual water levels—Difference between Digitized Marigram and Accepted Tide

Without posited exchange—As in **a**, the black line accepts, in full, the dates assigned to the curves by means of color ink in the marigram, and gaps are neglected.

With posited exchange—In the clerical-error hypothesis, the curve segment inked as November 29 (yellow) was mistakenly swapped, as in **a**, with a segment inked as November 28 (purple).

Figure C5 Scanned marigram between 2.2 and 9.7 ft on the water-level axis, showing areas of detail in Figure C6 and successive delay of high waters and low waters within lunar-day groups



EXPLANATION

56 Nov 29
Low-water set S_0

Observed extremum—Low water or high water, labeled here if between November 25 and December 1. Grouped in four sets (S_0, S_1, S_2, and S_3) that are defined in Appendices A and B. Corresponding predictions, from Admiralty tide tables, are plotted for Figures 3 and 4.

Rotated axes—The marigram axes above, and in Figures C6 and C7, are rotated and reversed with respect to the axes in Figure C4.

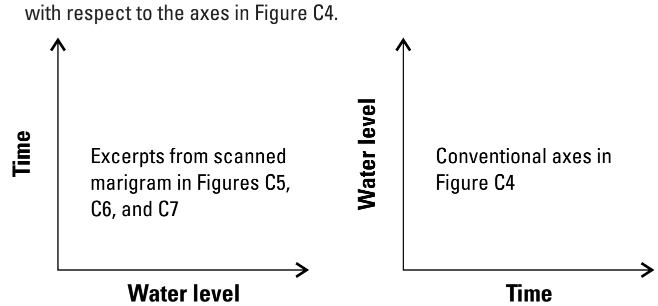
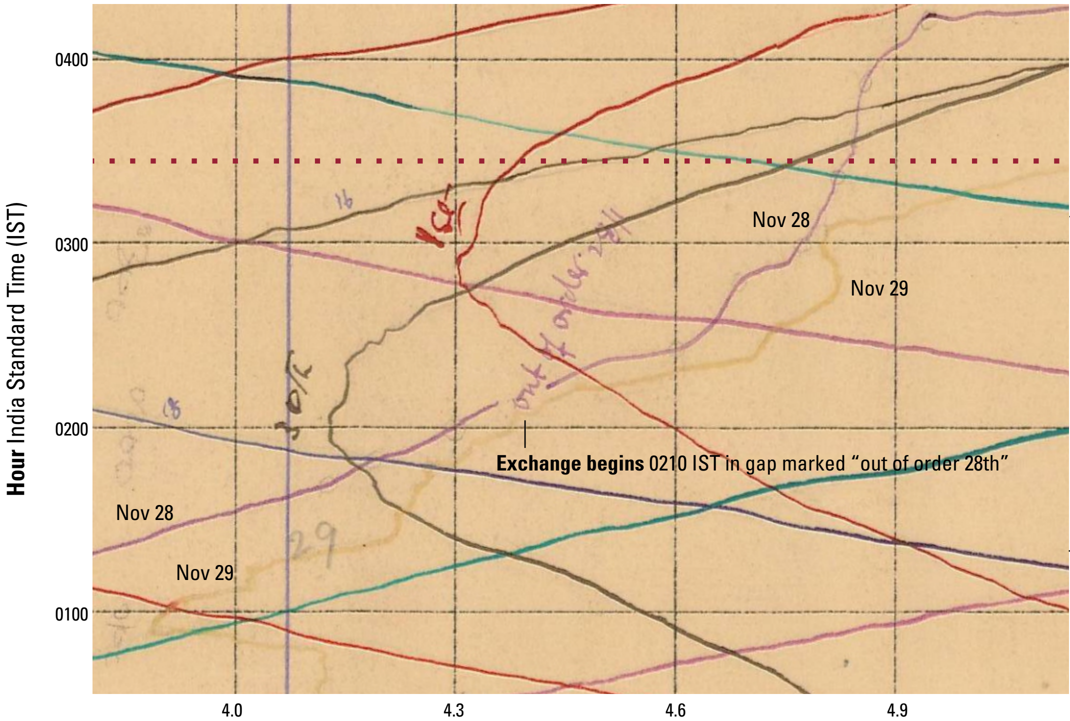


Figure C6 **Tidal curves for November 28 and 29** in vicinity of the posited error in inking

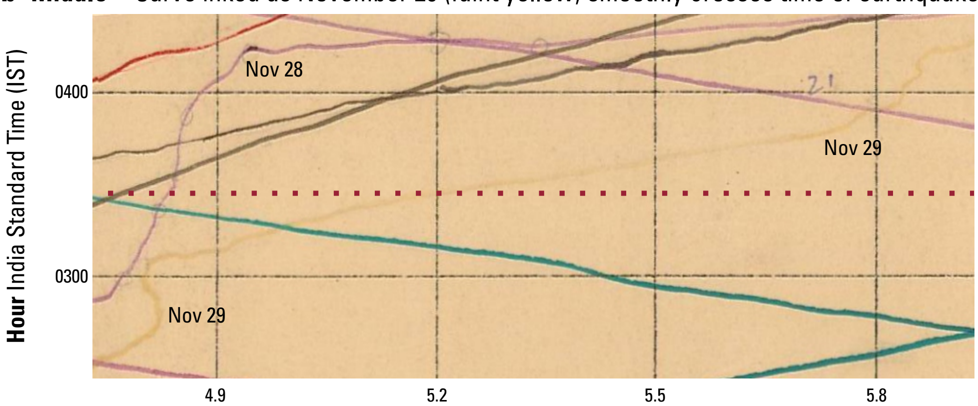
a **Start**—Curve inked as November 29 (yellow) approaches, but does not enter, gap in curve inked as November 28 (purple)



Earthquake 0327 IST November 28
(dotted line added to scanned image)

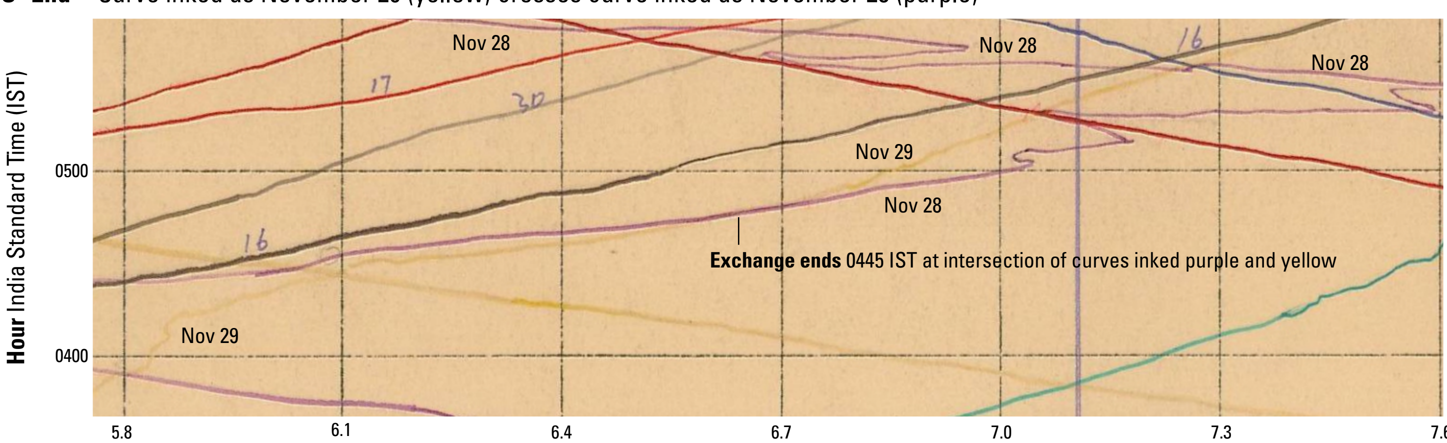
During these hours, the curve inked yellow (for November 29) would have been 0.3–0.6 ft (0.1–0.2 m) lower had it oscillated about the Accepted Tide (Fig. C4). Such a lowered level would move the yellow November 29 curve to the left of the purple curve for November 28. The morning flood tide on November 29 would then lag its November 28 counterpart, as expected from the succession of tides that are separated by one lunar day (24 hours 50 minutes) on average (Fig. C5).

b **Middle**—Curve inked as November 29 (faint yellow) smoothly crosses time of earthquake on November 28



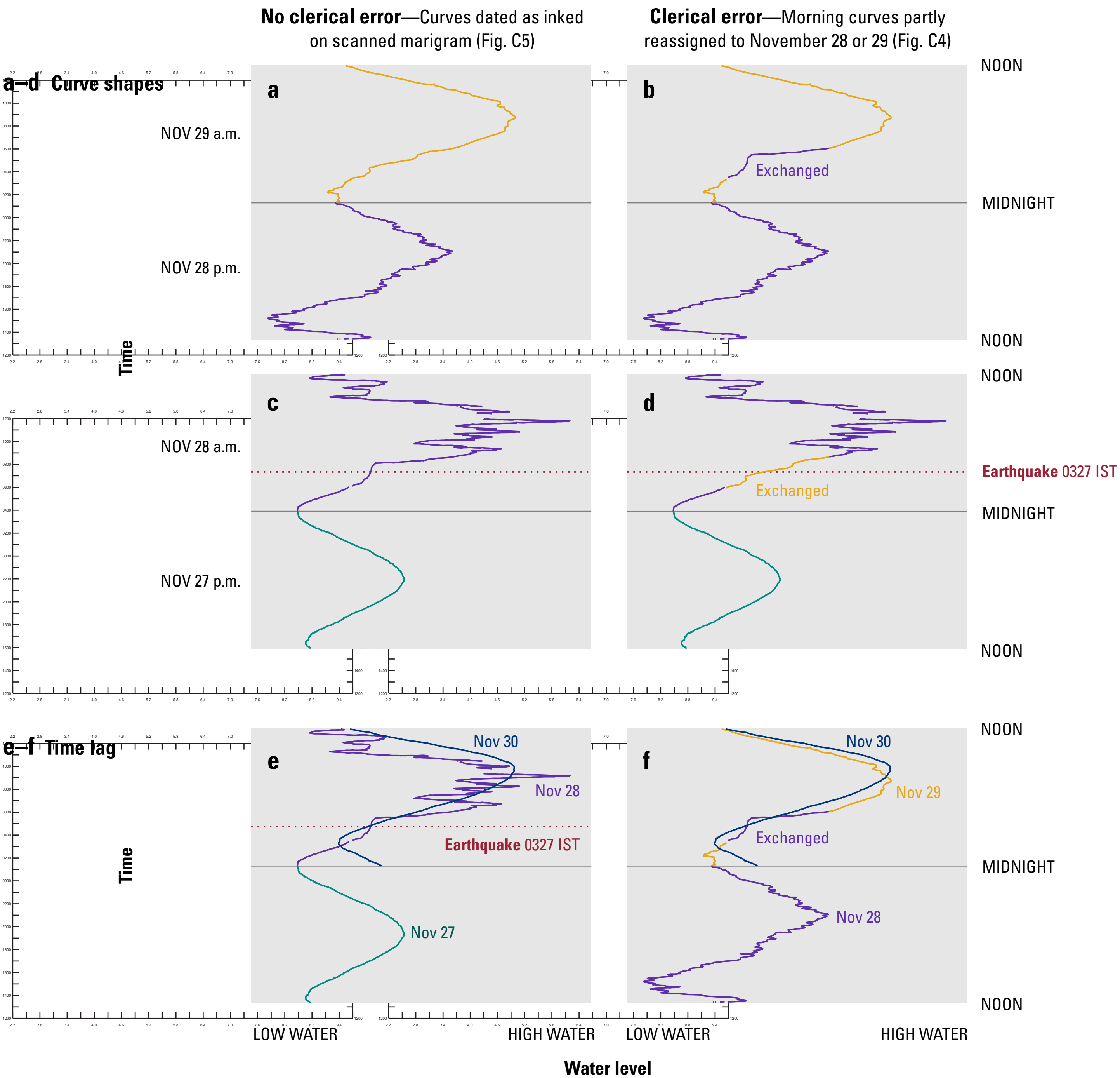
Earthquake 0327 IST November 28
(dotted line added to scanned image)

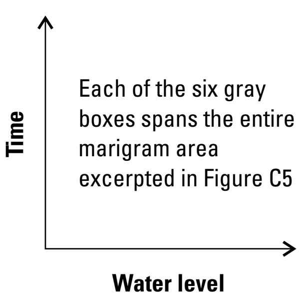
c **End**—Curve inked as November 29 (yellow) crosses curve inked as November 28 (purple)



Water level in **a**, **b**, and **c** (feet above datum)

Figure C7 Daily tidal curves showing effects of hypothetical exchange of curve segments from mornings of November 28 and 29



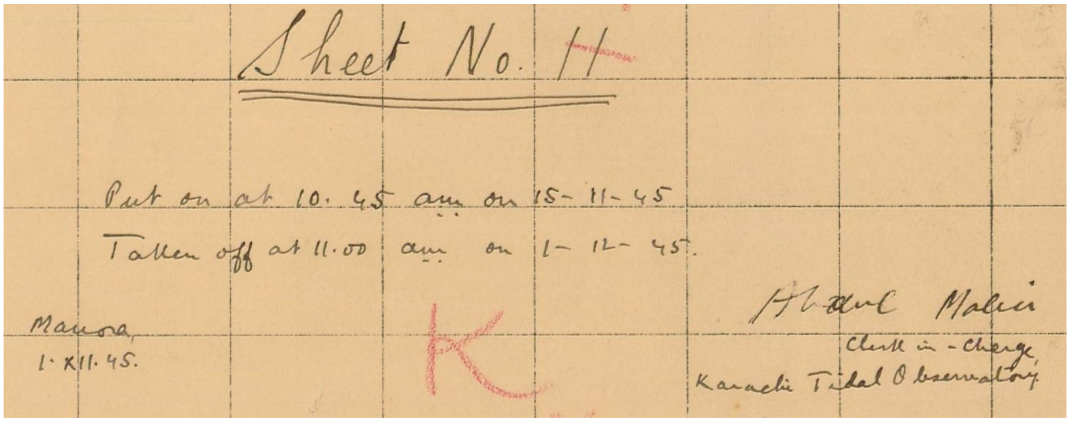


All tidal curves in this figure are tracings of the marigram scan. The scan, reproduced in full in Figure S1, is excerpted in Figure C5. Tracings of all curves can be found in Figure C2. The curves in Figure C4 are drawn through the points of a digitized version of these tracings. Those points, termed the Digitized Marigram, are listed in Table S1.

As explained in Appendix A, the Digitized Marigram includes smoothed representations of extrema (high waters and low waters) outside the tsunami interval. Fitting a least squares quadratic curve to each of these extrema provides an objective way of evaluating the extremum where oscillations are superimposed on the tidal crest or trough. Such oscillations are barely visible here in the raw tracings of the two extrema on November 27, the midnight extremum of November 27–28, and the two extrema on November 30.

Figure C8 **Official notes** on marigram (Fig. S1) that attest to quality control after earthquake and tsunami of November 28, 1945

a **Records maintained** by Clerk in Charge


Sheet No. 14

Put on at 10.45 am on 15-11-45

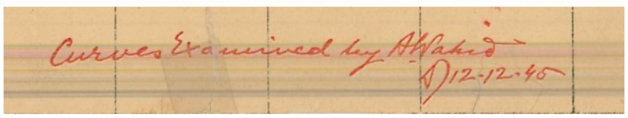
Taken off at 11.00 am on 1-12-45.

Abdul Malik
Clerk-in-Charge
Karachi Tidal Observatory

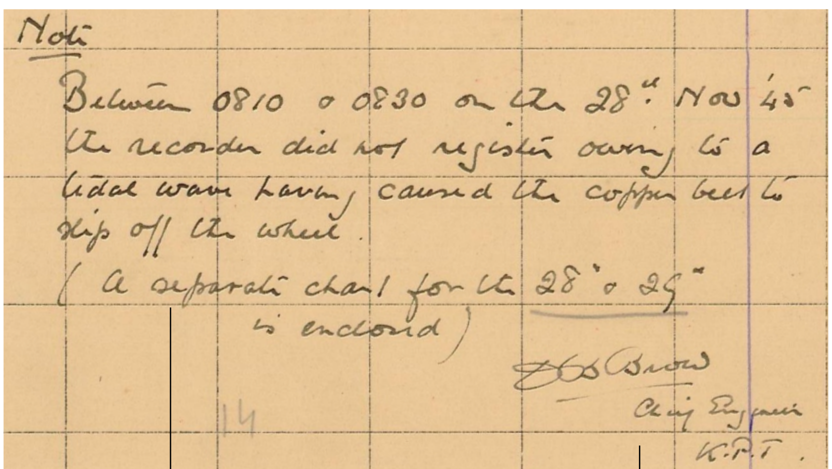
Manora,
1.XII.45.

K

b **Curves examined** two weeks after tsunami


Curves Examined by A Wahid
12-12-45

c **Additional scrutiny** from Chief Engineer


Note

Between 0810 & 0830 on the 28th Nov '45 the recorder did not register owing to a tidal wave having caused the copper belt to slip off the wheel.

(A separate chart for the 28th & 29th is enclosed)

D.B. Brow
Chief Engineer
K.P.T.

14

Curves for November 28 and 29 were likely isolated for clarity on this separate chart. The engineer's note does not imply that the separate chart corrects mistakes in the way that they are inked on the marigram.

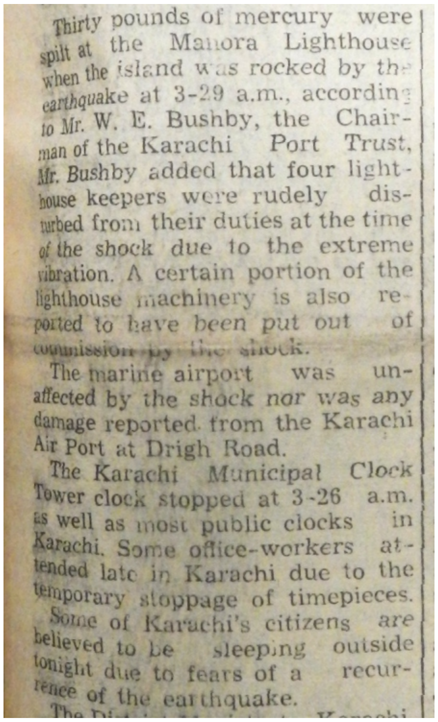
We sought the separate chart without success. We do not know whether it has been conserved.

D.B. Brow signed this note as Chief Engineer of Karachi Port Trust, the authority for port facilities and operations.

Mr. Brow, above, succeeded W.E. Bushby as K.P.T. Chairman in 1945 (http://kpt.gov.pk/pages/default.aspx?id=61) and reviewed port history in a posthumous article (Brow, 1947). Mr. Bushby, as chairman, commented on damage from the great earthquake of November 28, 1945 (Fig. C9a).

Figure C9 Earthquake intensity evidenced in Karachi newspapers of November 29, 1945

a ***Karachi Daily Gazette***



Thirty pounds of mercury were spilt at the Manora Lighthouse when the island was rocked by the earthquake at 3-29 a.m., according to Mr. W. E. Bushby, the Chairman of the Karachi Port Trust. Mr. Bushby added that four lighthouse keepers were rudely disturbed from their duties at the time of the shock due to the extreme vibration. A certain portion of the lighthouse machinery is also reported to have been put out of commission by the shock.

The marine airport was unaffected by the shock nor was any damage reported from the Karachi Air Port at Drigh Road.

The Karachi Municipal Clock Tower clock stopped at 3-26 a.m. as well as most public clocks in Karachi. Some office-workers attended late in Karachi due to the temporary stoppage of timepieces.

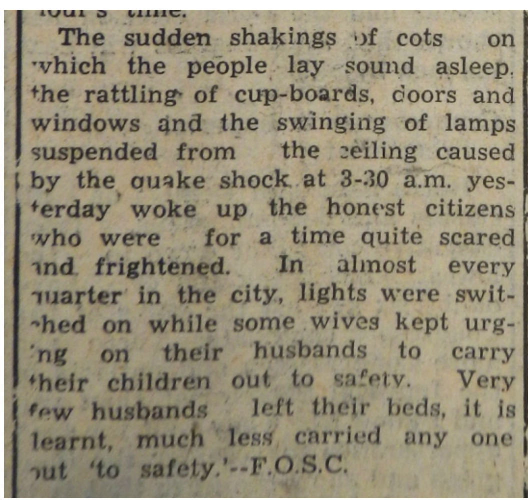
Some of Karachi's citizens are believed to be sleeping outside tonight due to fears of a recurrence of the earthquake.

Manora Lighthouse stands 1.3 km southeast of the 1945 site of the Karachi tidal observatory. The mercury was likely used as a lubricant for rotation of a Fresnel lens.

Mr. Bushby was soon succeeded as K.P.T. Chairman by David B. Brow, who documented mechanical problems from the 1945 tsunami (but not from the earthquake) at the Karachi tidal observatory (Fig. C8c).

The Karachi Municipal Corporation Building is 6.7 km northeast of the 1945 site of the Karachi tidal observatory.

b ***Sind Observer***



The sudden shakings of cots on which the people lay sound asleep, the rattling of cup-boards, doors and windows and the swinging of lamps suspended from the ceiling caused by the quake shock at 3-30 a.m. yesterday woke up the honest citizens who were for a time quite scared and frightened. In almost every quarter in the city, lights were switched on while some wives kept urging on their husbands to carry their children out to safety. Very few husbands left their beds, it is learnt, much less carried any one out 'to safety.'--F.O.S.C.