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The 1904 M_s 7.3 Earthquake in Central Alaska

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Abstract On 27 August 1904, seismic stations from around the globe recorded an $M > 7$ earthquake originating from central Alaska. Very little was known about this earthquake. One felt report from Rampart, Alaska, had been attributed to the notes of Harry Fielding Reid, yet its original source was unknown. Here, we present five felt reports for the 1904 earthquake that show evidence of felt shaking across most of central Alaska. Using the 1904 arrival-time data, we estimate an epicentral location near Lake Minchumina at the northeastern extent of the Iditarod–Nixon fault. Our preferred fault for the 1904 earthquake is the right-lateral Iditarod–Nixon fault, which, though relatively seismically quiet, generated an M 6.2 earthquake in 1935. Paleoseismic investigations are needed to search for evidence of fault activity, including the 1904 earthquake rupture, in the tectonically complex region of the 1904 earthquake.

Electronic Supplement: Tables of arrival time, figures of station registers, visualization of NonLinLoc (NLL) solution for the 1904 Alaska earthquake, distribution of depths of the posterior probability for the 1904 and 1935 events, epicenter and samples of the posterior probability distribution for the 1904 and 1935 earthquakes, map of southward shift of epicenters, and estimated epicenters for the 3 February 2000 Kaltag earthquake.

Introduction

The instrumental era of seismology began in the 1880s (Schweitzer and Lee, 2003), but it was not until 1904 that there was a sufficient number of global stations to allow seismologists to identify most of the large $M \geq 7$ earthquakes that were occurring. As Beno Gutenberg wrote in 1949, “The early instruments were very imperfect by present standards, and there were few observing stations; for years preceding 1904, despite the efforts of Milne and others, there are not even enough data to ensure reasonably complete cataloguing of the largest earthquakes” (Gutenberg and Richter, 1949, p. 4). Gutenberg goes on to recognize the comprehensive arrival-time tables that first appeared for the year 1904 (Rosenthal, 1907) as well as a pioneering global seismicity catalog that spanned the years 1904–1909 (Milne *et al.*, 1913). The compilation of Gutenberg and Richter (1954) started in 1904, as did several subsequent reanalyses (Geller and Kanamori, 1977; Kanamori, 1977; Abe, 1981). Although some analyses of global seismicity included data as early as 1898–1900 (Gutenberg, 1956; Abe and Noguchi, 1983a,b; Pacheco and Sykes, 1992; Storchak *et al.*, 2013), we will consider the instrumental era to start in 1904.

On Saturday, 27 August 1904, at 11:56 a.m. local time, an M_s 7.3 earthquake struck central Alaska (Gutenberg and Richter, 1954; Abe and Noguchi, 1983b). The earthquake was the second largest on Earth that year (Abe and Noguchi, 1983b; Pacheco and Sykes, 1992). It is the fifth largest earthquake to occur in mainland Alaska since the start of the instrumental era, behind the 1964 M_w 9.2 Prince William Sound earthquake, the 2002 M_w 7.9 Denali fault earthquake, the 1979 M_w 7.4 St. Elias earthquake, and the 1943 M_s 7.4 earthquake in the Susitna region north of Cook Inlet. It is larger than all but five earthquakes that have occurred in the lower 48 states since the start of the instrumental era (Pacheco and Sykes, 1992; Ekström *et al.*, 2012).

At the start of this study, published information on the 1904 Alaska earthquake was scant. A Google search would find a brief U.S. Geological Survey (USGS) event page that listed: “Fairbanks, Alaska, 1904 Aug 27 21:56 UTC, Magnitude 7.3, Buildings swayed and cracked,” citing Stover and Coffman (1993). The labeling of the earthquake as Fairbanks is likely based on the epicenter in Stover and Coffman (1993) (from Boyd and Lerner-Lam, 1988), which was 27 km from Fairbanks. “Buildings swayed and cracked” can be traced back to the first volume of *Earthquake History of the United States* to include Alaska earthquakes (Heck, 1947), which identified the felt report as coming from Rampart (Fig. 1) and referenced unpublished notes by Harry Fielding Reid. The original source for the felt report was unknown.

This study has four objectives: (1) to summarize the published literature on the 1904 earthquake, (2) to present five felt reports for the 1904 earthquake, (3) to estimate the epicenter using the 1904 arrival-time data, and (4) to

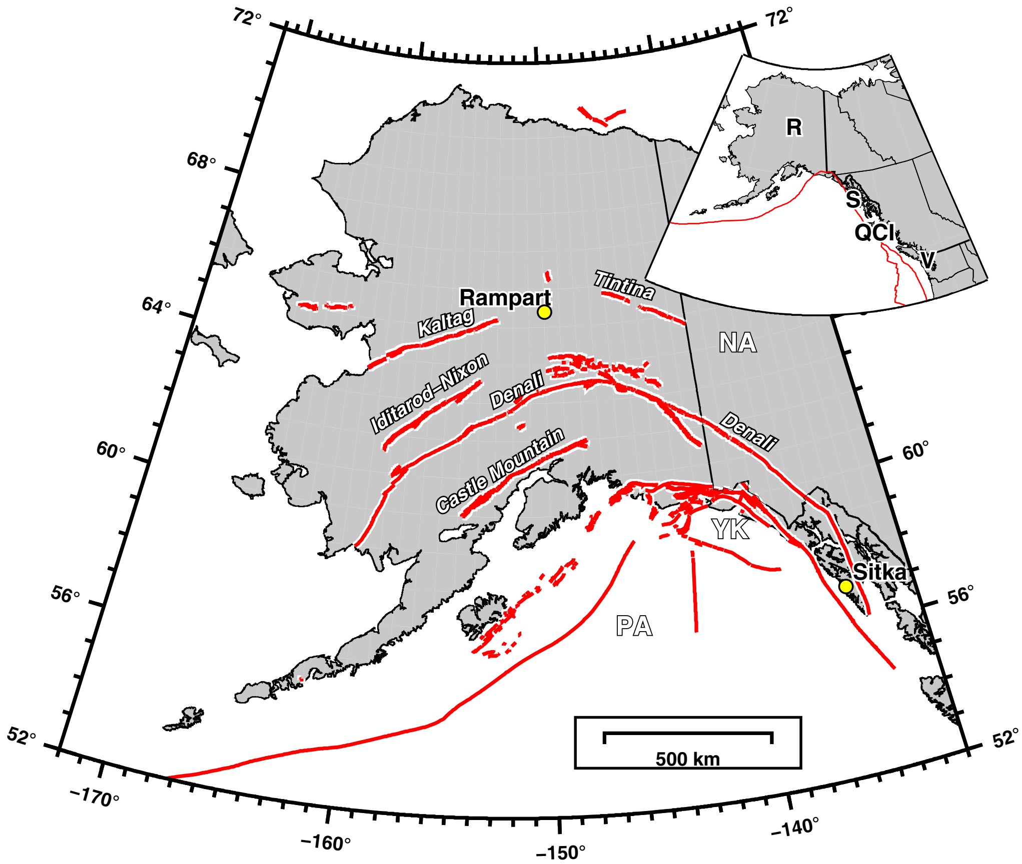

Figure 1. Map of active faults (Koehler *et al.*, 2012) and locations discussed in the Introduction. The Pacific plate (PA), the North American plate (NA), and the Yakutat block (YK) are also labeled. Inset map shows Rampart, Alaska (R), Sitka, Alaska (S), Queen Charlotte Islands (QCI) (Haida Gwaii), and Victoria, British Columbia (V). The color version of this figure is available only in the electronic edition.

assess the candidate faults—and most likely fault—for the 1904 earthquake on the basis of the new evidence. Our evidence points to the northeastern extent of the Iditarod–Nixon fault (Fig. 1) as the most likely source for the 1904 M_s 7.3 earthquake.

Previous Analyses with Instrumental Data

The early 1900s marked the start of the era of cataloging global seismicity (Schweitzer and Lee, 2003). John Milne and others in the United Kingdom collected station registers—tables of arrival times—for stations around the world. They distributed these station registers in "Shide Circulars," named after the station in Milne's hometown at Shide, Isle of Wight. The Seismological Committee of the British Association for the Advancement of Science used the arrival times to estimate epicenters for global earthquakes. The first global view was published as a pair of maps and tables for 1899–1903 (Milne *et al.*, 1912) and 1904–1909 (Milne *et al.*, 1913). The 1904 Alaska earthquake is labeled as <u>885</u>, the 885th earthquake identified at the Shide station (Judd and Milne, 1905), and underlined to denote that it was "recorded all over the world" (Milne *et al.*, 1913).

Harry Fielding Reid, known for his pioneering work on glaciers and on the theory of elastic rebound, was a central figure within seismology in the United States during the early 1900s. In studying North American earthquakes, Reid relied on historical felt reports (Woollard, 1968), but he also compiled instrumental data, including for the 1904 earthquake (Reid, 1905). Reid's tabulation of North American events from 1663 to 1909 did not include the 1904 Alaska earthquake (Reid, 1912); neither did the compilation of Alaska events from 1893 to 1909 by Martin (1910). In 1947, when Alaska earthquakes first appeared in the Coast and Geodetic Survey compilations of U.S. earthquakes (Heck, 1947), Reid's influence was clear: most Alaska events were based on felt reports, many from Reid's collected notes. Much earlier efforts based on instrumental data, such as Milne *et al.* (1913), seem to have gone unrecognized or ignored in Heck (1947).

A summary of published epicenters and magnitudes for the 1904 earthquake is presented in Tables 1 and 2. The earliest estimates for the epicenter ranged from Alaska to the Queen Charlotte Islands (Fig. 1). Reid (1905, p. 186) wrote, "This was a very heavy shock originating in the region just south of the Alaska Peninsula where many earthquakes occur. The origin of this shock seems to have been not far from the Queen Charlotte Islands… Although the shock must have

Table 1
Published Hypocenters and Origin Times for the 1904-08-27 Earthquake

Date	Reference	Longitude (°)	Latitude (°)	Depth	UTC Time (hh:mm)
1905	Reid (1905, p. 186)	"not far from the Queen Charlotte Islands"		—	—
1907	Rosenthal (1907, p. 23)	−120	55	—	22:00
1913	Milne *et al.* (1913, p. 72)	−141	67	—	21:56 ± 2
1954	Gutenberg and Richter (1954, p. 133)	−151	64	"shallow" (≤60 km)	21:56.1
1982	Woodward-Clyde Consultants (1982, their table 5-1)	−151.5	64.8	"crustal"	—
1988	Boyd and Lerner-Lam (1988, p. 639)	−148.08	64.66	33 km (fixed)	—
2016	This study	−153.12	63.79	< 55 km	21:56:11

An entry of "—" means that it was either not estimated or not provided in the study. Milne *et al.* (1913, p. 71) wrote: "When the time at which an earthquake originated is followed by *plus or minus* so many minutes, this means that there is considerable uncertainty in the position of its origin." Gutenberg's time of 21:56.1 corresponds to 21:56:06. Gutenberg's epicenter was first published in Gutenberg and Richter (1949, p. 119). The entry in Woodward-Clyde Consultants (1982) references Sykes (1981).

Table 2
Published Magnitudes for the 1904-08-27 and 1912-07-07 Earthquakes in Central Alaska

Date	Reference	Page Number		1904	1912
1954	Gutenberg and Richter (1954)	133	163	M 7$^{3/4}$	M 7.4
1958	Richter (1958)	711	—	M 8.3	—
1981	Abe (1981)	80	80	M_s 7.7, m_B 7.8	M_s 7.5, m_B 7.3
1983	Abe and Noguchi (1983a)	54	56	M_s 7.7	M_s 7.5
1983	Abe and Noguchi (1983b)	9	10	M_s 7.3	M_s 7.2
1992	Pacheco and Sykes (1992)	1332	1333	M_s 7.2	M_s 7.1
2004	Carver *et al.* (2004)	—	S63	—	M_w 7.2–7.4
1965	Duda (1965)	428	432	M 8.3	M 7.1
1988	Brockman *et al.* (1988)	15	16	M_s 8.3	M_s 7.4
1991	Page *et al.* (1991)	50	50	M_s 7.3	M_s 7.2
1993	Stover and Coffman (1993)	21	22	M_s 7.3	M_s 7.2

The bottom four rows in the table are compilations based on previously published estimates.

been felt generally in southern and southwestern Alaska, the only report which has come to the writer is from Ramport [sic], about the middle of the Alaskan Peninsula". (Here, the term "Alaska Peninsula" refers to all of mainland Alaska, surrounded by ocean on three sides. Today, the term refers to the peninsula in southwestern Alaska that forms part of the Aleutian–Alaska arc. The "many earthquakes" may be aftershocks of two $M \sim 8$ earthquakes in 1899 near Yakutat Bay [Plafker and Thatcher, 2008].)

Following Reid (1905), Rosenthal (1907) listed an epicenter near the Queen Charlotte Islands, which put Victoria, British Columbia, as the closest station (Fig. 1, inset). Rosenthal (1907, p. 23) wrote that (translated from German) "Reid placed the epicenter of this quake in the vicinity of the Queen Charlotte Islands. By contrast, the best European stations placed it near the northern Rocky Mountains. Therefore the coordinates of the above-mentioned epicenter are given as rounded numbers. Allegedly a faint tremor was observed almost simultaneously in Rampart, Alaska." It turns out that it was Reid's suspected epicenter that was far off the mark; the shaking reported in Rampart was from the big earthquake.

We can see from Beno Gutenberg's notes (Fig. 2) that he used the arrival times listed in Rosenthal (1907) (Ⓔ Fig. S1, available in the electronic supplement to this article). We are not aware of any attempts prior to Gutenberg to locate the 1904 earthquake using Rosenthal's arrival times. Gutenberg examined a monumental number of earthquakes during his career, and his epicenter, origin time, and magnitude carry Gutenberg's credibility. The precision of his entries in Gutenberg and Richter (1954)—0.1 min for origin time, 1/4 for magnitude, 1° in longitude and latitude—gives an indication of his estimated uncertainty in the source parameters.

Two additional attempts to estimate source parameters for the 1904 earthquake were published in Woodward-Clyde Consultants (1982) and Boyd and Lerner-Lam (1988) (see Table 1). Woodward-Clyde Consultants (1982, p. 5-15) stated: "Review of felt reports during the 1980 study, and data obtained from Sykes (1981), have resulted in the relocation of the earthquake 53 miles (85 km) northwest of the NOAA location." (The "NOAA location" is the one from Gutenberg and Richter, 1954, that was used within a compilation by the National Oceanic and Atmospheric Administration [NOAA].) We cannot find the reference of Sykes (1981), but we did learn that Sykes used published arrival times to estimate the epicenter (Lynn Sykes, e-comm., 2016).

The Boyd and Lerner-Lam epicenter is 27 km southwest of Fairbanks and, according to the authors, "is consistent

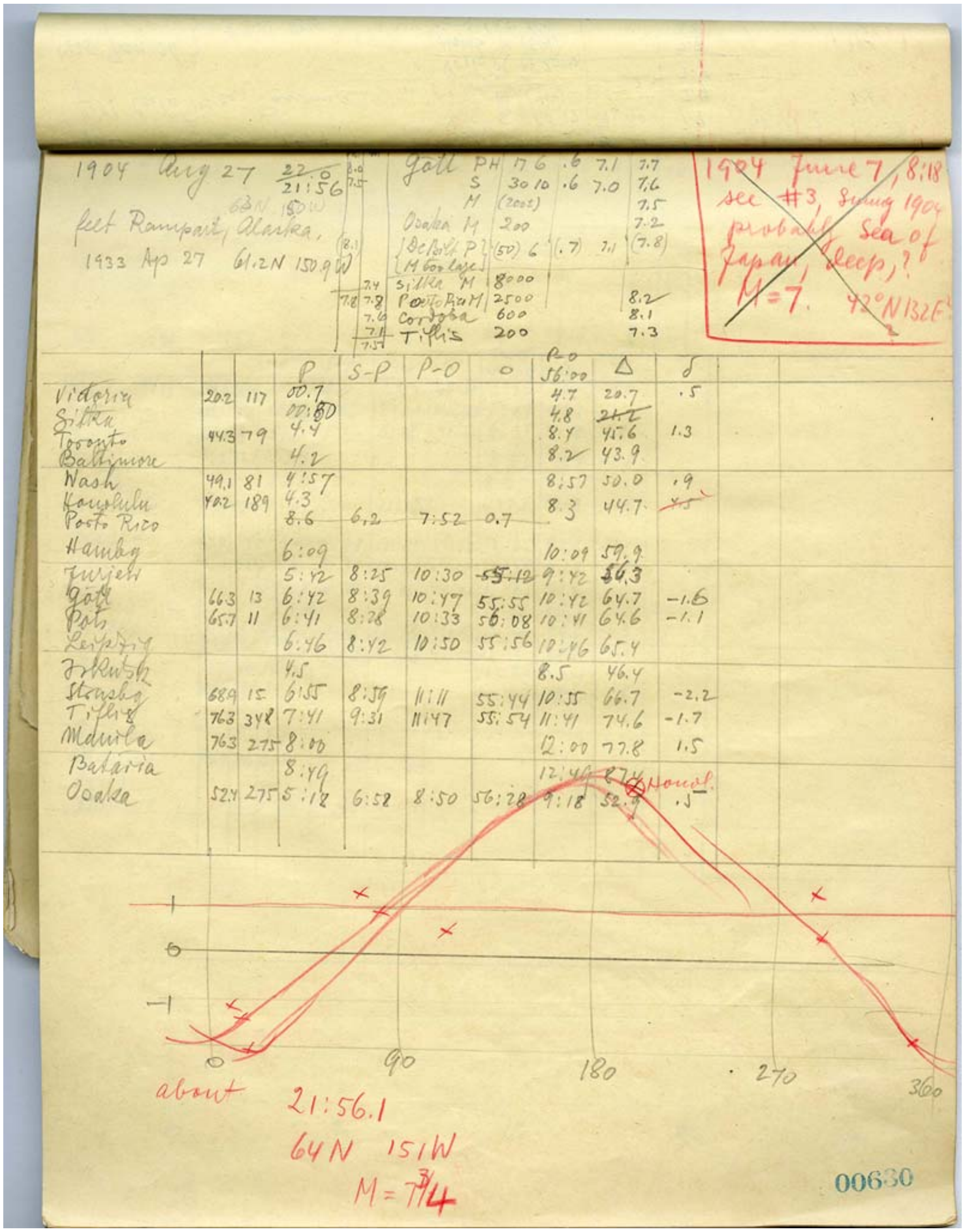

Figure 2. Beno Gutenberg's notepad for the 27 August 1904 Alaska earthquake (Gutenberg, 1908–1962). The origin time, epicenter, and magnitude were published in Gutenberg and Richter (1954, p. 133). Gutenberg used the arrival-time tables from Rosenthal (1907). His notes to estimate the magnitude are at the top center. He was aware of Reid's documented felt report in Rampart (Reid, 1905; Rosenthal, 1907), as indicated at the upper left: "felt Rampart, Alaska." The color version of this figure is available only in the electronic edition.

with the interpretation that this earthquake was related to a seismogenic feature south of Fairbanks that has been repeatedly active during the past 80 yr (e.g., Gedney 1985)" (Boyd and Lerner-Lam, 1988, p. 645).

Depth

The estimated depth for the 1904 earthquake is important, because the epicentral region for 1904 is close to the northward extent of the subducting Pacific slab. Arrival-time data can be used to estimate depth and origin time for the earthquake, but there are trade-offs between these two parameters: an earlier origin time and deeper event can produce the same arrival time as a later origin time and a shallower event. Early published estimates of source parameters for the 1904 earthquake did not list depth (Table 1). Gutenberg listed the depth as "shallow," which, for his tabulation, meant ≤60 km (Gutenberg and Richter, 1954). Gutenberg identified deep earth-

RAMPART SHAKEN BY EARTHQUAKE

Duration Less than a Minute and No Damage Done.

At 11:30 o'clock last Saturday Rampart experienced a distinct shock of earthquake. The disturbance was much more marked on second avenue and in that part of town lying along the foot of the hill than on First avenue and along the river front.

On Second avenue buildings swayed and cracked and inmates ran out in alarm. On First avenue in some instances the shock was not felt even by people on the sidewalk.

It continued slightly less than a minute and was most violent just after its beginning and before its close.

Most people in from the creeks say the shock was not felt there. Fred Bevere, at his Hunter creek claim, thought he felt a slight quake, but afterwards concluded he was mistaken.

right temple which staggered Monroe for a moment and quick to followup his advantage Jeffries went

look in the pink of condition. Jeffries leads with right and Monroe ducks. Monroe lands left light on stomach. Monroe feints with left and Jeffries lands right hook on back of

SEVERE EARTHQUAKE OCCURS AT ST. MICHAEL

(Special to THE NOME NEWS via Wireless Telegraph.)

St. Michael, Aug. 29.—This place was visited by a severe earthquake at 10:55 o'clock Saturday morning lasting for more than five minutes. Everything was violently disturbed while the shocks lasted and a number of people were made seasick from the movements of the ground. Beyond the fear engendered in the hearts of everyone here there was no damage done.

LARGE STOCK FOR TANANA

WILL SHIP ORE OUTSIDE

Figure 3. Felt reports from Rampart and St. Michael, published in the newspapers in Rampart (Yukon Valley News, 1904) and in Nome (Nome Semi-Weekly News, 1904). See Figure 6 for locations. Images from microfilm collection at University of Alaska Fairbanks Rasmuson Library.

quakes throughout the globe: for $M \geq 7$ events in his catalog, 38% of the events are deeper than 60 km (and within subducting slabs) (357/934); this fraction is comparable to the Global Centroid Moment Tensor (CMT) catalog ($132/400 = 28\%$) (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012). Gutenberg's catalog also contains a deep event in central Alaska (19 August 1948, 100 km depth, M 6.25). We therefore assume that Gutenberg had confidence in his depth assignment of ≤ 60 km for the 1904 earthquake.

Felt Reports

We performed a comprehensive search for felt reports of the 1904 earthquake (Tape, 2016). Here, we present five felt reports. Three are new to the seismological literature (Howard, 1904; Lawson, 1904; Wickersham, 1904), and two (Nome Semi-Weekly News, 1904; Yukon Valley News, 1904) were listed in the thesis of Agnew (1980) but did not enter the scientific literature. Here are the five reports.

- St. Michael, Alaska, reported in Nome Semi-Weekly News (1904):
  SEVERE EARTHQUAKE OCCURS AT ST. MICHAEL
  (Special to The Nome News via Wireless Telegraph.)
  "St. Michael, Aug. 29—This place was visited by a severe earthquake at 10:55 o'clock Saturday morning lasting for more than five minutes. Everything was violently disturbed while the shocks lasted and number of people were made seasick from the movements of the ground. Beyond the fear engendered in the hearts of everyone here there was no damage done."
- Rampart, Alaska, reported in Yukon Valley News (1904):
  RAMPART SHAKEN BY EARTHQUAKE
  Duration Less than a Minute and No Damage Done.
  "At 11:30 o'clock last Saturday Rampart experienced a distinct shock of earthquake. The disturbance was much more marked on second avenue and in that part of town lying along the foot of the hill than on First avenue and along the river front.
  On Second avenue buildings swayed and cracked and inmates ran out in alarm. On First avenue the shock was not felt even by people on the sidewalk.
  It continued slightly less than a minute and was most violent just after its beginning and before its close.
  Most people in from the creeks say the shock was not felt there. Fred Bevere, at his Hunter creek claim, thought he felt a slight quake, but afterwards concluded he was mistaken."

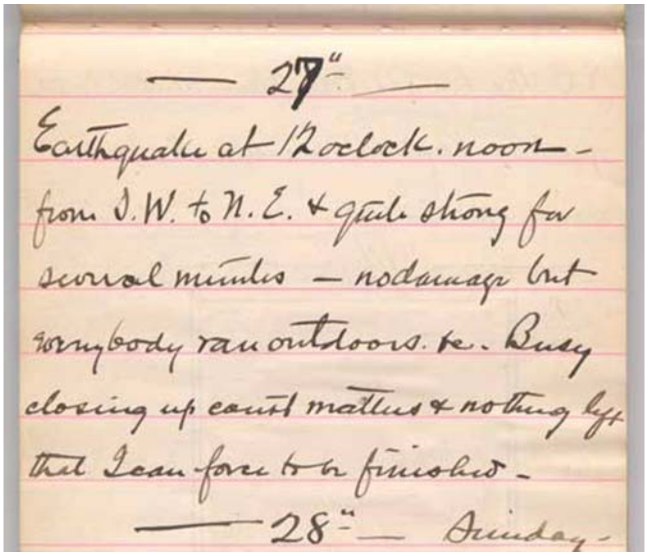
— 27th —
Earthquake at 12 oclock. noon -
from S.W. to N.E. & quite strong for
several minutes — no damage but
everybody ran outdoors. &c. Busy
closing up court matters & nothing left
that I can force to be finished -
— 28th — Sunday -

Figure 4. Felt report from the diary of U.S. Federal Judge James Wickersham in Fairbanks (Wickersham, 1904): "Earthquake at 12 oclock. noon. from S.W. to N.E. and quite strong for several minutes—no damage but everybody ran outdoors. Busy closing up court matters + nothing left that I can force to be finished." The color version of this figure is available only in the electronic edition.

- Fairbanks, Alaska, reported in Wickersham (1904): "Earthquake at 12 oclock. noon. from S.W. to N.E. and quite strong for several minutes—no damage but everybody ran outdoors."
  James Wickersham was the U.S. District Three Judge who resigned in 1908 to become the lone Alaska delegate to U.S. Congress.
- Sunrise, Alaska, reported in Lawson (1904): For the "MISCELLANEOUS PHENOMENA" column on 8/27, there is the label "Earthquake 11^{30} am."
- Coldfoot, Alaska, reported in Howard (1904). For the "MISCELLANEOUS PHENOMENA" column on 8/27, there is the label "Earthquake – 30 seconds."
  Frank E. Howard was a U.S. Commissioner in District Three, stationed in Coldfoot (Brady, 1904).

The original felt reports are reproduced in Figures 3–5. The five locations span a large region of Alaska, as shown in Figure 6. A summary of the described shaking onset times and durations is listed in Table 3. A discussion of not-felt reports for the 1904 earthquake is included in Appendix A. An example of a not-felt report is from Valdez, whose eight-page Saturday weekly newspaper did not mention the earthquake in its issues on 27 August 1904 or 3 September 1904.

Reporting Earthquakes by Volunteer Weather Observers

Daily weather records in Alaska began in the late 1800s at a small number of stations along the Alaska coast. As the population of Alaska increased, due largely to placer gold mining, many new locations began collecting weather information and sending the handwritten forms to the U.S. Weather Bureau at the end of each month. On the Voluntary Observers' Meteorological Record form, there is a column labeled Miscellaneous Phenomena that provides space for reporting phenomena such as earthquakes.

Out of about 1900 daily observations spanning the months of July, August, and September 1904, there were four reports of earthquakes, two of which were for the 27 August 1904 earthquake (Tape, 2016). The low number of felt reports is important, because it suggests that only the strongest shaking was reported and that shaking from smaller local events was not likely to be noticed or reported. The observer at Sunrise, on the Kenai peninsula in southern Alaska, noted two earthquakes in a 3-month period. It is very likely that the reported earthquake in Sunrise on 27 August 1904 at 11:30 a.m. is from the M_w 7.3 in central Alaska. The region of Coldfoot, in northern Alaska, is far less seismically active than the Kenai peninsula. The lone earthquake observation reported from Coldfoot for the month of August, on 27 August, is undoubtedly the M_s 7.3 earthquake.

Assignment of Shaking Intensity Values

The modified Mercalli intensity (MMI) scale (Wood and Neumann, 1931) provides a guide for assigning felt reports a numerical value ranging from 1 to 12. It has been widely used, including within the most comprehensive compilation of felt reports for Alaska (Brockman *et al.*, 1988). (Note that Stover and Coffman, 1993, make further modifications to the intensity scale. In our assignments of MMI values, we adhere to Wood and Neumann, 1931, for consistency with Brockman *et al.*, 1988.) In Table 4, we associate each felt report detail with a criterion on the MMI scale. Then, we assign an overall MMI for each felt report: St. Michael MMI 6, Rampart MMI 5, Fairbanks MMI 5, Coldfoot MMI 3, and Sunrise MMI 2. These are the values listed in Figure 6.

We also provide a set of adjusted MMI values in Table 5. Our rationale for them is as follows: the earthquake occurred in late summer on Saturday at noon and was reported in gold-rush settlements only. We do not know whether the observers in Sunrise and Coldfoot were outside or inside, though there is certainly a reasonable possibility that they were outside, given the nature of gold prospecting. If they were outside, then the MMI estimates would be 4: "felt indoors by many, outdoors by few" (Wood and Neumann, 1931). The meteorological report forms (Fig. 5) do not leave much room for details. Several people in Rampart, in the town and outside the town, did not feel the earthquake outside; therefore MMI 4–5 would be more appropriate, because MMI 5 is "Felt… outdoors by many or most…" (Wood and Neumann, 1931). The language within the Nome newspaper for the felt observations from St. Michael suggests exaggeration ("fear in the hearts of everyone"); hence, the lower value of MMI 5–6 is appropriate (Table 5).

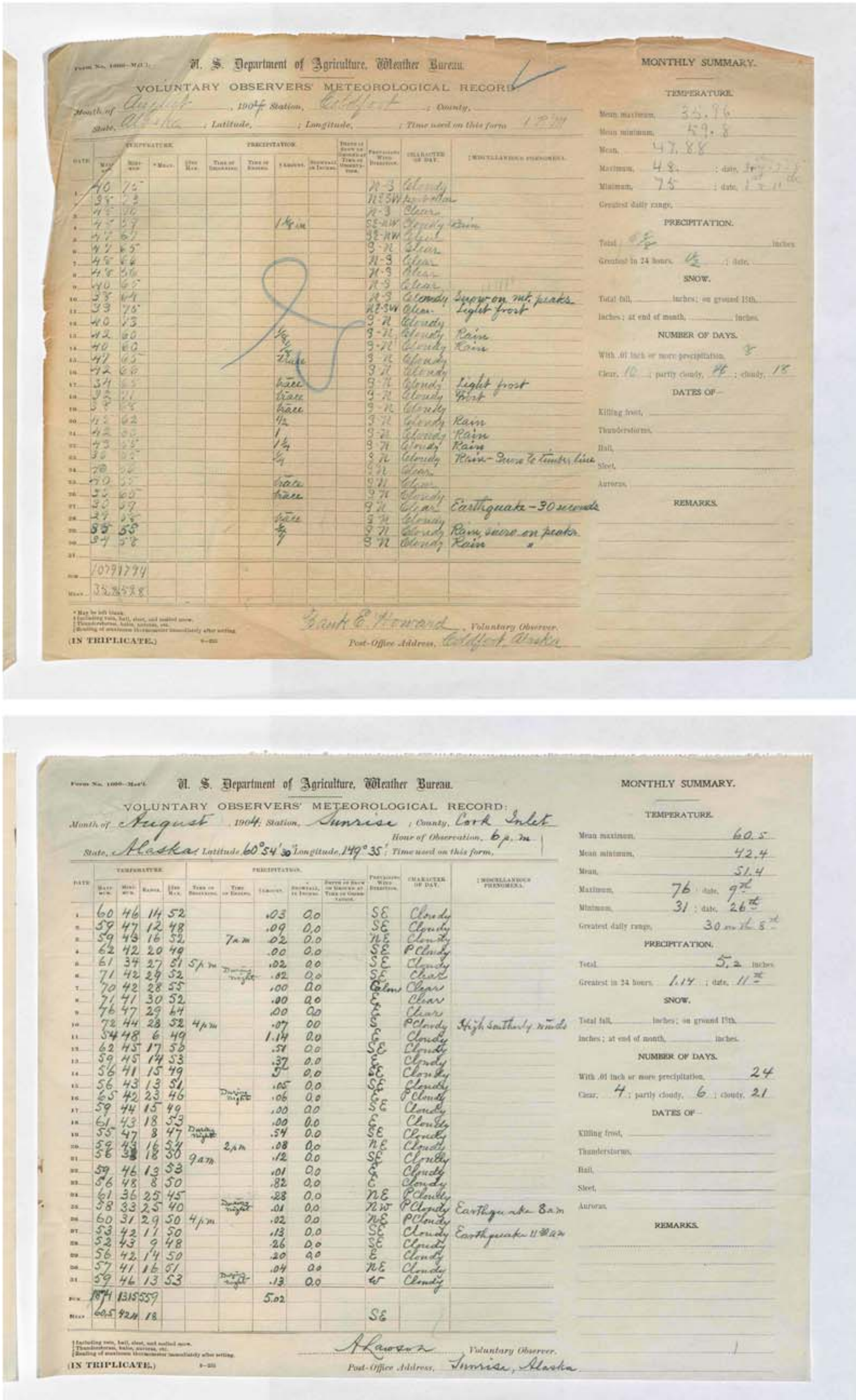

Figure 5. Felt reports from weather records at Coldfoot (Howard, 1904) and Sunrise (Lawson, 1904). See Figure 6 for locations. For the 27 August 1904 entry, the Coldfoot report lists "Earthquake – 30 seconds," and the Sunrise entry lists "Earthquake 11^{30} a.m." The color version of this figure is available only in the electronic edition.

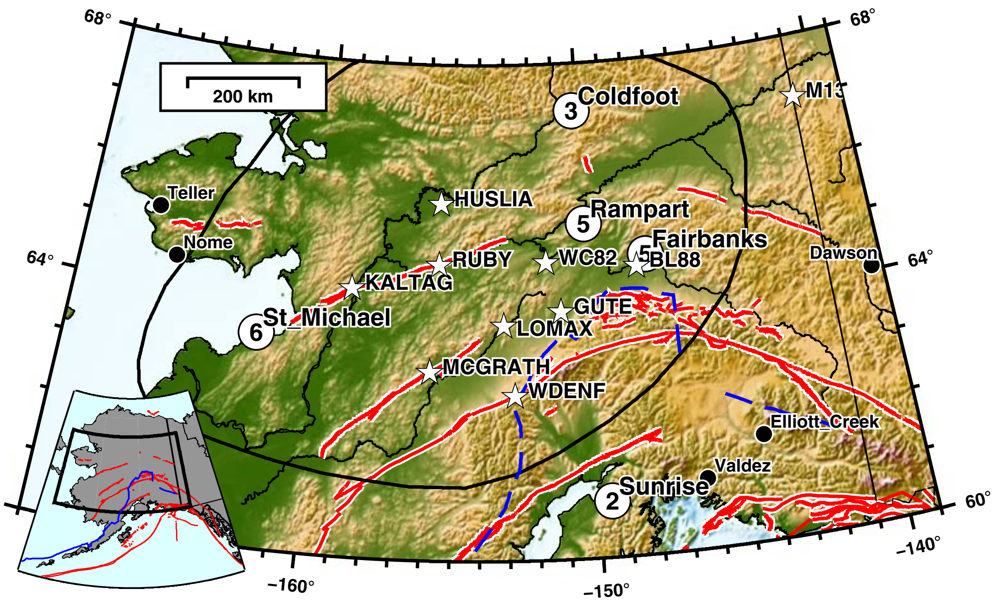

Figure 6. Locations of felt reports, with labeled estimated shaking intensity values, from St. Michael (Nome Semi-Weekly News, 1904), Rampart (Yukon Valley News, 1904), Fairbanks (Wickersham, 1904), Sunrise (Lawson, 1904), and Coldfoot (Howard, 1904). Locations of not-felt reports are plotted as black circles. Nine candidate epicenters are plotted as stars: KALTAG, RUBY, HUSLIA, MCGRATH, and WDENF, as well as published epicenters of Milne *et al.* (1913) (M13), Gutenberg and Richter (1954) (GUTE), Woodward-Clyde Consultants (1982) (WC82), Boyd and Lerner-Lam (1988) (BL88); and this study (LOMAX). Our estimated felt extent (modified Mercalli intensity [MMI] 3 and higher) for the 1904 earthquake is outlined in black. Active faults from Koehler *et al.* (2012) are plotted; they can be identified from the labels in Figure 10b. The lateral extent of slab seismicity is plotted as a dashed curve at the lower center and right. The color version of this figure is available only in the electronic edition.

No damage was reported for the 1904 Alaska earthquake. The lack of damage may be partly explained by the presence solely of wooden structures—either cabin construction from logs or frame construction from milled timber. In the gold-rush settlements of Alaska, the most prevalent structures were single-story log cabins. Fairbanks was the largest town in Alaska in 1904, and as a result there are more written records and photographs for buildings in Fairbanks (Matheson, 1985; Hoagland, 1993) than for the other felt regions. Matheson (1985, p. 26) writes: "Early buildings in Fairbanks were built from materials close at hand on the banks of the Chena River: rough-hewn spruce logs, mud or sod chinking, sawdust insulation, whip-sawn spruce boards—set on board sills, and roofed with sheets of tin." The prevalence of wooden buildings was still true 25 years later, as evidenced from a report for the 21 January 1929 $M > 6$ earthquake near Fairbanks: "Many of the houses are one-story and built of logs, specially developed for the winter conditions and are especially suited to resist earthquakes" (Heck and Bodle, 1931). (The first nonwood building in Fairbanks was the F. E. Company office building, a two-story reinforced concrete building built in 1926; Hoagland, 1993; Reckard, 1993.) Given the wooden construction in Fairbanks, the lack of damage from the 1904 earthquake does not imply lack of shaking.

Damage to buildings is listed in the MMI scale for MMI 6 and higher (Wood and Neumann, 1931). For MMI 6, one might expect "Damage slight in poorly built buildings" such as "cracked plaster somewhat" or "fine cracks in chimneys in some instances." For MMI 7: "Damage negligible in buildings of good design and construction, considerable in poorly built or badly-designed buildings," again referring to plaster and chimneys. Based on photographs and on limited literature of buildings in western and central Alaska in 1904, we found no evidence of plaster or chimneys (instead: stove

Table 3
Reported Onset Times and Durations of Shaking for the 1904-08-27 Earthquake

Location (Fig. 6)	Reference	Reported Time (hh:mm)	Local Origin Time (hh:mm)	Duration
St. Michael	Nome Semi-Weekly News (1904)	10:55	10:56 (UTC–11)	"more than five minutes"
Rampart	Yukon Valley News (1904)	11:30	11:56 (UTC–10)	"slightly less than a minute"
Sunrise	Lawson (1904)	11:30	11:56 (UTC–10)	—
Fairbanks	Wickersham (1904)	noon	11:56 (UTC–10)	"several minutes"
Coldfoot	Howard (1904)	—	11:56 (UTC–10)	"30 seconds"

The column "local origin time" refers the time for UTC 21:56 estimated by Gutenberg. (Note that today Alaska Standard Time is UTC–9.)

Table 4
Assignment of Modified Mercalli Intensity (MMI; Wood and Neumann, 1931) Values for Comments within Felt Reports (see also Table 5)

Location	Felt Report	MMI Criteria	MMI
St. Michael	"fear in the hearts of everyone"	"Frightened all"	7
	"a number of people were made seasick from the movements of the ground"	"Persons made to move unsteadily… Felt by all, indoors and outdoors"	6
		"sometimes dizziness or nausea experienced… Felt indoors by few"	2
	"everything was violently disturbed" but "no damage done"	[lack of damage is consistent with MMI ≤5]	5
Rampart	"On Second avenue… inmates ran out in alarm."	"Frightened few—slight excitement, a few ran outdoors"	5
	"On First avenue the shock was not felt even by people on the sidewalk." "Most people in from the creeks say the shock was not felt there."	"Felt indoors by many, outdoors by few"	4
	"buildings swayed and cracked" but "No Damage Done"*	"Buildings trembled throughout"	5
Fairbanks	"everybody ran outdoors"	"Frightened all—general alarm, all ran outdoors"	7
	"no damage"	[lack of damage is consistent with MMI ≤5]	5
	"from S.W. to N.E. and quite strong for several minutes"	"outdoors direction estimated"	5
Coldfoot	"30 seconds"	"Duration estimated" and "Felt indoors by several"	3
Sunrise	[no comments in felt report]	"Felt indoors by few"	2

*Given the combination of these two Rampart observations, we interpret that the verb "cracked" refers to an audible sound, rather than to cracks forming in the buildings.

pipes). The MMI 6 value for St. Michael—based on the report of people "made seasick" (Table 4)—could thus be consistent with no damage being reported, if the structures in St. Michael were well built.

Estimation of Felt Region and Epicentral Region

Felt reports provide shaking estimates at isolated points. It is also desirable to estimate a surface of MMI that is defined everywhere. Such a surface is typically estimated by imposing smoothing constraints or other bias while minimizing the differences between the MMI observations and the MMI of the surface. The estimated surface can diminish the effects of spurious observations while also providing some predictive capability for the expected shaking in regions without observations.

In the case of the 1904 earthquake, we only have five felt reports, with no reports from the region of strongest shaking. With more felt reports, we could attempt to formally estimate a surface of shaking intensity. Instead we outline in Figure 6 a single contour representing the "felt indoors by several" criterion of MMI 3 (Wood and Neumann, 1931).

Table 5
MMI Values for Felt Reports

Location	MMI (Table 4 and Fig. 7a)	MMI Adjusted (Fig. 7b)
St. Michael	6	5–6
Rampart	5	4–5
Fairbanks	5	5
Coldfoot/Wiseman	3	3–4
Sunrise/Hope	2	2–4

Based on the MMI values of the five felt reports (Fig. 6) alone, we would infer an epicentral region to be somewhere between St. Michael and Fairbanks. We can formalize this estimate using empirical relationships from Bakun and Wentworth (1997), who used a training set of 22 $M_w < 7$ earthquakes in California to determine empirical equations for estimating epicentral regions using MMI values. (The MMI values used in Bakun and Wentworth, 1997, are based on Wood and Neumann, 1931, with some minor modifications.) Using equation 6 of Bakun and Wentworth (1997), which is the most appropriate for the large earthquake in consideration, we calculated the unweighted root mean square (rms) of the residuals between reported MMI and empirically predicted MMI for a grid of possible epicenters in Alaska.

We performed a grid search using the two versions of MMI values in Table 5. The results are shown in Figure 7. For the unadjusted MMI values, we obtained an epicentral region along the western end of the Kaltag fault (Fig. 7a). Using the adjusted MMI values, we obtain a better fit (1.07 vs. 1.37 rms residual), and the epicentral region is just south of the Kaltag fault near Ruby. In our remaining analysis and interpretations, we will use the adjusted MMI values and Figure 7b.

The California calibration study of Bakun and Wentworth (1997) has not been undertaken for events in Alaska, as far as we know. Such a study could include $M > 7$ earthquakes and would provide a more appropriate empirical relationship for us to use in estimating the 1904 epicentral region from felt reports alone.

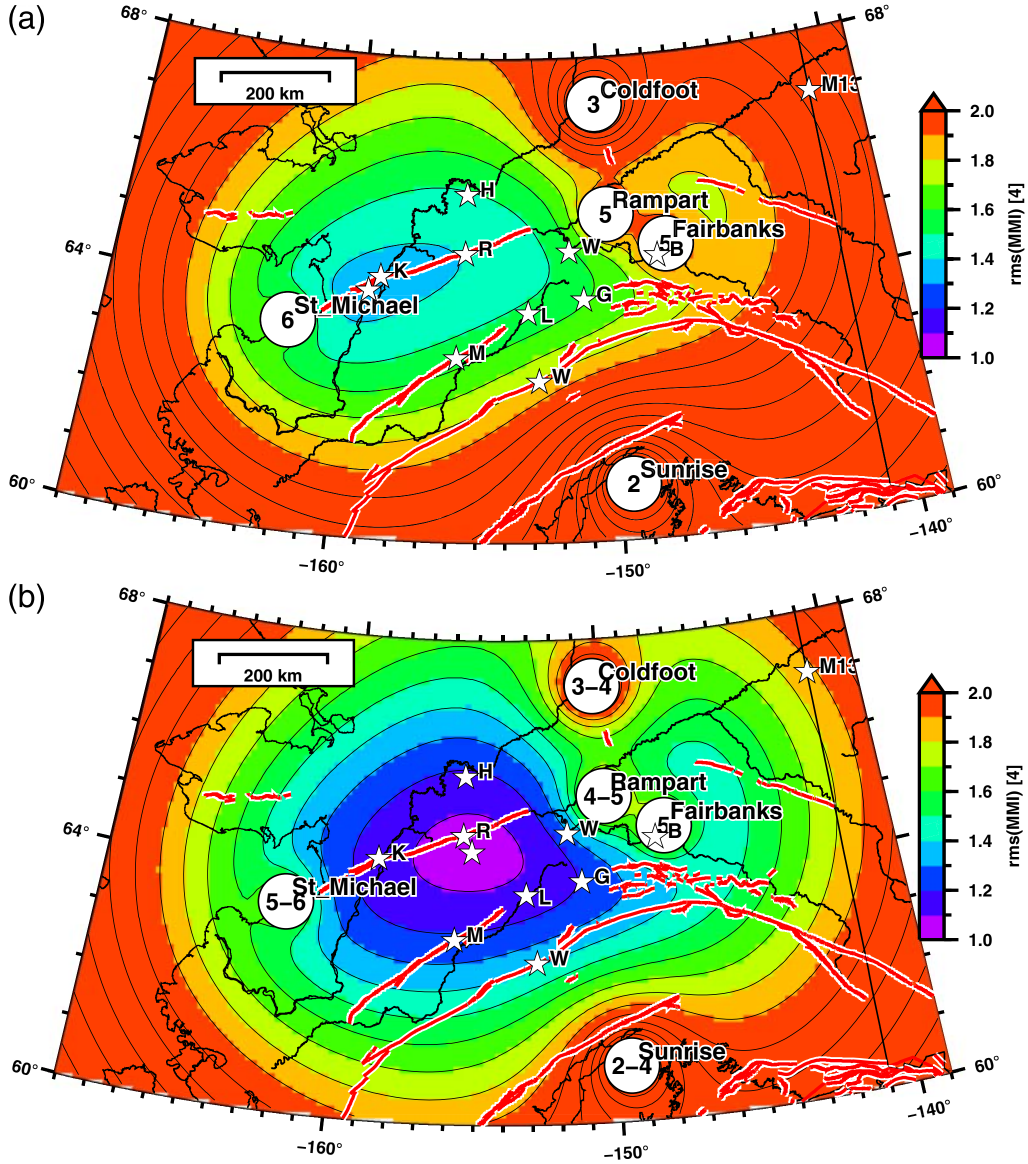

Figure 7. Estimated epicentral region for the 1904 earthquake based on the five felt reports and using the empirical relationship of Bakun and Wentworth (1997, their equation 6). The scale bar shows root mean squared (rms) residuals of MMI values, which have a minimum value of (a) 1.37 and (b) 1.07 at the unlettered plotted stars. Stars with letters denote the 10 candidate epicenters considered in this study. (a) Using MMI values based on Table 4. (b) Using adjusted MMI values based on additional considerations (see the Assignment of Shaking Intensity Values section). The color version of this figure is available only in the electronic edition.

Estimation of Hypocenter and Origin Time Using Arrival-Time Data

The 1904 Alaska earthquake is not yet included in the International Seismological Centre-Global Earthquake Model (ISC-GEM) catalog or the ISC-GEM supplementary catalog (Storchak *et al.*, 2013), but ISC does have arrival-time data and seismic phase identifications (*P* and *S*) for the earthquake. These data are listed in Ⓔ Table S1 and used in our effort to relocate the 1904 earthquake. Figure 8 shows the global station coverage of arrival-time data for the 1904 earthquake. Station azimuthal coverage to the north was relatively dense, owing to European stations, whereas station azimuthal coverage to the south was sparse. All stations except for two (Sitka and Victoria) were greater than 40° from the epicenter.

We use a robust probabilistic approach—implemented in the code NonLinLoc (NLL)—to estimate hypocenter and origin time. NLL uses an efficient global sampling algorithm to map the posterior probability density function (PDF; Tarantola 2005) in 3D space for the hypocenter location. The location PDF provides a complete description of likely hypocenter locations and includes comprehensive uncertainty information. A PDF solution is particularly important for early instrumental locations, where there may be few stations, poorly distributed with respect to the epicenter, and for

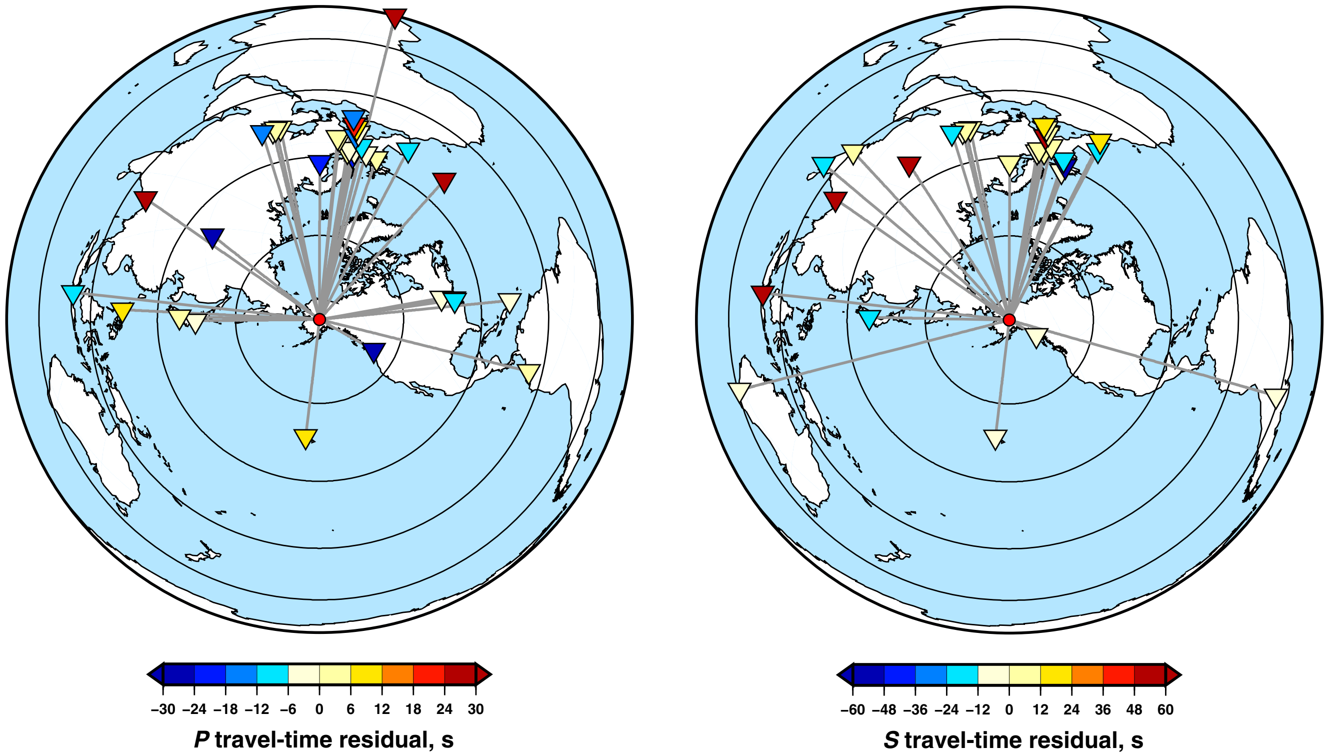

Figure 8. Station coverage for (left) *P* arrival times and (right) *S* arrival times used in estimating the epicenter for the 1904 Alaska earthquake, plotted at center. Circles show epicentral distances of $\Delta = 30°$, 60°, 90°, 120°, and 150°. Station triangles are indicated by the travel-time residual for our preferred epicenter (LOMAX), with the sign convention of observed minus predicted. Stations are listed in Ⓔ Table S1 and can be identified in the plots by their azimuthal angles and epicentral distances. There are 35 *P* arrival times and 28 *S* arrival times recorded by 45 stations. The color version of this figure is available only in the electronic edition.

which there may be large data errors, leading to large and sometimes highly irregular epicenter and depth uncertainties.

NLL is described in detail in Lomax *et al.* (2000, 2014); here, we review some key features. For a single earthquake, NLL thoroughly explores and maps over the whole Earth the PDF for the hypocenter parameters, such as longitude, latitude, and depth, using tens of thousands of evaluations of a misfit function. This procedure is guided by an efficient cascading grid-search importance-sampling method called octree (Lomax *et al.*, 2014). The result is a multiscale gridded representation of the PDF, with smaller grid cells and higher resolution toward the maximum-likelihood hypocenter and higher confidence regions for the PDF. Additionally, to aid in statistical calculations and for ease of visualization, a compact set of about 10,000 posterior samples is drawn stochastically from the octree PDF grid. These posterior samples form a 3D cloud of points for which spatial density follows the posterior PDF and can be used to represent our confidence in the solution; for example, within the volume containing 90% of the posterior, there should be ~90% of the posterior samples.

The NLL misfit function we use is based on the equal differential time (EDT) formulation of Font *et al.* (2004), which is a generalization of the master-station method (Zhou, 1994). All of these approaches are extensions of the "method of hyperbolas" cited by Milne (1886), the same person who recorded the 1904 earthquake in the Shide register in his hometown. The NLL-EDT misfit is based on a function of differences between observed arrival times and differences between calculated travel times, summed over all pairs of arrivals. (If there are n arrivals, then there are $n(n-1)/2$ unique pairs of arrivals.) Standard absolute location methods, such as iterative least-squares techniques, are based on the product of functions of the difference of observed and predicted times for individual arrivals. The differencing of times between arrivals makes the EDT search independent of origin-time estimates, reducing the 4D problem to a 3D search over latitude, longitude, and depth. Moreover, this differencing and the summing over pairs of arrivals make the EDT likelihood function more robust than standard location methods in the presence of outliers in the data. (An outlier observation has a residual much larger than its nominal uncertainty.)

Travel times are calculated using the TauP Toolkit (Crotwell *et al.*, 1999) with the spherical Earth model ak135 (Kennett *et al.*, 1995). Uncertainties for calculated travel times are set to 1%, with a minimum of 0.5 s and maximum of 2.0 s. The travel-time and phase-pick observation uncertainties (discussed below) are included explicitly in the EDT misfit function and mapped into the PDF solution (see equation 8 in Lomax *et al.*, 2014). An increase in these uncertainties will enlarge the extent and volume of the PDF for any given confidence level and may introduce other deformations to the PDF. Because the NLL algorithm is a global-search method, it does not require an initial guess for the hypocenter or origin time, nor does it require fixing the hypocenter depth when depth is not well constrained.

For early instrumental arrival data, the observation errors can be large due to clock errors, reading or reporting errors (inducing frequent errors close to multiples of 1 min), low reporting precision in catalogs (often 0.1 min), phase misidentification, and other factors. Here, we assign the observation uncertainties to be 10 s to account for smaller random observation errors and reporting precision. We primarily rely on the insensitivity of the NLL EDT formulation to outliers to effectively ignore observations with large errors. But our procedure also relocates iteratively, allowing identification of obvious reading and reporting errors and phase misassociations, and zero weighting of observations with very large residuals ($|r| > 50$ s). For the locations presented here, iteration gave only very minor changes and improvements to the results (for more details, see Ⓔ the electronic supplement). An example application of NLL using historical data comparable to the 1904 Alaska earthquake is for the 1906 San Francisco earthquake, presented in Lomax (2005, 2008).

We performed the global 3D NLL EDT search for the 1904 Alaska event over the whole Earth down to 1000 km depth. Our maximum-likelihood epicenter for the 1904 earthquake is (−153.12°, 63.79°), plotted in Figure 9, along with 9981 posterior samples drawn from the PDF which show the hypocenter uncertainty. Using a slice of the PDF near the surface, we calculate confidence contours of 50%, 70%, and 90% to illuminate the structure of the PDF. The output from NLL provides a detailed characterization of the PDF and estimated uncertainties. Ⓔ Table S1 shows the phase associations, timing adjustments, weighting, and travel-time residuals. Figure 8 shows a global map of stations and P and S travel-time residuals for our maximum-likelihood epicenter. Importantly, Figure 8 does not reveal strong systematic patterns of the residuals, such as spatial clustering of residuals with high values or of one sign.

We perform two analyses to verify the robustness of the estimated epicentral region: (1) re-estimation using random subsets of the arrival-time data (bootstrapping) and (2) a test for bias due to lack of local and regional stations; this serves as a proxy test for the influence of regional 3D Earth structure. These analyses, presented in Ⓔ the electronic supplement, show that our PDF for the 1904 earthquake is stable. Our test for 3D Earth structure suggests that, within the region of the 1904 earthquake, there may be a bias of 5–40 km (mean 17 km) to the south for estimated epicenters. In other words, for interpretation purposes, the cloud of points in Figure 9 could be shifted to the north by about 20 km, which is a small fraction of the size of the cloud itself.

The posterior samples also allow us to estimate the depth of the 1904 earthquake. Based on the arrival times alone, our hypocenter indicates a crustal origin (Ⓔ Fig. S2): 80% of the posterior hypocenter depths are <55 km, the median depth is 29 km, the mean depth is 36 km, and the maximum-likelihood depth is near the surface (6.5 km). In Figure 9, we see that $>90\%$ of the samples fall northwest of the lateral extent of the underlying Pacific slab seismicity. (This percentage is slightly higher if we apply a 5–40 km northerly shift of the points, to account for the effects of 3D Earth structure.) As shown in Figure 6, most of the felt regions, as well as all candidate epicenters, are northwest of the region of slab seismicity. The St. Michael felt report alone is evidence against a hypocenter within the subducting slab, because the event would have to produce MMI 5–6 shaking at a distance of at least 500 km (e.g., Fig. 9); a deeper hypocenter would produce weaker surface waves, which are responsible for long-duration felt ground motions at large distances. Based on our analysis of instrumental data and felt reports, we conclude that the 1904 earthquake occurred within the crust, consistent with the findings of Gutenberg, discussed previously.

An estimation of origin time is available for any hypocenter location visited by the NLL search, and, in general, the origin time varies across the location PDF. Our maximum-likelihood hypocenter provides an estimated origin time of 21:56:11, which is 5 s later than the Gutenberg time (Table 1).

We can use the posterior samples of the PDF to approximate the distribution of origin times. The two source parameters depth and origin time will trade off, especially when using only teleseismic stations, where the ray paths leave the source region at near-vertical angles. An observed arrival time can be explained either by a later origin time and shorter path (deeper event) or by an earlier origin time and a longer path (shallower event). Hence, an increased (deeper) source depth results in an increased (delayed) origin time. In our case, a change in depth from 0 to 50 km results in an origin time delay of ∼8 s (to 21:56:19), which is consistent with a 6.5 km/s average P velocity of the crust and uppermost mantle. The results indicate that the true origin time for the 1904 earthquake is most likely within 10 s following 21:56:11.

1935 Earthquake

Our estimated epicenter for the 1904 earthquake is very close to a 1935 M 6.25 earthquake analyzed by Gutenberg (Gutenberg and Richter 1954, p. 162). Pulpan (1988, p. 6) wrote: "This event conceivably could be associated with the Iditarod-Nixon fault, although it is located almost 50 km away. No known faults are closer to the epicenter, but no current evidence indicates the Iditarod-Nixon fault to be active."

Two felt reports for the 1935 earthquake are listed in Brockman *et al.* (1988), who assigned MMI 3 at Flat and Nenana. Presumably these reports were from the annual compilation of Neumann (1937, p. 38): "September 3: 15:25. Nenana and Flat. Slight shock." The original source of these reports is likely from the meteorological observations summarized in Thompson (1935). We did not perform a

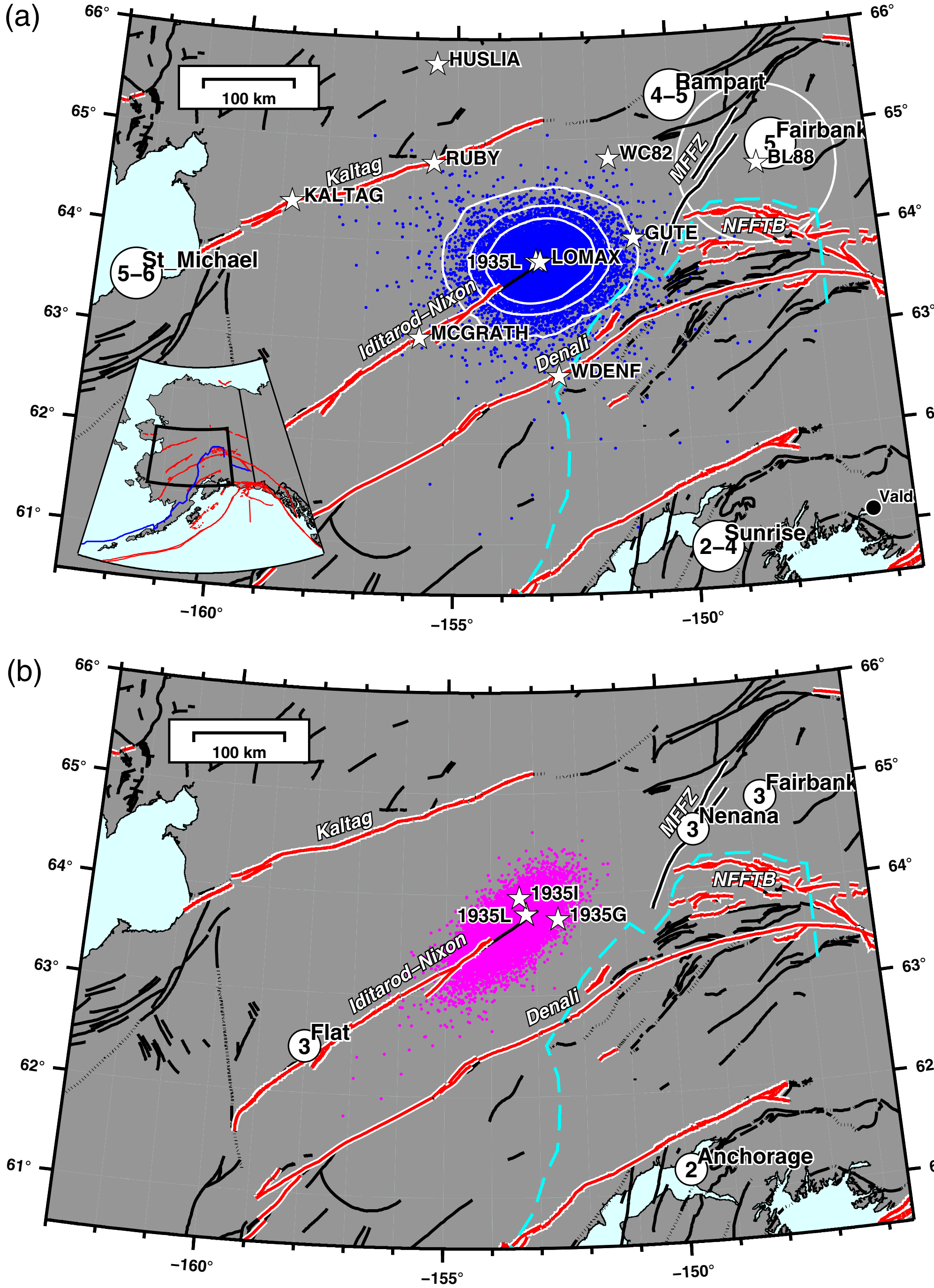

Figure 9. Epicenter and samples of the posterior probability distribution for the 1904 and 1935 earthquakes. Plotted for reference are the active faults of Koehler *et al.* (2012; Fig. 6), the faults of Plafker *et al.* (1994), the Minto Flats fault zone (MFFZ) of Tape *et al.* (2015), and the lateral extent of slab seismicity (dashed line). (a) 1904-08-27 M_s 7.3 earthquake (LOMAX) plotted as posterior samples with confidence curves for 50%, 70%, and 90%. The epicenter LOMAX is 107 km west of Gutenberg's (GUTE) and 5 km from the epicenter of the 1935 earthquake (1935L). The expected rupture length for the M_s 7.3 earthquake is 120 km, which is approximately the scale bar at upper left. The 75% confidence ellipse reported for BL88 (Boyd and Lerner-Lam, 1988) is plotted by a white circle. (b) 1935-09-04 M 6.2 earthquake (1935L). The epicenter 1935L is 36 km west of Gutenberg's (1935G) and 20 km south of International Seismological Centre's (ISC's) (1935I). The earthquake was reported felt at Flat and Nenana. The color version of this figure is available only in the electronic edition.

comprehensive search for felt reports (as in Tape, 2016), though we did examine the available newspaper records. We found that the earthquake was felt in Fairbanks, Anchorage, and probably Seward. The felt reports are summarized in Table 6 and shown in Figure 9b.

We apply the same NLL location procedure to the 1935 event as for the 1904 earthquake, using phase times and phase identifications from the ISC-GEM supplementary catalog. Our maximum-likelihood epicenter for the 1935 earthquake is 36 km west of Gutenberg's epicenter, 20 km

Table 6
Felt Reports for the 1935-09-04 Earthquake (Fig. 9b), which Occurred at UTC 01:27:42 (Local Time 1935-09-03 15:27:42)

Location	MMI		Source
Nenana (218 km)	3	"slight earthquake at 3:25 pm"	Johnson (1935)
Flat (285 km)	3	"3:26 p. m."	Thompson (1935)
Fairbanks (290 km)	3	"Earthquakes were felt in Fairbanks twice this afternoon, once at 2:27 o'clock and once at 3:32. The latter was of the more severe intensity and stopped clocks in the Federal building. The first earthquake also was felt in Nenana."	Fairbanks Daily News-Miner (1935)
Anchorage (334 km)	2	"Mysterious forces exerted themselves at 3:29 p. m. to give Anchorage another slight earthquake shock. The tremor was barely noticeable, but sufficient to set pendant lamps and other articles swaying."	Anchorage Daily Times (1935)
Seward (457 km)	2	"Seward and Anchorage both had heavy earthquakes last week, the tremors lasting for several seconds."	The Valdez Miner (1935)

The distance listed is from the preferred epicenter (−153.21°, 63.80°) to the felt location. The Nenana time of 3:35 listed in Thompson (1935) may be a typo, since Johnson (1935) listed 3:25. The Seward and Anchorage felt reports from the Valdez newspaper (The Valdez Miner, 1935) are inconclusive, because no day or time is listed. However, we know that the earthquake was felt in Anchorage (Anchorage Daily Times, 1935) during this time period; also no other earthquake during this time period is mentioned in the monthly meteorological summary (Thompson, 1935).

south of the ISC epicenter, and 5 km west of the 1904 maximum-likelihood epicenter (Table 7). The earthquake is crustal (Ⓔ Fig. S3): 80% of the posterior hypocenter depths are <35 km, the median depth is 17 km, the mean depth is 22 km, and the maximum-likelihood depth is near the surface (0.7 km). In Figure 9, we see that all samples are northwest of the lateral extent of slab seismicity. The posterior distribution of samples in Figure 9b is larger than it need be, because we used the same 10 s uncertainty on phase picks as we did for the 1904 event, whereas a 5 s uncertainty could have been used for the 1935 event. A comparison between the posterior samples for the 1904 and 1935 earthquakes (Fig. 9) shows that these events occurred in the same region: their PDF distributions are overlapping and nearly cocentered. Thus, the 1904 earthquake is not the only large earthquake to occur in this region.

Description of Candidate Faults

Active faults of Alaska are plotted in Figure 6. They were compiled in Koehler *et al.* (2012) and are used within the Quaternary Fault and Fold (QFF) Database of the United States (see Data and Resources). The compilation is based on geologically identified faults, and it is important to note that many earthquakes in Alaska—for example, the 1958 M_s 7.3 Huslia earthquake—do not have an associated mapped fault.

Our analysis of instrumental data and felt reports points us toward an epicentral region that contains several active fault systems (Fig. 9), including three right-lateral strike-slip faults—the Iditarod–Nixon fault, the Kaltag fault, and the Denali fault—and the Northern Foothills fold-and-thrust belt (NFFTB) (Grantz, 1966; Koehler and Carver, 2017). Our analysis of candidate epicenters in the next section leads us to conclude that the Denali fault and NFFTB are unlikely sources for the 1904 earthquake. In this section, we focus on the two remaining candidates, the Kaltag and Iditarod–Nixon faults.

The Kaltag fault is identified as a geologically active strike-slip fault along a 410 km distance between the coast of western Alaska and the village of Tanana (Koehler *et al.*, 2012). Based on geologic mapping, Patton and Hoare (1968, p. D147) reported that "between 40 and 80 miles of right-lateral offset may have occurred since Cretaceous time" (implying an average slip rate of 0.4–2.0 mm/yr), and from an analysis of aerial photographs they found "evidence of recent activity over nearly its entire length" with "local drainage offset of as much as 1.5 miles". The QFF database categorizes the fault as active within the mid-Quaternary ($<750{,}000$ yrs) with a slip rate of <0.2 mm/yr (Koehler *et al.*, 2012).

The Iditarod–Nixon fault is expressed as a topographic lineament extending from Aniak through Takotna for a distance of at least 370 km (Koehler *et al.*, 2012, Koehler and Carver, 2017). The fault map of Plafker *et al.* (1994; Fig. 9) included an additional northeast segment—inferred to have pre-Neogene activity (but nothing more recently)—to a point just west of Lake Minchumina. St. Amand (1957, p. 1352) suggested that the Iditarod–Nixon fault could extend "perhaps as far as the Tanana River", representing an additional

Table 7
Published Hypocenters and Origin Times for the 1935-09-04 Earthquake (Fig. 9b)

Label	Reference	Longitude (°)	Latitude (°)	Depth	UTC Time (hh:mm:ss)
1935G	Gutenberg and Richter (1954, p. 162)	−152.5	63.75	"shallow" (≤60 km)	01:27:39
1935I	ISC-GEM supplementary catalog (Storchak *et al.*, 2013)	−153.37	63.97	15 ± 25 km	01:27:43
1935L	This study	−153.21	63.80	<35 km	01:27:42

ISC-GEM, International Seismological Centre-Global Earthquake Model.

150 km from the termination of the fault in Plafker *et al.* (1994).

There have been few studies of the Iditarod–Nixon fault. The topographic expression of the Iditarod–Nixon fault was identified by Mertie and Harrington (1924, p. 76): "A striking feature of the topography is the remarkable conformity of the stream courses with the regional trend of the rocks… The most striking example of all is the continuity of a structural line marked by the valleys of Nixon Fork of the Kuskokwim, lower Takotna River, Fourth of July Creek, upper Moore Creek, Bonanza Creek, and upper Iditarod River. This structural line, with a direction of N50°E, extends 140 miles diagonally across the Innoko-Iditarod region and continues both to the northeast and southwest." Geologic mapping by Brown (1926) led Grantz (1966) to write: "Displacement is latest Cretaceous or Cenozoic, and the fault is still active. Large lateral slip is indicated by the great length and straightness of the fault, the reversals in stratigraphic throw, and by 110 km (but possibly only 35 km) [of] right-lateral separation of Cretaceous rocks along it. However, geologists have variously classed the fault as a thrust fault, a scissors fault, and a strike-slip fault." Miller and Bundtzen (1988) used dated volcanic rocks to infer a right-lateral offset of 88–94 km since the Late Cretaceous (66–100 Ma), which would imply an average slip rate of 0.9–1.4 mm/yr since that time. The QFF database categorizes the fault (specifically the Fourth of July Creek section) as active within the mid-Quaternary (<750,000 yrs) with a slip rate of <0.2 mm/yr (Koehler *et al.*, 2012).

The current slip rate and the history of slip of the Kaltag and Iditarod–Nixon faults remain poorly known, because there have been no trenching studies performed, and earlier reports of offsets have not been verified by modern paleoseismic methods (Koehler and Carver, 2017).

Seismicity provides an additional measure of fault activity. Both the Iditarod–Nixon and Kaltag faults have some $M > 3$ earthquakes, though there are no identifiable seismic lineaments (Fig. 10a). Only the Kaltag fault has experienced an $M_w > 5$ earthquake during the time span of the Global CMT catalog (1976–2016) (Fig. 10b). In Appendix B, we estimate a source mechanism for this M_w 5.5 earthquake and confirm that it is consistent with right-lateral strike-slip faulting on the Kaltag fault. The Kaltag fault appears to connect into the Tintina fault (Fig. 10b), which produced an M_s 5.0 earthquake on 1972-11-28 that was consistent with right-lateral faulting (Estabrook *et al.*, 1988).

Evaluation of Candidate Epicenters

In maps such as Figures 6 or 9a, it is important to keep in mind that our candidate earthquake rupture is a segment, rather than a point. For the 1904 earthquake, the rupture length should be ~120 km, described next. The magnitude of the event can be used to estimate the length of the rupture. Mai and Beroza (2000) present empirical relationships between magnitude and rupture length for different categories of faults (strike-slip, normal, reverse, and oblique-slip). For these purposes, we choose strike-slip, which is the predominant style of faulting and earthquake mechanisms within the felt region (Fig. 11; Ratchkovski and Hansen, 2002; Koehler *et al.*, 2012). Using the relationship from Mai and Beroza (2000), we would expect fault lengths of about 100, 120, and 130 km for magnitudes of M_w 7.2, 7.3, and 7.4, respectively. For comparison, the rupture length of the M_w 7.2 El Mayor–Cucapah strike-slip earthquake was 120 km (Oskin *et al.*, 2012), whereas the rupture length of the M_w 7.9 Denali fault earthquake was 340 km (Eberhart-Phillips *et al.*, 2003).

We tabulate historical earthquake felt reports to help evaluate the possible epicentral regions for the 1904 earthquake. Table 8 lists notable crustal earthquakes in Alaska since 1904. Shaking intensities from the largest of these earthquakes are tabulated in Table 9 and plotted in Figure 11. These data help rule out certain faults for the 1904 earthquake. For example, the MMI 5–6 shaking in St. Michael in 1904 was not repeated in either the 1912, 1937, 1947, or 2002 earthquakes, all of which had magnitude $M > 7$.

Felt reports from smaller earthquakes ($M < 7$) can also be used to exclude candidate regions for the 1904 epicenter. The 1904 earthquake could not have occurred within the Rampart seismic zone (Gedney *et al.*, 1969; Huang and Biswas, 1983; Koehler *et al.*, 2012), a north-trending seismic lineament that is defined primarily by the 29 October 1968 M_w 6.7 earthquake (Table 8) and is associated with a possible fault aligned with Minook Creek (Gedney *et al.*, 1969; Plafker *et al.*, 1994). An M_s 7.3 earthquake in the Rampart seismic zone would generate far stronger shaking at Rampart than the reported MMI 4–5 in 1904 (Table 5). The much smaller 1968 earthquake generated MMI 7–8 shaking in the Rampart region, as well as "practically continuous landslides" along a 16 km length of Hunter Creek valley (Coffman and Cloud, 1970).

The 1904 earthquake could not have occurred within the Fairbanks seismic zone (Gedney *et al.*, 1980), as inferred by Boyd and Lerner-Lam (1988) and, subsequently, by Biswas and Tytgat (1988) who wrote that the 1904 earthquake is "located further south along the trend of the Fairbanks Seismic Zone." The largest earthquake known to occur in the Fairbanks seismic zone is the 21 June 1967 M_w 5.7 earthquake (Table 8), which generated MMI 7 shaking and widespread minor damage in Fairbanks (Cloud and Knudson, 1968). An M_s 7.3 earthquake in the Fairbanks seismic zone would generate far stronger shaking in Fairbanks than the reported MMI 5 in 1904 (Table 5) and far stronger shaking than the MMI 7 from the M_w 5.7 earthquake in 1967.

We consider 10 candidate epicenters, including five published epicenters (M13, GUTE, WC82, BL88, and LOMAX) and five points from within the felt region that are on active faults (WDENF, MCGRATH, KALTAG, and RUBY) or within seismically active regions (HUSLIA). For each epicenter we consider five factors, listed in approximate order

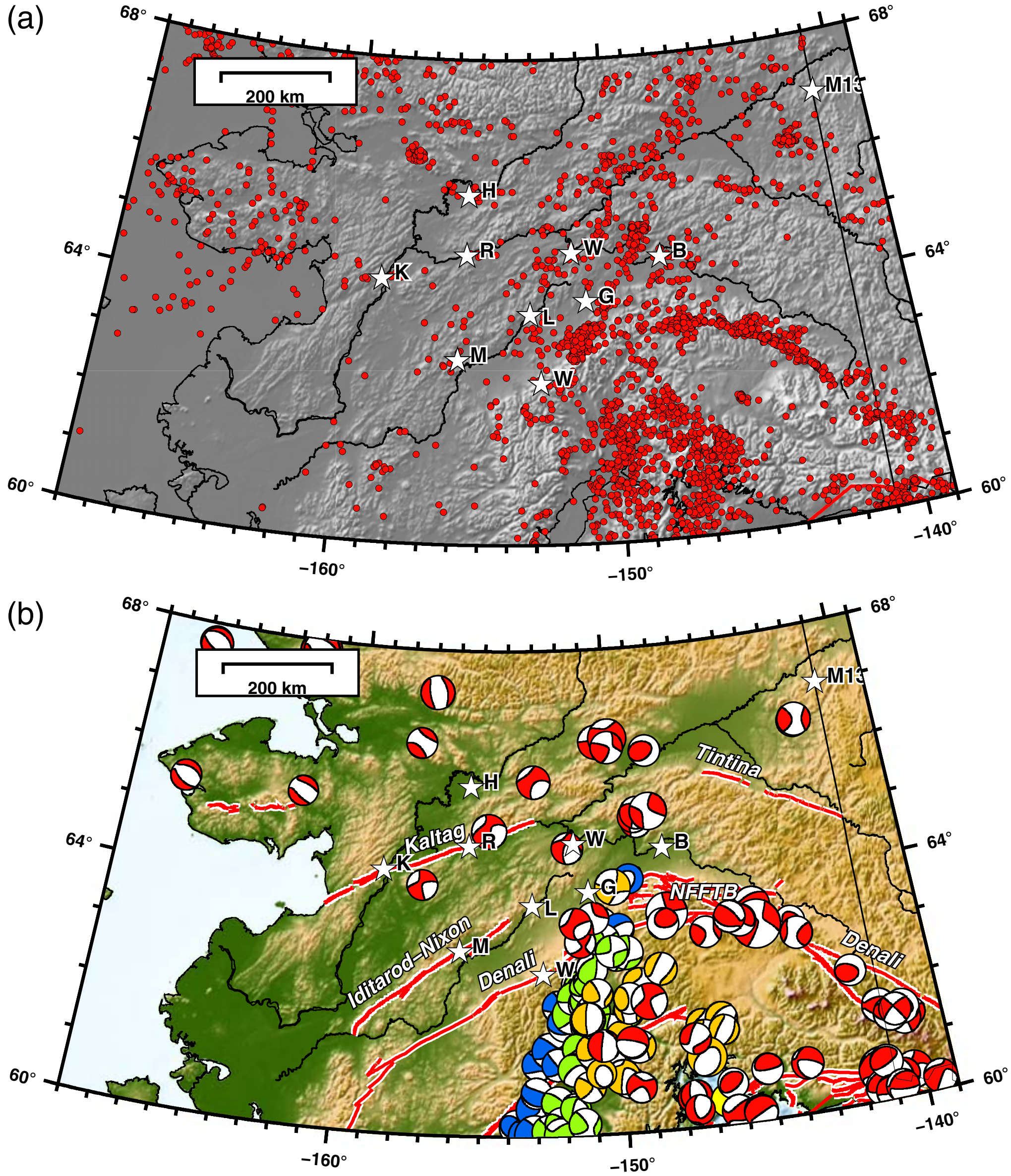

Figure 10. Seismicity in central Alaska. Stars denote the candidate epicenters discussed in this study (Table 10). (a) Crustal seismicity from the Alaska Earthquake Center catalog: $M_l \geq 3.0$, 1990–2015, depths shallower than 60 km. Stars denote the possible epicenters for the 1904 earthquake discussed in this study (Table 10). (b) Global Centroid Moment Tensor (CMT) catalog, 1976–2015 (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012), with active faults (Koehler *et al.*, 2012). The earthquake on the Kaltag fault is examined in Figure B1. The color version of this figure is available only in the electronic edition.

of (decreasing) influence: (A) consistency with instrumental data (Fig. 9), (B) consistency with felt reports (Fig. 7b), (C) history of previous $M \geq 5$ earthquakes (Table 8), (D) occurrence of small-magnitude earthquakes since 1990 (Fig. 10a), and (E) presence of geologically identified active fault (Fig. 6). We rate each of these factors for each candidate epicenter in Table 10. On the basis of these ratings, we list the candidate epicenters from the highest to the lowest likelihood of being the 1904 earthquake epicenter. Next, we explain some of our decisions.

- *LOMAX*. LOMAX is our preferred epicenter and provides the best fit to instrumental data. It is consistent with felt reports (Fig. 7b), though it is 446 km from the strong shaking reported at St. Michael, and it is 457 km from the Valdez, where it was not reported as felt (Appendix A). The observer at Coldfoot (distance 406 km) reported 30 s of shaking, whereas St. Michael (distance 446 km) reported more than 5 min (Table 3); this could be a real difference, or it could be attributed to differences in the observers' perceived duration times.

  LOMAX is on the trace of the Iditarod–Nixon fault (Figs. 9 and 12), for which recent activity is not well known, as previously discussed. There are some $M > 3$ earthquakes in the region, but more notable is the occurrence of the M 6.2 earthquake in 1935 (Fig. 9b).

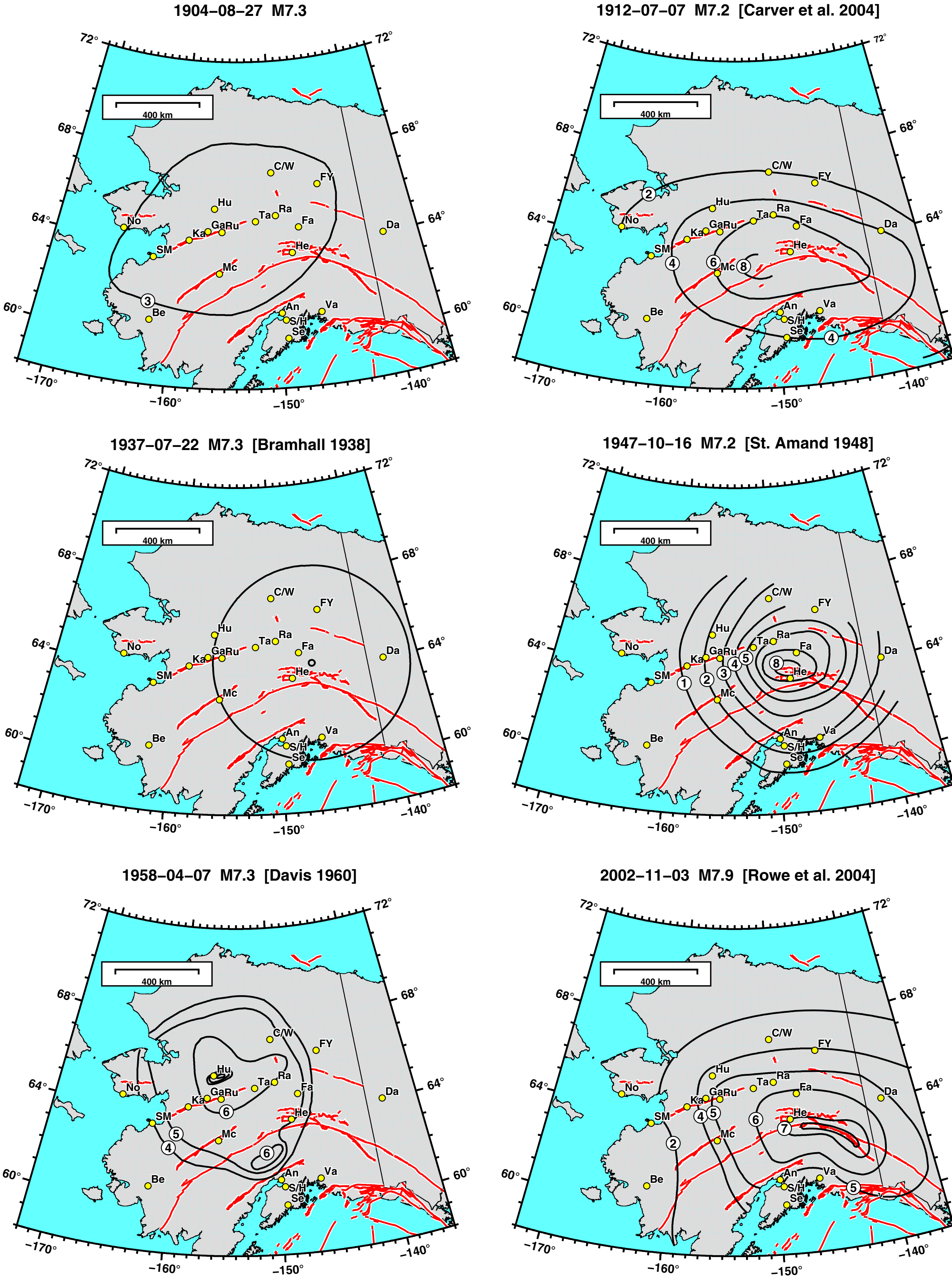

Figure 11. Shaking intensity contour maps from $M > 7$ earthquakes in central Alaska: 1904-08-27 (this study), 1912-07-07 (Carver *et al.*, 2004), 1937-07-22 (Bramhall, 1938), 1947-10-16 (St. Amand, 1948), 1958-04-07 (Davis, 1960), and 2002-11-03 (Rowe *et al.*, 2004). MMI values are labeled for selected contours. The same sets of cities are shown in each figure and within Table 9 to allow for comparison across all events at the same locations. The actual felt report locations for each event are listed within each reference. Note that the 1904, 1912, and 1937 earthquakes are not included within the compilation of Espinosa *et al.* (1986). The color version of this figure is available only in the electronic edition.

Table 8
Crustal Earthquakes in Central Alaska, $M \geq 5.5$, Since the Start of the Instrumental Era in 1904

Origin Time (yyyy-mm-dd hh:mm:ss)	Ref	Magnitude	Ref	GR	ISCB	ISCG	Eng	E86	P91	SC93	P82	WC82	B88	P88
1904-08-27 21:56:06	GR	7.3	Abe	X	X	–	X	–	X	X	X	X	X	X
1912-07-07 07:57:36	GR	7.2	Abe	X	X	–	X	–	X	X	X	X	X	X
1923-06-19 22:43:42	ISCG	6.0	ISCG	–	X[†]	X	–	–	–	X	–	–	X	–
1923-07-17 01:02:11	GR	5.6*	GR	X	X	–	–	–	–	X	–	X	–	–
1929-01-21 10:30:59	ISCG	6.1	ISCG	X	X	X	–	–	X	X	X	X	X	X
1929-07-03 00:53:04	ISCG	5.8	ISCG	X	X	X	–	–	–	X	X	X	X	–
1929-07-04 04:28:40	ISCG	6.0	ISCG	X	X	X	–	–	X	X	–	X	X	X
1931-05-29 05:16:32	GR	5.6*	GR	X	X	–	–	–	–	X	–	X	X	–
1931-10-17 12:34:50	GR	5.6*	GR	X	X	–	–	–	–	X	–	X	X	–
1932-03-25 23:54:51	GR	6	GR	X	X	–	–	–	–	X	–	–	X	–
1932-03-25 23:58:40	ISCG	6.7	ISCG	X	X	X	X	–	–	X	–	–	X	–
1932-06-08 07:52:46	ISCG	6.0	ISCG	X	X	X	–	–	–	X	–	–	–	–
1933-07-26 04:57:26	GR	5.6*	GR	X	X	–	–	–	–	X	–	X	–	–
1935-09-04 01:27:43	ISCG	6.25	GR	X	X	X[‡]	–	–	–	X	X	–	X	X
1937-07-22 17:09:32	ISCG	7.3	Abe	X	X	X	X	–	X	X	X	–	X	X
1947-10-16 02:09:51	ISCG	7.2	Abe	X	X	X	X	X	X	X	X	–	X	X
1947-10-20 01:43:21	ISCG	6.4	ISCG	–	X[†]	X	–	–	–	X	–	–	–	–
1948-02-11 15:41:59	ISCG	6.2	ISCG	–	X[†]	X	–	–	–	X	–	–	X	–
1950-05-25 08:34:40	ISCG	6.0	ISCB	–	X	X[‡]	–	–	X	X	X	–	X	–
1958-04-07 15:30:45	ISCG	7.3	Abe	NA	X	X	X	X	X	X	–	–	X	X
1958-04-08 00:14:21	ISCG	5.9	ISCG	NA	X	X	–	–	X	X	–	–	–	–
1958-04-13 09:07:28	ISCG	5.9	ISCG	NA	X	X	–	–	X	X	–	–	X	X
1958-05-10 22:54:44	ISCG	5.9	ISCG	NA	X	X	–	–	X	X	X	–	X	X
1958-05-11 05:23:59	ISCG	5.9	ISCG	NA	X	X	–	–	X	X	X	–	X	X
1958-08-31 23:00:19	ISCG	5.9	ISCG	NA	X	X	–	–	X	X	–	–	X	–
1961-01-30 12:12:36	ISCB	5.5	ISCB	NA	X	–	–	–	–	X	–	–	X	–
1962-08-18 17:46:17	ISCG	5.6	ISCG	NA	X	X	–	X	–	X	–	–	X	–
1964-06-29 07:21:33	ISCG	5.6	ISCG	NA	X[†]	X	–	–	–	X	–	X	X	–
1965-04-16 23:22:22	ISCG	6.0	ISCG	NA	X	X	X	X	X	X	–	–	X	–
1967-06-21 18:13:04	ISCG	5.7	ISCG	NA	X	X	X	X	X	X	X	–	X	–
1968-10-29 22:16:18	ISCG	6.7	ISCG	NA	X	X	X	X	X	X	X	–	X	X
1985-03-09 14:08:06	ISCG	6.1	GCMT											
1995-10-06 05:23:21	ISCG	6.0	GCMT											
1996-10-22 22:15:04	ISCG	5.7	GCMT											
2000-02-03 10:24:59	ISCG	5.6	GCMT											
2000-11-29 10:35:48	ISCG	5.8	GCMT											
2002-10-23 11:27:20	ISCG	6.6	GCMT											
2002-11-03 22:12:43	ISCG	7.9	GCMT											

The catalog searched is the ISC Bulletin (International Seismological Centre, 2013). Here, "central Alaska" is defined by the latitude bounds 62° and 66.5° and longitude bounds −161° and −141°. The bold-typed events ($M > 7$) are used within the comparisons of felt reports in Figure 11 and Table 9. Seismicity catalogs: Abe, Abe (1981) and Abe and Noguchi (1983b); GR, Gutenberg and Richter (1954) (events labeled NA postdate the catalog); ISCB, ISC Bulletin (International Seismological Centre, 2013); ISCG, ISC-GEM 4.0 (Storchak *et al.*, 2013); Eng, Centennial Catalog (Engdahl and Villasenor, 2002); GCMT, Global Centroid Moment Tensor catalog (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012). Compilations: E86, Espinosa *et al.* (1986); P91, Page *et al.* (1991); SC93, Stover and Coffman (1993); P82, Péwé (1982); WC82, table 5-1 of Woodward-Clyde Consultants (1982); B88, Brockman *et al.* (1988); P88, Pulpan (1988). The magnitude estimates for the 1937, 1947, and 1958 earthquakes are lower in ISCG (7.12, 7.15, and 7.12) than those in Abe (1981) (7.3, 7.2, and 7.3).

*Class d (M 5.3–5.9) earthquake of Gutenberg and Richter (1954).

[†]This 'X' for ISCB denotes an event for which magnitude is not listed or < 5.5 in ISCB.

[‡]This 'X' for ISCG denotes an event in the ISC-GEM supplementary catalog.

Our preferred epicenter (LOMAX) is 263 km southwest of the epicenter of Boyd and Lerner-Lam (1988; Fig. 9), which has been adopted by other sources, such as Biswas and Tytgat (1988), Pacheco and Sykes (1992), Stover and Coffman (1993), and the USGS webpage for this earthquake.

- *GUTE.* The Gutenberg epicenter is consistent with most felt reports (Fig. 7b), though it is 550 km from St. Michael, where strong shaking was reported. Among the candidate epicenters, GUTE is the only one inside (barely) the 90% confidence interval for LOMAX. No active faults are mapped within ~50 km of GUTE, though there is active crustal seismicity in the region. GUTE is 35 km west of an M_w 5.8 earthquake that occurred on 29 November 2000 in the southern end of the Minto Flats fault zone (MFFZ; Tape *et al.*, 2015). However, given that the entire MFFZ is outside

Table 9
MMI (Wood and Neumann, 1931) Values for Large Earthquakes in Central Alaska

Location		1904		1912		1937		1947		1958		2002	
Rampart	Ra	4–5	(F)	—	(6)	—	(F)	5	(6)	1–4	(6)	—	(5)
Fairbanks	Fa	5	(F)	6	(6)	6	(F)	8	(7)	6	(5)	5	(6)
Coldfoot/Wiseman	C/W	3–4	(F)	—	(2)	3	(F)	1–3	(3)	5	(5)	—	(4)
Sunrise/Hope	S/H	2–4	(F)	—	(4)	—	(F)	—	(2)	—	(NF)	—	(4)
St. Michael	SM	5–6	(F)	—	(3)	—	(NF)	—	(NF)	—	(4)	—	(2)
Kaltag	Ka	—	(F)	—	(4)	—	(NF)	NF	(1)	—	(5)	—	(3)
Galena	Ga	—	(F)	4	(4)	—	(NF)	—	(2)	6	(6)	3	(4)
Ruby	Ru	—	(F)	5	(5)	3	(F)	—	(2)	7	(6)	5	(5)
Tanana	Ta	—	(F)	6	(6)	3	(F)	—	(5)	7	(6)	—	(5)
Huslia	Hu	—	(F)	—	(4)	—	(NF)	—	(2)	8	(8)	3	(4)
Healy	He	—	(F)	—	(7)	—	(F)	6	(7)	1–4	(5)	6	(7)
Nome	No	NF’	(NF)	1–2	(2)	—	(NF)	—	(NF)	NF	(NF)	—	(NF)
Seward	Se	—	(NF)	4	(3)	NF	(NF)	F	(1)	—	(NF)	4	(4)
Valdez	Va	NF’	(NF)	5	(5)	3	(F)	—	(2)	—	(NF)	4	(4)
Sitka	Si	NF’	(NF)	1–2	(1)	—	(NF)	—	(NF)	—	(NF)	1	(3)
Fort Yukon	FY	—	(F)	1–2	(2)	3	(F)	—	(4)	1–4	(NF)	4	(4)
Bethel	Be	—	(NF)	—	(3)	NF	(NF)	—	(NF)	—	(NF)	1	(4)
McGrath	Mc	—	(F)	—	(6)	3	(F)	5	(2)	5	(5)	3	(4)
Anchorage	An	—	(F)	—	(5)	5	(F)	4	(2)	NF	(NF)	4	(5)
Dawson	Da	NF’	(NF)	4	(4)	F	(F)	—	(2)	—	(NF)	—	(5)

A reference set of locations is selected (Fig. 11) to compare shaking from different events. Values without parentheses are based on actual reports: 1904 (this study), 1912 (Carver *et al.*, 2004), 1937 (Bramhall, 1938; Brockman *et al.*, 1988), 1947 (St. Amand, 1948; Murphy, 1950; Brockman *et al.*, 1988), 1958 (Brazee and Cloud, 1960), and 2002 (U.S. Geological Survey "Did You Feel It" archives; see Data and Resources). Dash means there is no report. NF means not felt, based on a report. NF’ for the 1904 earthquake is based on our inference of a written source (see Appendix A). The solid dots in figure 9 of Brazee and Cloud (1960) are interpreted as not-felt reports. Values in parentheses are interpolated from published contours shown in Figure 11. For the 1904 (Fig. 6) and 1937 (Bramhall, 1938) earthquakes, (F) denotes that a site was within the estimated felt region. (NF) means not felt, based on the estimated felt region. The MMI 1–2 value for Fort Yukon for 1912 is from figure 7 of Carver *et al.* (2004), though it does not appear in their table 1.

the 90% confidence region for LOMAX (Fig. 12), it seems unlikely that the MFFZ hosted the 1904 earthquake.

- *MCGRATH.* McGrath is on the Iditarod–Nixon fault (Koehler *et al.*, 2012). The epicenter is more consistent with felt reports than the WDENF epicenter to the southeast. The Coldfoot felt report—30 s of shaking at 535 km from MCGRATH—is problematic. There is limited seismicity (Fig. 10) and no known historical earthquakes on this section of the fault.
- *RUBY.* The village of Ruby is on the eastern portion of the Kaltag fault. Given the instrumental data (Fig. 9), this epicenter is unlikely. Our analysis in Ⓔ Figure S5 implies that the cloud of points in Figure 9 should be shifted northward (toward the Kaltag fault) by 5–40 km, but even with the shift the Kaltag fault remains unlikely.
  There are some factors that lead us not to discount RUBY. First, RUBY provides the best fit to felt reports (Fig. 7b). Second, the Kaltag fault is mapped as active and it has produced an M_w 5.5 strike-slip earthquake about 70 km east of Ruby (Appendix B). Third, a westward rupture on the Kaltag fault might explain the strong shaking at St. Michael, even for an epicenter as far east as Ruby.
- *WDENF.* An epicenter on the western Denali fault is inconsistent with the felt reports. For an $M > 7$ earthquake on the western Denali fault, we would expect moderate shaking in Valdez (at 375 km), lighter shaking in St. Michael (at 480 km), and perhaps not felt in Coldfoot (at 525 km). WDENF is a poor but possible fit to the instrumental data (Fig. 9).
- *KALTAG.* We consider a candidate epicenter on the western portion of the Kaltag fault, near the village of Kaltag. The Kaltag fault approximately connects the felt reports in the east (Fairbanks, Rampart) to the felt report in the west at St. Michael (Fig. 6). Although KALTAG fits the felt reports (Fig. 7b), it is inconsistent with the instrumental data (Fig. 9).
- *WC82.* The instrumental data indicate that the Woodward-Clyde epicenter would be unlikely. For WC82, one would expect the strongest shaking in Rampart (at 100 km).
- *HUSLIA.* The instrumental data (Fig. 9) exclude the possibility of the 1904 epicenter being near Huslia. Furthermore, the Sunrise felt report would be unlikely for a Huslia epicenter: the 1904 Sunrise felt report is 620 km from Huslia, and there was no reported shaking in Anchorage or the Kenai peninsula from the 1958 M_s 7.3 Huslia earthquake.
  Although HUSLIA is not on an active fault that is identified at the surface (Koehler *et al.*, 2012), we know that the area is capable of $M > 7$ earthquakes, as evidenced by the one in 1958. We have no written records from Huslia for the time period of 1904, though we know it experienced MMI 8 shaking during the 1958 earthquake (Brazee and Cloud, 1960; Davis, 1960). Davis (1960) documented field evi-

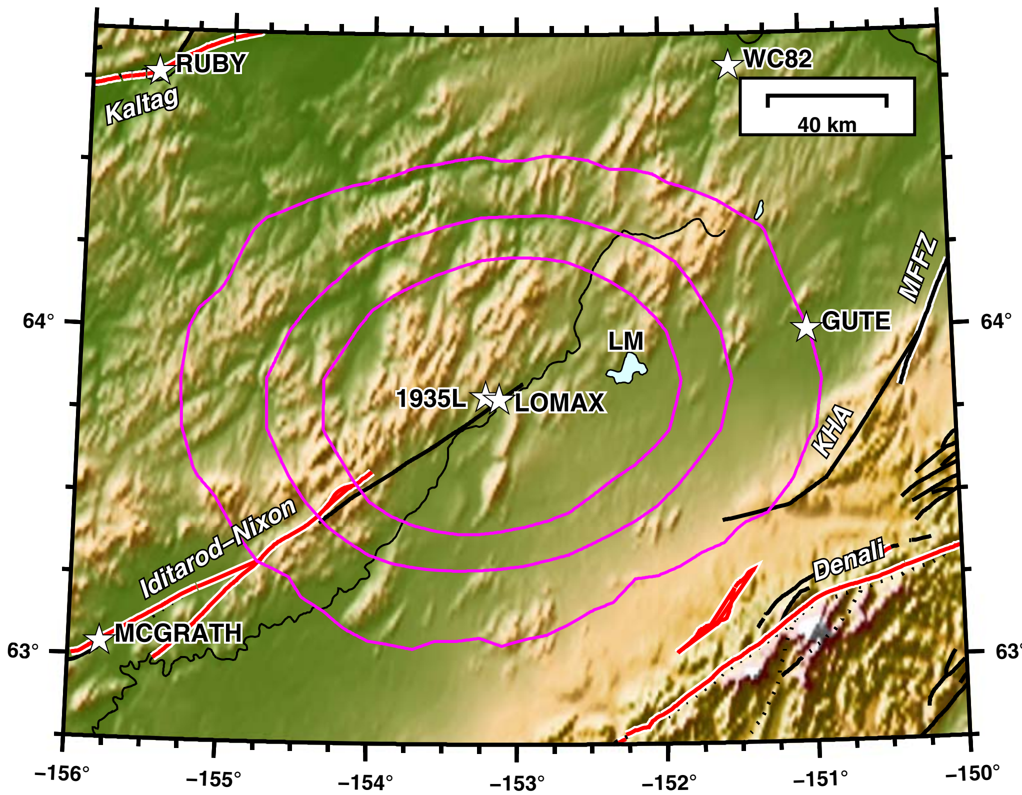

Figure 12. Enlarged view of the epicentral region for the 1904 Alaska earthquake, showing confidence contours of 50% (inner), 70%, and 90% (outer) (Fig. 9a). The preferred epicenters for the 1904 and 1935 earthquakes are labeled as LOMAX and 1935L. These epicenters are on the northeastern extent of the Iditarod–Nixon fault (Plafker *et al.*, 1994). They are on the north fork of the Kuskokwim River, west of Lake Minchumina (LM), and south of the Sischu mountains. Other active faults and folds in this region (Koehler *et al.*, 2012) include the Denali fault, Kantishna Hills Anticline (KHA), the MFFZ (Tape *et al.* (2015), and the Kaltag fault. The color version of this figure is available only in the electronic edition.

dence and remembrances from Huslia elders of an earlier earthquake, in fact prior to 1930.

- *BL88.* The epicenter from Boyd and Lerner-Lam (1988) is 27 km from Fairbanks and is inconsistent with the felt reports. The felt report from Fairbanks (Fig. 4) is consistent with an epicenter at >100 km. For a BL88 epicenter, the shaking at St. Michael, 695 km from BL88, would be weak or not felt, as in the 1937 and 1947 $M > 7$ earthquakes near Fairbanks (Fig. 11).
- *M13.* The epicenter from Milne *et al.* (1913) is inconsistent with felt reports and instrumental data.

Discussion and Summary

We present five felt reports and a new analysis of instrumental data for the 27 August 1904 M_s 7.3 earthquake in central Alaska. From the 10 candidate epicenters in Table 10, we judge that four are possible: LOMAX, GUTE, MCGRATH, and RUBY, in decreasing order of preference. Our top three candidates are aligned with the Iditarod–Nixon fault (Fig. 9), which we interpret as the most likely source of the 1904 M_s 7.3 earthquake and also for the 1935 M 6.2 earthquake. Our preferred epicenter (LOMAX) is 41 km west of Lake Minchumina, on the north fork of the Kuskokwim river, at the northeastern terminus of a section of the Iditarod–Nixon fault mapped as having pre-Neogene activity (Plafker *et al.*, 1994; Fig. 12).

Our preferred epicenter (LOMAX) would predict shaking intensities at St. Michael (distance 446 km) that are less than those reported. Based on the epicentral distance and using Bakun and Wentworth (1997), the predicted MMI is 3.3, whereas the reported MMI is 6, inferred from Table 4. The felt report at St. Michael is an outlier, whether we use the unadjusted or the adjusted MMI values (Table 5). The newspaper report (Fig. 3) contains exaggerated language that might warrant a lower assignment of MMI, such as MMI 5. The accounts of seasickness could possibly be interpreted as people feeling nausea (MMI 2), rather than people "made to move unsteadily" (MMI 6); however, the description that "everything was violently disturbed" led us to the higher MMI assignment (Table 4). Lowering the MMI value for St. Michael would pull the felt-report-estimated epicenter to the southeast and toward the region of the instrumental estimated epicenter. It is also possible that the reported shaking in St. Michael (MMI 6) is accurate. In that case, we can contemplate two factors that could enhance shaking at St. Michael, relative to what would be expected for its epicentral

Table 10
Summary of Evidence Used to Evaluate a Set of Alternative Epicenters as Candidates for the Epicenter of the 1904 Earthquake

				A	B	C	D	E
Epicenter	Longitude (°)	Latitude (°)	Distance to LOMAX, km (Fig. 6)	Instrumental Data (Fig. 9)	Felt Reports (Fig. 7b)	Previous Equations $M \geq 5$ (Table 8)	Seismically Active Region (Fig. 10a)	Geologically Active Fault (Fig. 6)
LOMAX	−153.12	63.79	0	39 [4]	1.14 [3]	1935-09-04 (6.2) [3]	[3]	[3]
GUTE	−151	64	92	36 [3]	1.21 [2]	2000-11-29 (5.8) [3]	[3]	[2]
MCGRATH	−155.79	63.04	170	32 [2]	1.22 [2]	[0]	[2]	[4]
RUBY	−155.53	64.77	170	33 [2]	1.07 [4]	2000-02-03 (5.6) [3]	[2]	[4]
WDENF	−152.75	62.66	126	33 [2]	1.38 [1]	[0]	[3]	[4]
KALTAG	−158.76	64.34	296	30 [1]	1.14 [3]	[0]	[2]	[4]
WC82	−151.5	64.8	129	33 [2]	1.29 [2]	1958-05-10 (5.9) [3]	[3]	[1]
HUSLIA	−155.5	65.75	252	27 [1]	1.18 [3]	1958-04-07 (7.3) [4]	[4]	[0]
BL88	−148.08	64.66	250	34 [2]	1.87 [1]	1967-06-21 (5.7) [3]	[4]	[0]
M13	−141	67	654	28 [1]	1.87 [1]	[0]	[2]	[0]

We rate each of five factors (A–E) on a scale of [0]–[4], with [4] indicating that the factor constitutes strong evidence for the 1904 epicenter being near the candidate epicenter and [0] indicating that the factor constitutes no evidence for the 1904 epicenter being near the candidate epicenter. The values in column A are the number of P and S observations (out of 61 total) with residuals $|r| \leq 10$ s after one iteration of the NonLinLoc (NLL) equal differential time (EDT) location procedure described here, applied with the hypocenter fixed at the candidate epicenter and 5 km depth. The decimal values in column B are the root mean square (rms) residual MMI values, based on Figure 7b.

distance from LOMAX. First, local or regional crustal structures near St. Michael could enhance shaking. Second, St. Michael could have been in a direction of maximal radiation with respect to the source mechanism or to the directivity of the rupture.

We are not aware of any attempt to estimate a source mechanism for the 1904 earthquake, probably due to the challenges associated with collecting waveforms from this time period. (The epicentral estimates in Table 1 all used tabulated arrival-time data, such as Rosenthal, 1907. Magnitude estimates were also based on tabulated amplitudes.) On the basis of geological evidence for right-lateral strike-slip faulting on the Iditarod–Nixon fault (Miller and Bundtzen, 1988), we speculate that the 1904 earthquake was also a strike-slip earthquake; we note that faults to the south (Denali) and north (Kaltag) are also right lateral (Page *et al.*, 1995). A future effort to estimate the source mechanism for the 1935 earthquake could—if the mechanism were reliable enough—provide insights into the style of faulting in the region of the 1904 earthquake.

If the 1904 earthquake occurred on the Iditarod–Nixon fault—or a possible extension of the fault to the northeast—then it is possible that the earthquake rupture left a geological record. Trenches across the fault would provide useful data regarding the 1904 rupture and, potentially, previous earthquakes. (Of course, not all earthquake ruptures reach the surface, so lack of evidence of surface deformation does not rule out the Iditarod–Nixon fault.) Our top two candidates, LOMAX and GUTE, are northeast of the geologically identified active section of the Iditarod–Nixon fault (Fourth of July Creek; Koehler *et al.*, 2012) and west of the NFFTB and Minto Flats fault zone (Fig. 9). The presence of the 1904 M_s 7.3 and 1935 M 6.2 earthquakes in this region hints that there could be a connection between active faulting to the east and strike-slip faulting to the southwest.

Sparse geodetic observations (Fletcher, 2002; Cross and Freymueller, 2008; Freymueller *et al.*, 2008) and geologic observations (Koehler and Carver, 2017) show that a small amount of slip (<3 mm/yr) between the Pacific and North America plates must be accommodated by faults in west-central Alaska. Better coverage of Global Positioning System (GPS) velocity measurements across the Iditarod–Nixon and Kaltag faults could provide estimates for strain rates and slip rates across the faults.

Future efforts to model ground motion in central Alaska should consider two possible scenarios for the 1904 earthquake. The first would be an $M > 7$ earthquake—perhaps on the Iditarod–Nixon fault—with a rupture length of ~120 km. The second, less likely, scenario would be a rupture on the eastern Kaltag fault. Wherever the epicenter, the ground-motion simulations for the 1904 earthquake would need to produce strong shaking over the observed region spanning >700 km from coastal St. Michael to interior Fairbanks (Fig. 6).

The current seismic-hazard map for Alaska (Wesson *et al.*, 2007) is based on seismicity from 1898 to 2004. The magnitude of completeness of the catalog decreases over this time period, due to increasing station coverage in Alaska. The catalog is complete down to magnitude 4.5 since 1964, 6.0 since 1932, and 6.9 since 1898 (Wesson *et al.*, 2007). In central Alaska (the region of Fig. 6), with the exception of the Denali fault, all seismic-hazard estimates are derived from applying the frequency–magnitude relationship ($\log_{10} N = a - bM$) to the seismicity catalog, with an upper-limit magnitude of M_w 7.3. The Denali fault has a conspicuous signature on the hazard map, because it is modeled explicitly as a fault source, with an estimated maximum magnitude and recurrence rate. It seems prudent to identify other faults based on historical earthquakes, such as those in 1904, 1937, 1947, and 1958 (Table 8). Currently the hazard associated with these epicentral regions relies on the identification of a surface-mapped fault or is derived from seismicity that is decades (or even a century) after the events. Based on the seismological evidence, we believe that the northeast reaches of the Iditarod–Nixon fault should be considered as an $M > 7$ potential source for future earthquakes. This should inform seismic-hazard estimates and future efforts for designing or retrofitting critical structures such as pipelines, dams, or military sites.

Faults in mainland Alaska have relatively slow-slip rates with long recurrence intervals between earthquakes (Koehler and Carver, 2017). A 40-yr picture of $M_w \geq 5$ earthquake activity—such as the 1976–2016 Global CMT catalog in Figure 10b—thus provides only a limited view of fault activity. To improve this picture, we can turn to historical earthquakes, despite the larger uncertainties in their epicenters and source mechanisms. For historical earthquakes since the start of the instrumental era in 1904, we can use arrival-time data and felt reports to improve epicentral estimates, as we have done for the 1904 M_s 7.3 earthquake. Looking back further requires labor-intensive paleoseismic investigations, for which target sites are informed by geologic mapping, seismicity, and GPS-derived strain rates across faults. These components—active seismicity, historical earthquakes, and paleoseismic evidence of ancient earthquakes—provide foundational data to inform future earthquake activity and seismic-hazard assessments.

Data and Resources

Arrival-time data for the 1904 and 1935 earthquakes (Ⓔ Tables S1 and S2) were provided by Domenico Di Giacomo at International Seismological Centre (ISC). Global station locations (Ⓔ Tables S1 and S2) were downloaded from the ISC station register (http://www.isc.ac.uk/registries, last accessed October 2016). The seismic waveforms in Figure B1 were collected as part of the Broadband Experiment Across the Alaska Range (BEAAR) project from the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) (Christensen *et al.*, 1999; Ferris *et al.*, 2003). These waveforms are available at the Incorporated Research Institutions for Seismology (IRIS) Data Management Center. The seismicity catalog for Alaska in Figure 10a was obtained from the Alaska Earthquake Center and was last updated on 29 April 2016. The Global Centroid Moment Tensor (CMT) Project database (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012) in Figure 10b was downloaded from http://www.globalcmt.org/CMTfiles.html (last accessed June 2016). In Table 8, we use earthquake catalog data from the Centennial Catalog of Engdahl and Villasenor (2002), the ISC Bulletin (International Seismological Centre, 2013), and the International Seismological Centre Global Earthquake Model (ISC-GEM) Catalogue (Storchak *et al.*, 2013), Version 4.0, released 26 January 2017. The USGS Quaternary Fault and Fold database is available at https://earthquake.usgs.gov/hazards/qfaults/ (last accessed February 2017). The MMI values in Table 9 for the 2002 earthquake are from the USGS Did-You-Feel-It database, available from the earthquake catalog at http://earthquake.usgs.gov/data/dyfi/ (last accessed February 2017). The images in Figure 3 were obtained from microfilm at the Alaska and Polar Regions Collections & Archives at the Rasmuson Library at University of Alaska Fairbanks. The image in Figure 4 is available online within the Alaska Digital Archives at http://vilda.alaska.edu/cdm/compoundobject/collection/cdmg22/id/1479 (last accessed February 2017) as image identifier ASL-MS0107-Diary08-1904-August27&28a. The image from the Shide Circular in Ⓔ Figure S1d was obtained from the digital supplement to Schweitzer and Lee (2003). The National Center for Environmental Information (NCEI), formerly the National Climate Data Center, archives all weather and climate forms for the United States. The NCEI scanned all archived forms and made them available to researchers and the public through a variety of internet databases, for example, https://www.ncdc.noaa.gov/IPS/coop/coop.html (last accessed February 2017). We downloaded the Voluntary Observers' Meteorological Record forms.

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References

Abe, K. (1981). Magnitudes of large shallow earthquakes from 1904 to 1980, *Phys. Earth Planet. In.* **27,** 72–92.

Abe, K., and S. Noguchi (1983a). Determination of magnitude for large shallow earthquakes 1898–1917, *Phys. Earth Planet. In.* **32,** 45–59.

Abe, K., and S. Noguchi (1983b). Revision of magnitudes of large shallow earthquakes, 1897–1912, *Phys. Earth Planet. In.* **33,** 1–11.

Agnew, J. D. (1980). Seismicity of the central Alaska Range, *M.S. Thesis*, University of Alaska Fairbanks, Fairbanks, Alaska.

Anchorage Daily Times (1935). Another Quake, *Anchorage Daily Times*, September 3, p. 5.

Bakun, W. H., and C. M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seismol. Soc. Am.* **87,** no. 6, 1502–1521.

Biswas, N. N., and G. Tytgat (1988). Intraplate seismicity in Alaska, *Seismol. Res. Lett.* **59,** no. 4, 227–233.

Boyd, T. M., and A. L. Lerner-Lam (1988). Spatial distribution of turn-of-the-century seismicity along the Alaska-Aleutian Arc, *Bull. Seismol. Soc. Am.* **78,** no. 2, 636–650.

Brady, J. G. (1904). *Report of the Governor of the District of Alaska to the Secretary of the Interior*, Government Printing Office, Washington, D.C.

Bramhall, E. H. (1938). The central Alaska earthquake of July 22, 1937, *Bull. Seismol. Soc. Am.* **28,** 71–75.

Brazee, R. J., and W. K. Cloud (1960). *United States Earthquakes 1958*, U.S. Department of Commerce.

Brockman, S. R., A. F. Espinosa, and J. A. Michael (1988). Catalog of intensities and magnitudes for earthquakes in Alaska and the Aleutian Islands—1786–1981, *U.S. Geol. Surv. Bull. 1840*.

Brown, J. S. (1926). The Nixon Fork Country, in *Mineral Resources of Alaska: Report on Progress of Investigations in 1924, U.S. Geol. Surv. Bull. 783-D*, Washington, D.C., 97–150.

Carver, G., G. Plafker, M. Metz, L. Cuff, B. Slemmons, E. Johnson, J. Roddick, and S. Sorensen (2004). Surface rupture on the Denali fault interpreted from tree damage during the 1912 Delta River M_w 7.2–7.4 earthquake: Implications for the 2002 Denali fault earthquake slip distribution, *Bull. Seismol. Soc. Am.* **94,** no. 6B, S58–S71.

Christensen, D., R. Hansen, and G. Abers (1999). Broadband Experiment across the Alaskan Range, International Federation of Digital Seismograph Networks, Other/Seismic Network, doi: 10.7914/SN/XE_1999.

Cloud, W. K., and C. F. Knudson (1968). *The Fairbanks, Alaska, Earthquakes of June 21, 1967: Preliminary Engineering Seismological Report*, U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, p. 33–60.

Coffman, J. L., and W. K. Cloud (1970). *United States Earthquakes 1968*, U.S. Department of Commerce.

Cross, R. S., and J. T. Freymueller (2008). Evidence for and implications of a Bering plate based on geodetic measurements from the Aleutians and western Alaska, *J. Geophys. Res.* **113,** doi: 10.1029/2007JB005136.

Crotwell, H. P., T. J. Owens, and J. Ritsema (1999). The TauP Toolkit: Flexible seismic travel-time and ray-path utilities, *Seismol. Res. Lett.* **70,** no. 2, 154–160.

Davis, T. N. (1960). A field report on the Alaska earthquakes of April 7, 1958, *Bull. Seismol. Soc. Am.* **50,** no. 4, 489–510.

Duda, S. J. (1965). Secular seismic energy release in the circum-Pacific belt, *Tectonophysics* **2,** no. 5, 409–452.

Dziewonski, A., T.-A. Chou, and J. H. Woodhouse (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* **86,** no. B4, 2825–2852.

Eberhart-Phillips, D., P. J. Haeussler, J. T. Freymueller, A. D. Frankel, C. M. Rubin, P. Craw, N. A. Ratchkovski, G. Anderson, G. A. Carver, A. J. Crone, *et al.* (2003). The 2002 Denali fault earthquake, Alaska: A large magnitude, slip-partitioned event, *Science* **300,** 1113–1118.

Ekström, G., M. Nettles, and A. M. Dziewoński (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth Planet. In.* **200–201,** 1–9, doi: 10.1016/j.pepi.2012.04.002.

Engdahl, E. R., and A. Villasenor (2002). Global seismicity: 1900–1999, in *International Handbook of Earthquake and Engineering Seismology*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Vol. 81A, International Geophysics Series, Academic Press, London, United Kingdom, 665–690.

Espinosa, A. F., S. R. Brockman, and J. A. Michael (1986). Modified Mercalli intensity distribution for the most significant earthquakes in Alaska, 1899–1981, *U.S. Geol. Surv. Open-File Rept. 86-203*, 1 sheet, scale 1:12,500,000.

Estabrook, C. H., D. B. Stone, and J. N. Davies (1988). Seismotectonics of northern Alaska, *J. Geophys. Res.* **93,** no. B10, 12,026–12,040.

Fairbanks Daily News-Miner (1935). Earthquakes Felt Today in Fairbanks, Fairbanks Daily News-Miner, September 3, p. 4.

Ferris, A., G. A. Abers, D. H. Christensen, and E. Veenstra (2003). High resolution image of the subducted Pacific (?) plate beneath central Alaska, 50–150 km depth, *Earth Planet. Sci. Lett.* **214,** 575–588.

Fletcher, H. (2002). Crustal deformation in Alaska measured using the Global Positioning System, *Ph.D. Thesis*, University of Alaska Fairbanks, Fairbanks, Alaska.

Font, Y., H. Kao, S. Lallemand, C.-S. Liu, and L.-Y. Chiao (2004). Hypocentre determination offshore of eastern Taiwan using the Maximum Intersection method, *Geophys. J. Int.* **158,** 655–675, doi: 10.1111/j.1365-246X.2004.02317.x.

Freymueller, J. T., H. Woodard, S. C. Cohen, R. Cross, J. Elliott, C. F. Larsen, S. Hreinsdóttir, and C. Zweck (2008). Active deformation processes in Alaska, based on 15 years of GPS measurements, in *Active Tectonics and Seismic Potential of Alaska*, J. T. Freymueller, P. J. Haeussler, R. Wesson, and G. Ekström (Editors), Vol. 179, American Geophysical Monograph, Am. Geophysics Union, Washington, D.C., 1–42.

Gedney, L. (1985). Stress trajectories across the northeast Alaska Range, *Bull. Seismol. Soc. Am.* **75,** no. 4, 1125–1134.

Gedney, L., E. Berg, H. Pulpan, H. Davies, and W. Feetham (1969). A field report on the Rampart, Alaska earthquake of October 29, 1968, *Bull. Seismol. Soc. Am.* **59,** no. 3, 1421–1423.

Gedney, L., S. Estes, and N. Biswas (1980). Earthquake migration in the Fairbanks, Alaska seismic zone, *Bull. Seismol. Soc. Am.* **70,** no. 1, 223–241.

Geller, R. J., and H. Kanamori (1977). Magnitudes of great shallow earthquakes from 1904 to 1952, *Bull. Seismol. Soc. Am.* **67,** 587–598.

Grantz, A. (1966). Strike-slip faults in Alaska, *U.S. Geol. Surv. Open-File Rept. 66-53*, Washngton, D.C.

Gutenberg, B. (1908–1962). 1904 Aug 27, in *The Papers of Beno Gutenberg*, California Institute of Technology, Notepad #75, p. 630.

Gutenberg, B. (1956). Great earthquakes 1896–1903, *Eos Trans. AGU* **37,** no. 5, 608–614.

Gutenberg, B., and C. F. Richter (1949). *Seismicity of the Earth and Associated Phenomena*, First Ed., Princeton University Press, Princeton, New Jersey.

Gutenberg, B., and C. F. Richter (1954). *Seismicity of the Earth and Associated Phenomena*, Second Ed., Princeton University Press, Princeton, New Jersey.

Hazard, D. L. (1911). Earthquakes, in *Results of Observations Made at the Coast and Geodetic Survey Magnetic Observatory at Sitka, Alaska, 1907 and 1908*, U.S. Department of Commerce and Labor, Coast and Geodetic Survey, Washington, D.C., 92–94.

Heck, N. H. (1947). *Earthquake History of the United States, Part I—Continental United States (Exclusive of California and Western Nevada) and Alaska*, Serial No. 609 Revised (1947) edition, U.S. Department of Commerce Coast and Geodetic Survey, Washington, D.C., 83.

Heck, N. H., and R. R. Bodle (1931). *United States Earthquakes 1929*, U.S. Department of Commerce.

Hoagland, A. K. (1993). *Buildings of Alaska*, Oxford University Press, New York, New York.

Howard, F. E. (1904). Voluntary Observers' Meteorological Record, August, 1904, Coldfoot, Alaska. Meteorological Observation Reports, 1881–1924; Division of Station Facilities & Meteorological Observations, Alaska, *Records of the Weather Bureau, Record Group 27*, National Archives at Seattle, Seattle, Washington.

Huang, P. Y., and N. N. Biswas (1983). Rampart seismic zone of central Alaska, *Bull. Seismol. Soc. Am.* **73,** no. 3, 813–829.

International Seismological Centre (2013). On-line Bulletin, International Seismological Centre, Thatcham, United Kingdom, http://www.isc.ac.uk, (last accessed October 2016).

Johnson, C. (1935). Voluntary Observers' Meteorological Record, September, 1935, Nenana, Alaska, downloaded from NOAA Cooperative Observations website https://www.ncdc.noaa.gov/IPS/coop/coop.html (last accessed February 2017).

Judd, J. W., and J. Milne (1905). British Association for the Advancement of Science, Circular No. 11, Newport, Isle of Wight, United Kingdom (also p. 321–348 of Vol. 2).

Kanamori, H. (1977). The energy release in great earthquakes, *J. Geophys. Res.* **82,** 2981–2987.

Kennett, B. L. N., E. R. Engdahl, and R. Buland (1995). Constraints on seismic velocities in the Earth from traveltimes, *Geophys. J. Int.* **122,** 108–124.

Koehler, R. D., and G. A. Carver (2017). Active faults and seismic hazards in Alaska, *Alaska Div. Geol. Geophys. Surv.*, Miscellaneous Publication 160, doi: 10.14509/29705.

Koehler, R. D., R.-E. Farrell, P. A. C. Burns, and R. A. Combelick (2012). Quaternary faults and folds in Alaska: A digital database, *Alaska Div. Geol. Geophys. Surv. Miscellaneous Publication 141*, 31 p., 1 sheet, scale 1:3,700,000.

Lawson, A. (1904). Voluntary Observers' Meteorological Record, August, 1904, Sunrise, Alaska. Meteorological Observation Reports, 1881–1924; Division of Station Facilities & Meteorological Observations, Alaska, *Records of the Weather Bureau, Record Group 27*, National Archives at Seattle, Seattle, Washington.

Lomax, A. (2005). A reanalysis of the hypocentral location and related observations for the great 1906 California earthquake, *Bull. Seismol. Soc. Am.* **95,** no. 3, 861–877, doi: 10.1785/0120040141.

Lomax, A. (2008). Location of the focus and tectonics of the focal region of the California earthquake of 18 April 1906, *Bull. Seismol. Soc. Am.* **98,** no. 2, 846–860, doi: 10.1785/0120060405.

Lomax, A., A. Michelini, and A. Curtis (2014). Earthquake location, direct, global-search methods, in *Encyclopedia of Complexity and System Science*, Second Ed., R. A. Meyers (Editor), Springer, New York, New York, 1–33, doi: 10.1007/978-3-642-27737-5_150-2.

Lomax, A., J. Virieux, P. Volant, and C. Berge (2000). Probabilistic earthquake location in 3D and layered models: Introduction of a Metropolis–Gibbs method and comparison with linear locations, in *Advances in Seismic Event Location*, C. H. Thurber and N. Rabinowitz (Editors), Kluwer, Amsterdam, The Netherlands, 101–134.

Mai, P. M., and G. C. Beroza (2000). Source scaling properties from finite-fault-rupture models, *Bull. Seismol. Soc. Am.* **90,** no. 3, 604–615.

Martin, L. (1910). Alaskan earthquakes of 1899, *Geol. Soc. Am. Bull.* **21,** 339–406.

Matheson, J. (1985). *Fairbanks: A City Historic Building Survey*, City of Fairbanks, Fairbanks, Alaska.

Mertie, J. B., Jr., and G. L. Harrington (1924). The Ruby-Kuskokwim region, Alaska, *U.S. Geol. Surv. Bull. 754*, Washington, D.C.

Miller, M. L., and T. K. Bundtzen (1988). Right-lateral offset solution for the Iditarod–Nixon Fork fault, western Alaska, *Geologic Studies in Alaska by the U.S. Geological Survey during 1987*, J. P. Galloway and T. D. Hamilton (Editors), *U.S. Geol. Surv. Circular 1016*, 99–103.

Milne, J. (1886). *Earthquakes and other Earth Movements*, Vol. 55, International Scientific Series, Appleton, New York.

Milne, J., H. H. Turner, C. V. Boys, G. Darwin, H. Darwin, L. Darwin, R. T. Glazebrook, M. H. Gray, R. K. Gray, J. W. Judd, *et al.* (1912). Seismological Investigations—Sixteenth Report of the Committee, *Report of the Eightieth Meeting of the British Association for the Advancement of Science*, Portsmouth, England, 31 August to 7 September 1911, 30–67.

Milne, J., H. H. Turner, C. V. Boys, G. Darwin, H. Darwin, R. T. Glazebrook, M. H. Gray, R. K. Gray, J. W. Judd, C. G. Knott, *et al.* (1913). Seismological Investigations—Seventeenth Report of the Committee, *Report of the Eighty-second Meeting of the British Association for the Advancement of Science*, Dundee, Scotland, 4–11 September 1912, 69–103.

Murphy, L. M. (1950). *United States Earthquakes 1947*, U.S. Department of Commerce.

Neumann, F. (1937). *United States Earthquakes 1935*, U.S. Department of Commerce.

Nome Semi-Weekly News (1904). Severe earthquake occurs at St. Michael, *Nome Semi-Weekly News*, August 30, p. 1.

Oskin, M. E., J. R. Arrowsmith, A. H. Corona, A. J. Elliott, J. M. Fletcher, E. J. Fielding, P. O. Gold, J. J. G. Garcia, K. W. Hudnut, J. Liu-Zeng, *et al.* (2012). Near-field deformation from the El Mayor–Cucapah earthquake revealed by differential LIDAR, *Science* **335,** 702–705.

Pacheco, J. F., and L. R. Sykes (1992). Seismic moment catalog of large shallow earthquakes, 1900 to 1989, *Bull. Seismol. Soc. Am.* **82,** 1306–1349.

Page, R. A., N. N. Biswas, J. C. Lahr, and H. Pulpan (1991). Seismicity of continental Alaska, in *Neotectonics of North America, The Geology of North America*, Chapter 4, D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell (Editors), Boulder, Colorado, Geol. Soc. Am., Decade Map Vol. 1, 47–68.

Page, R. A., G. Plafker, and H. Pulpan (1995). Block rotation in east-central Alaska: A framework for evaluating earthquake potential? *Geology* **23,** no. 7, 629–632.

Patton, W. W., Jr., and J. M. Hoare (1968). The Kaltag fault, west-central Alaska, in *Geo. Surv. Res. 1968*, Professional Paper 600-D, U.S. Government Printing Office, Washington, D.C., D147–D153.

Péwé, T. L. (1982). Geologic Hazards of the Fairbanks Area, Alaska, *Alaska Div. Geol. Geophys. Surv., Special Rept. 15*, 109 p.

Plafker, G., and W. Thatcher (2008). Geological and geophysical evaluation of the mechanisms of the great 1899 Yakutat Bay earthquakes, in *Active Tectonics and Seismic Potential of Alaska*, J. T. Freymueller, P. J. Haeussler, R. Wesson, and G. Ekström (Editors), Vol. 179 of Geophysical Monograph, American Geophysical Union, Washington, D.C., 215–236.

Plafker, G., L. M. Gilpin, and J. C. Lahr (1994). Neotectonic map of Alaska, in *Geology of Alaska*, G. Plafker and H. C. Berg (Editors), Vol. G-1, The Geology of North America, Geological Society of America, Boulder, Colorado, Plate 12.

Pulpan, H. (1988). Seismic-hazard analysis of the Nenana agricultural development area, central Alaska, *Alaska Div. Geol. Geophys. Surv. Rept. Investigations 88-1*.

Ratchkovski, N. A., and R. A. Hansen (2002). New constraints on tectonics of interior Alaska: Earthquake locations, source mechanisms, and stress regime, *Bull. Seismol. Soc. Am.* **92,** no. 3, 998–1014, doi: 10.1785/0120010182.

Reckard, M. K. (1993). The F.E. Company industrial site: Historic resources and preservation potential, *Master's Thesis*, University of Oregon, Eugene, Oregon.

Reid, H. F. (1905). Records of seismographs in North America and the Hawaiian Islands. No. II, *Terr. Magn. Atmos. Electr.* **10,** no. 4, 177–189.

Reid, H. F. (1912). List of strong shocks in the United States and dependencies, *Report of the Eightieth Meeting of the British Association for the Advancement of Science*, Portsmouth, England, 31 August to 7 September 1911, 41–45.

Richter, C. F. (1958). *Elementary Seismology*, W. H. Freeman, San Francisco, California.

Rosenthal, E. (1907). *Katalog der im Jahre 1904 Registrierten Seismischen Störungen*, Veröffentlichungen des Zentral-Bureaus der Internationalen Seismologischen Assoziation, Serie B Kataloge, Strasbourg (in German).

Rowe, C., D. Christensen, and G. Carver (2004). Preface to the issue dedicated to the 2002 Denali fault earthquake sequence, *Bull. Seismol. Soc. Am.* **94,** no. 6B, S1–S4.

Schweitzer, J., and W. H. K. Lee (2003). Old seismic bulletins to 1920: A collective heritage from early seismologists, in *International Handbook of Earthquake and Engineering Seismology*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger (Editors), Vol. 81B of International Geophysics Series, Academic Press, London, United Kingdom, 1665–1723.

Silwal, V., and C. Tape (2016). Seismic moment tensors and estimated uncertainties in southern Alaska, *J. Geophys. Res.* **121,** 2772–2797, doi: 10.1002/2015JB012588.

St. Amand, P. (1948). The central Alaska earthquake swarm of October 1947, *Eos Trans. AGU* **29,** no. 5, 613–623.

St. Amand, P. (1957). Geological and geophysical synthesis of the tectonics of portions of British Columbia, the Yukon Territory, and Alaska, *Bull. Seismol. Soc. Am.* **68,** 1343–1370.

Storchak, D. A., D. Di Giacomo, I. Bondár, E. R. Engdahl, J. Harris, W. H. K. Lee, A. Villasenor, and P. Bormann (2013). Public release of the ISC-GEM Global Instrumental Earthquake Catalogue (1900–2009), *Seismol. Res. Lett.* **84,** no. 5, 810–815, doi: 10.1785/0220130034.

Stover, C. W., and J. L. Coffman (1993). Seismicity of the United States, 1568–1989 (Revised), *U.S. Geol. Surv. Profess. Pap. 1527*, Denver, Colorado.

Sykes, L. (1981). Written communication to Acres included as part of the review of Woodward-Clyde Consultants interim report on seismic studies, Final draft dated 23 February 1981.

Tape, C. (2016). Archival search for felt reports for the Alaska earthquake of August 27, 1904, ScholarWorks@UA at http://hdl.handle.net/11122/6589 (last accessed February 2017).

Tape, C., V. Silwal, C. Ji, L. Keyson, M. E. West, and N. Ruppert (2015). Transtensional tectonics of the Minto Flats fault zone and Nenana basin, central Alaska, *Bull. Seismol. Soc. Am.* **105,** no. 4, 2081–2100, doi: 10.1785/0120150055.
Tarantola, A. (2005). *Inverse Problem Theory and Methods for Model Parameter Estimation*, SIAM, Philadelphia, Peninsula.
The Valdez Miner (1935). Clipped from our Alaskan exchanges, The Valdez Miner, September 6, p. 2.
Thompson, H. J. (1935). Climatological data: Alaska section, U.S. Department of Agriculture, Weather Bureau, Vol. 21, 37–40.
Wald, D. J., V. Quitoriano, B. Worden, M. Hopper, and J. W. Dewey (2011). USGS "Did You Feel It?" Internet-based macroseismic intensity maps, *Ann. Geophys.* **54,** no. 6, 688–707, doi: 10.4401/ag-5354.
Wesson, R. L., O. S. Boyd, C. S. Mueller, C. G. Bufe, A. D. Frankel, and M. D. Petersen (2007). Revision of time-independent probabilistic seismic hazard maps for Alaska, *U.S. Geol. Surv. Open-File Rept. 2007-1043*.
Wickersham, J. A. (1904). James Wickersham Diary, July 31, 1904 to Feb. 20, 1905, MS1907–Diary 08–8/27/1904, *James Wickersham Papers Manuscript Collection*, Alaska State Library.
Wood, H. O., and F. Neumann (1931). Modified Mercalli intensity scale of 1931, *Bull. Seismol. Soc. Am.* **21,** no. 4, 277–283.
Woodward-Clyde Consultants (1982). *Final Report on Seismic Studies for Susitna Hydroelectric Project*, Acres American Incorporated, Buffalo, New York, 363 p.
Woollard, G. P. (1968). A catalogue of earthquakes in the United States prior to 1925 based on unpublished data compiled by Harry Fielding Reid and published sources prior to 1930, *Hawaii Institute of Geophysics Data Rept. No. 10*.
Yukon Valley News (1904). Rampart shaken by earthquake, Yukon Valley News, August 31, p. 3.
Zhou, H. (1994). Rapid three-dimensional hypocentral determination using a master station method, *J. Geophys. Res.* **99,** no. B8, 15,439–15,455.

Appendix A

Classification of Archival Records

Today, earthquake felt reports are efficiently collected from a "Did You Feel It?" questionnaire on the Internet (see Data and Resources; Wald *et al.*, 2011). Prior to the Internet, this information was collected by mail or phone. As early as at least 1937 in Alaska, there was a scientist who collected information about shaking intensity for major earthquakes (Bramhall, 1938). A scientist would ask people whether they felt a particular earthquake—a negative response would represent a not-felt report, such as those listed in Bramhall (1938) for the 1937 earthquake. In 1904, there was no such mechanism for gathering information. In this section, we adopt a different usage for not-felt report that is based on our assessment of the type of written record, as described next.

Our archival search is documented in Tape (2016). Here, we classify each written record into one of the following four categories:

- felt reports: written sources that reported the earthquake;
- not-felt reports: written sources that would be expected to report the earthquake, had the writer felt it;
- maybe-not-felt reports: written sources that might have reported the earthquake, had the writer felt it;
- null report: written sources that are unlikely to have reported the earthquake.

The first stage of the classification involves making an archival-based subjective judgment about the written source. We use the following four factors to assess the likelihood that a written source would mention the earthquake:

1. written entry is on 27 August 1904 or within a couple of days after;
2. written entries include day-to-day musings, such as local events or the weather, rather than business items;
3. written entries are lengthy; and
4. written entries mention earthquakes in other cases.

A felt report or not-felt report would be characterized by at least the first three factors. A null report would include the first factor only (or none). A maybe-not-felt report is in between. The second, and less important, stage of the classification is based on the likelihood of the written source to be within the felt region of the earthquake. For this we need to know the felt region (Fig. 6), which requires felt reports. Figure A1 presents a summary of the classification scheme. We provide some examples to illustrate these choices (for details, see Tape, 2016).

Not-felt reports include the newspapers in Nome, Dawson, Valdez, Juneau, and Skagway. The register for the seismograph station at Sitka noted felt earthquakes, such as the 28 June 1907 earthquake (Hazard, 1911), so we assume that the 1904 earthquake was not felt in Sitka. A diary entry on 27 August 1904 by Edgar O. Campbell from Teller, northwest of Nome, makes no mention of the earthquake. Isaac M. Preston, a prospector on Elliott Creek, northeast of Valdez, makes no mention of the 1904 earthquake, though he does mention feeling three earthquakes on the night of 30 August.

Maybe-not-felt reports come from house diaries at Jesuit missions at Akulurak, Holy Cross, and Nulato, as well as a Moravian mission at Bethel. U.S. Geological Survey (USGS) geologists at the southwest end of Becharof Lake (on the Alaska peninsula) and Gazzam Creek (near Rampart) make no mention of the earthquake. The diary entries of Orville Herning in Wasilla are lengthy but are mainly about his homestead and business, and there is no entry on 27 August 1904. Finally, the weekly one-page newspaper from Council (near Nome) does not mention the earthquake. For some of these cases, such as Nulato, it is difficult to envision how the earthquake could not have been felt, given the strong shaking in St. Michael (to the west) and in Fairbanks (to the east).

Null reports are from sources by other USGS geologists (whose field notebooks tend to be strictly geological mapping, with some mentions of the weather) and from volunteer weather observers, including those at Kenai and Tanana (Fort Gibbon). The observer in Fort Gibbon (Tanana) writes nothing at all in the Miscellaneous Phenomena column, neither about weather details nor earthquake occurrences. His location is between Rampart and St. Michael and would probably have felt the earthquake. Notes from the Fairbanks Council Meeting on 29 August 1904 list budget items, including repairs needed for the bridge, but there is no mention of the earthquake that occurred two days earlier.

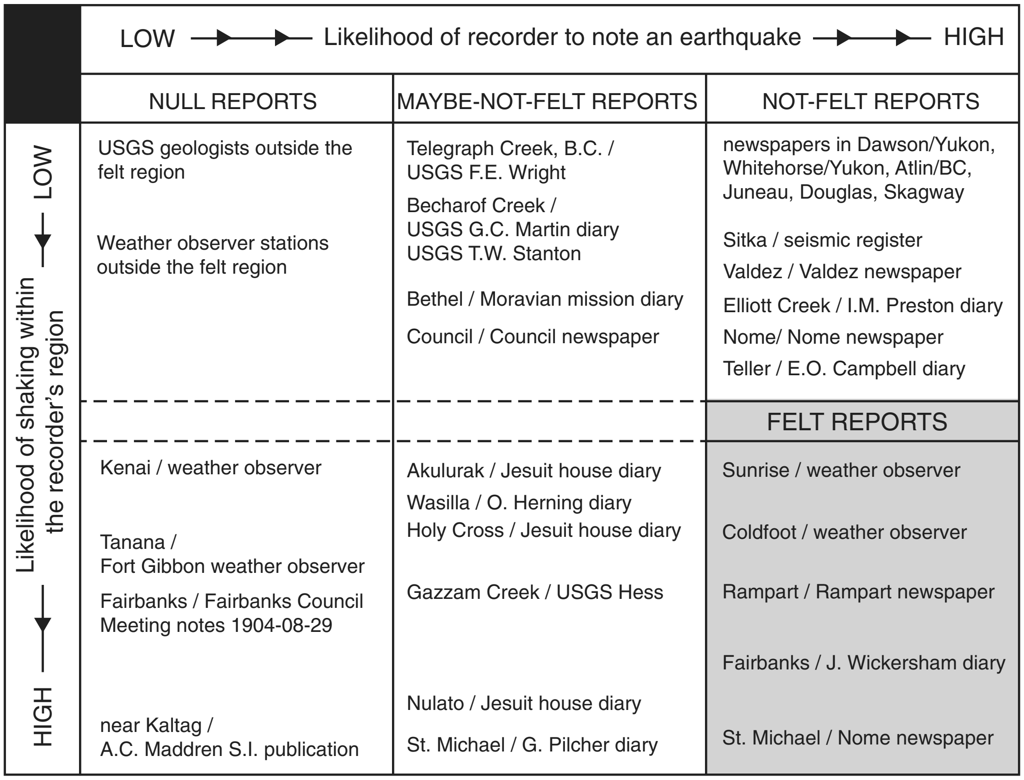

Figure A1. Classification of archival records from the time period of the 1904 Alaska earthquake. Each written record is classified as a felt report, not-felt report, maybe-not-felt report, and a null report. Two factors are used to classify the written records: (1) the likelihood of a recorder to note an earthquake; and (2) the proximity of the observer to the felt region. The archival search notes are in Tape (2016). The color version of this figure is available only in the electronic edition.

George Pilcher lived in Alaska and wrote in his diary almost every day from 1898 to 1933 (Tape, 2016). His diary places him in St. Michael on 27 August 1904, but the entire entry for this date is "very fine Day." On the basis of his daily writing, we classify this as a maybe-not-felt report. He has an entry on the day of the earthquake and his writing includes day-to-day activities (including the weather), but his entries are brief (especially near 27 August 1904), and we are not aware of any entries where he mentions earthquakes. But based on our knowledge of historical earthquakes, we could choose to categorize Pilcher's entry as a null report: someone who would either not be aware of earthquake shaking or not feel compelled to write about it. Pilcher spent most of his daily life outside and alone, so any report would need to be strong enough for him alone to feel it outside, consistent with modified Mercalli intensity (MMI) 5 shaking (felt "outdoors by many or most"). Pilcher appears to have been within the felt region for the 1904 earthquake, as well as for the 7 July 1912 Denali fault earthquake (Carver *et al.*, 2004). He has entries on both dates, but neither one mentions an earthquake.

Perspectives on 1904 Felt Reports

The five felt reports for the 1904 earthquake are important for estimating the epicentral region. Given the extent of shaking (Fig. 6) and the thousands of people within the felt region, it is hard to believe that there are only five felt reports. Probably there are more, but we have not found them after an extensive search (Tape, 2016). What we find is that there is very little information of any kind recorded within the felt region within days after the earthquake.

But perhaps we are fortunate to even have five reports. The report for St. Michael was the second wireless telegraph message ever received by the Nome newspaper. Had the earthquake occurred a few days earlier, we would not have the St. Michael felt report, and our interpretation could have been different. Federal Judge Wickersham was at the end of his judicial season on 27 August; on the 30th at midnight he boarded the steamship *Koyukuk* in Fairbanks and headed out on the Tanana River on the long trip to the States. Had the earthquake occurred a few days later, we would not have the Wickersham entry, which was critical for ruling out the (up-to-now) prevailing relocation of Boyd and Lerner-Lam (1988). We are lucky that two volunteer weather observers noted the earthquake, because this was supplemental to their duties. Furthermore, the entry in Coldfoot on 31 August 1904 was the last weather record from this site until 1 May 1908.

If shaking was significant across a broad region of Alaska, then one would hope that every log-like entry within the felt region would mention it (Fig. 6). This was not the

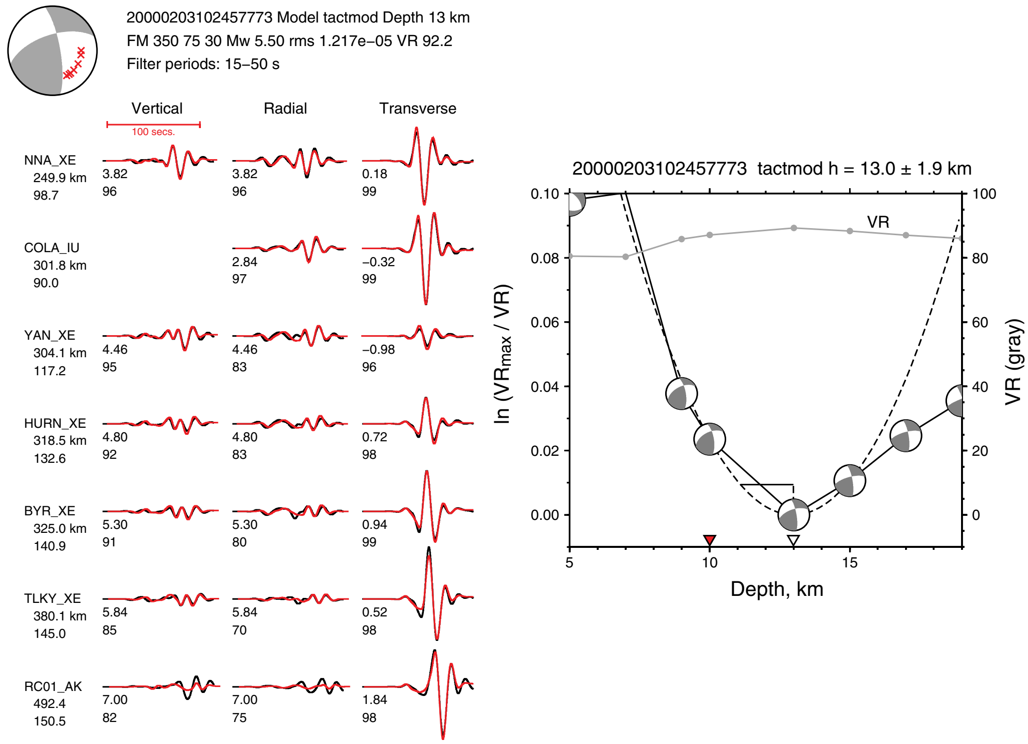

Figure B1. Moment tensor solution for the 3 February 2000 M_w 5.5 earthquake on the Kaltag fault. Regional broadband waveforms from the Broadband Experiment Across the Alaska Range (BEAAR) temporary deployment were used (Christensen *et al.*, 1999). See Silwal and Tape (2016) for a description of the moment tensor inversion method. (Left) Best-fitting double-couple moment tensor, along with waveform fits between observed seismogram and synthetic seismograms. The distance and azimuth for each station are listed below the station label. Two numbers are listed below each pair of waveforms: (1) the time shift (in seconds) applied to the synthetic seismogram to maximize the cross correlation, and (2) the cross-correlation value (in percentage) between the waveforms. See Table B1 for comparison with the Global CMT solution. (Right) Grid search over depth, which gives a best-fitting depth of 13 ± 2 km. The concave-down curve is the variance reduction (VR), which is a maximum for our best-fitting moment tensor. The concave-up curve shows the fractional deviation from our best-fitting solution as $\ln(\mathrm{VR}_{max}/\mathrm{VR})$. The triangles denote the catalog depth (10 km) and our depth (13 km). The color version of this figure is available only in the electronic edition.

case, as indicated from the maybe-not-felt reports discussed above. It is impossible to say whether these writers experienced the shaking or not. But what we do know is that life was not easy in 1904 in Alaska. Disease ravaged the native communities, the gold rush boomed and busted across communities on the Yukon and Tanana rivers, and the prospect of cold winters (and the next river shipment of supplies) weighed heavily. Perhaps the shaking from the 1904 earthquake did not stand out from daily events and challenges associated with survival in Alaska.

The St. Michael felt report (Fig. 3) from the western coast of Alaska is a critical one, as it puts strong shaking to the west of previous large earthquakes in central Alaska (Fig. 11 and Table 9). Lacking a second felt report from St. Michael, we considered the possibility that the telegraph received in Nome was relaying news from somewhere else, say, Fairbanks. There is one detail that refutes this possibility and points to St. Michael as the source of the report: the reported time of 10:55. This is corresponds to the time zone for western Alaska but not central Alaska. The instrumentally determined origin time from Gutenberg was 10:56, leaving no question that the St. Michael report was for the M_s 7.3 earthquake.

Appendix B

The 3 February 2000 Earthquake on the Kaltag Fault

There are few earthquakes on the Kaltag fault (Fig. 10). The largest earthquake on the fault within the past 40 years was an M_w 5.5 in 2000. The epicenter is 2 km from the digitized fault (Koehler *et al.*, 2012) and has an estimated uncertainty of 2.1 km listed in the Alaska Earthquake Center catalog. The Global Centroid Moment Tensor (CMT) catalog includes a moment tensor solution for this event (visible in Fig. 10b) that is consistent with right-lateral strike-slip motion on the Kaltag fault. This right-lateral sense-of-slip is consistent with geological observations (Patton and Hoare, 1968).

The Global CMT solution is derived from global seismic data, including one station in mainland Alaska (COLA, in Fairbanks) (Göran Ekström, e-comm., 2016). Given the importance of this earthquake to our study, we performed an additional moment tensor inversion using only regional waveforms at distances less than 500 km (Fig. B1). The mo-

Table B1

Source Parameters for the 3 February 2000 Kaltag Fault Earthquake from the Global Centroid Moment Tensor (CMT) Catalog (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012) and from This Study (Fig. B1)

	Global CMT		Figure B1	
Strike angle (°)	255	(347)	252	(350)
Dip angle (°)	57	(86)	61	(75)
Slip angle (°)	175	(33)	163	(30)
M_w	5.6		5.5	
Depth (km)	15		13	
Number of stations	146		7	

The angles in parentheses are for the assumed auxiliary plane.

ment tensor solution is consistent with the Global CMT solution; a comparison of the two sets of source parameters is listed in Table B1. The 3 February 2000 M_w 5.5 event is the largest known earthquake on the Kaltag fault.

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