1 **Resolving Northern Alaska Earthquake Sequences Using the**

2 **Transportable Array and Probabilistic Location Methods**

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24 ABSTRACT

25 Between 2014 and 2017, almost 200 new seismic stations were installed in Alaska and northwestern

26 Canada as part of the EarthScope USArray Transportable Array (TA). These stations currently provide

27 an unprecedented capability for the detection and location of seismic events in regions with

28 otherwise relatively sparse station coverage. Two interesting earthquake sequences in 2018/2019 in

29 the north eastern Brooks Range were exceptionally well recorded due to this deployment. First is the

30 aftershock sequence of the M_W 6.4 and M_W 6.0 Kaktovik earthquakes of 12 August 2018, the largest

31 earthquakes recorded to-date in the region. The second is the Niviak swarm, southwest of the

32 Kaktovik sequence. Since July 2018, over 4000 earthquakes between magnitudes 1 and 4.3 have

33 been recorded across a region exceeding 5000 square kilometers. We explore how the Bayesloc

34 probabilistic multiple seismic event location algorithm can better resolve features of these two

35 sequences, exploiting the large numbers of readings that the improved station coverage provides

36 from events down to magnitudes below 2. The Bayesloc calculations consistently move events in the

37 Kaktovik sequence a few kilometers to the northeast, providing an almost linear ESE-striking

38 southern limit to the aftershock zone. Analysis of the Bayesloc joint probability distribution of

39 corrections to travel time predictions indicate that anomalously fast wave propagation to the

40 southwest is likely the most significant contribution to the seismic event mislocation. The joint

41 relocations are more consistent with InSAR-inferred coseismic displacement than the network

42 location estimates. The Bayesloc relocation of the Niviak events confirms that the earthquakes are

43 distributed between many distinct clusters of seismicity which have clearer spatial separation

44 following the relocation. The probabilistic relocations motivate both double-difference studies to

45 better resolve clustered seismicity at the smallest spatial scales and systematic multiple event

46 relocation studies to calculate structure and travel time corrections over larger scales.

INTRODUCTION

47 Between 2004 and 2015, the EarthScope USArray Transportable Array (TA) of ~400 digital broadband

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49 seismometers was deployed from west to east across the "Lower 48" states, with stations remaining

50 in place for 1.5-2 years before being moved to a new location to the east. Deployment in Alaska and

51 northwest Canada began in 2014 after initial test installs, and the full network was operational by the

52 end of the 2017 field season. A comprehensive review of the deployment is provided by Busby and

53 Aderhold (2020). Whereas the permanent networks are concentrated in the most seismically active

54 regions of Alaska, the TA provides a remarkably uniform coverage of the remaining territory. Ruppert

55 and West (2020) discuss the lowering of the seismic detection thresholds that the additional stations

56 provide and draw attention to two extensive seismic sequences in the relatively aseismic regions,

57 which could only be characterized to the degree they are because of the TA presence. The first is the

58 aftershock sequence of the 12 August 2018 M_W 6.4 Kaktovik earthquake, the second is the 2018-

59 2019 Eastern Brooks Range sequence (Figure 1).

60 Seismicity in northeastern Alaska is distributed over a ~200-km-wide, ~500 km-long zone that trends

61 southwest to northeast. The northern limit of this zone extends into the Beaufort Sea, while its

62 southern end is truncated by the Tintina Fault, a major right-lateral strike slip fault that extends

63 eastward into Canada. Earthquakes have been recorded in this region since regional monitoring

64 began in the early 1970s (Gedney et al., 1977; Estabrook et al., 1988). Although the seismic record

65 until recently has been poor, moderate-sized earthquakes have been recorded in the region for

66 decades, albeit with highly variable accuracy. There has been one magnitude 5 or greater earthquake

67 every few years on average. The earthquakes have occurred throughout the entire region, generally

68 do not follow well-defined linear trends, and sometimes present swarm-like behavior for months to

69 years before returning to its previous state.

70 There are no mapped active faults between the Tintina fault to the south and the offshore faults in

71 the Beaufort Sea to the north (Koehler et al., 2012). Given the extensive seismicity in the area,

72   however, this apparent lack of active faults may be attributed to limited geologic field mapping,

73   which is due in large part to the remoteness of the area and the challenges this presents for

74   undertaking geologic mapping studies. Crustal seismicity of northeastern Alaska has long been

75   recognized as an earthquake hazard; it has been attributed to far-field deformation from the

76   subduction of the Pacific plate compounded by collision of the Yakutat block by a variety of studies

77   (e.g., Mazzotti and Hyndman, 2002; Leonard et al., 2008; Mazzotti et al., 2008).

78   Gaudreau et al. (2019) provide a thorough study of the August 2018 earthquake and aftershock

79   sequence both with seismological and InSAR data. They find that seismological location estimates of

80   the mainshock and numerous aftershocks are a few kilometers to the south of the InSAR-inferred

81   fault plane and discuss hypotheses for the discrepancy. These include the possibility of instrumental

82   timing errors, which could be significant given the unfavorable azimuthal station coverage. They

83   conclude that heterogeneous velocity structure in the crust is a more likely explanation. In this study

84   we try to resolve the issue by applying the Bayesloc probabilistic multiple-event location algorithm

85   (Myers et al., 2007) which has been shown to provide improved locations for clustered seismicity,

86   partly by mitigating the influence of velocity heterogeneity. This procedure provides both

87   probabilistic hypocenter and origin time estimates for the earthquakes and estimates of bias and

88   uncertainty in travel time predictions. We present Bayesloc relocations of earthquakes in both

89   sequences and provide justification as to why we can have confidence in the results.

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AFTERSHOCKS OF THE 12 AUGUST 2018, M_w 6.4 KAKTOVIK EARTHQUAKE

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93   Figure 2a) displays locations of events in the Alaska Earthquake Center (AEC) catalog likely to be

94   associated with the 12 August 2018 Kaktovik earthquake sequence, based on location and time.

95   Earthquakes in this catalog are located by automatic detection algorithms and later reviewed event-

96   by-event by human analysts who correct erroneous auto-picks and add more phase picks that the

97   auto-detectors may have missed. We apply Bayesloc, which locates multiple events simultaneously in

98   a probabilistic framework, to see if structure can be identified in the aftershock distribution not

99   found in the network locations. The motivation is that Bayesloc seeks a joint probability distribution

100 of all event hypocenters, origin times, arrival time uncertainty, and corrections to travel time

101 predictions, and may be able to compensate for geologic heterogeneity and consequent deficiencies

102 in the underlying velocity model used. In contrast, the network solutions are forced to assume zero-

103 mean Gaussian distributions for all uncertainties and are therefore unable to identify bias in any

104 parameters common to multiple events. Gibbons and Kværna (2017) applied Bayesloc to the

105 aftershocks of the October 2005 Kashmir earthquake and found far more structured event clusters

106 than could be resolved in the single-event network solutions. In that case study, the primary cause of

107 mislocation in the network solutions was deemed likely to be anomalous travel times to stations at

108 regional distances. The probabilistic estimates for travel time corrections transformed the clouds of

109 aftershocks to align convincingly with the strike of the surface rupture. Bayesloc was applied by

110 Hayes et al. (2015) for accurate relocations of aftershocks from the Mw 7.8 April 2015 Gorkha

111 earthquake, Nepal, by Nealy et al. (2017) to constrain the 2008 Wells, Nevada, sequence, and by Pyle

112 et al. (2015) to provide accurate event locations for seismicity in Rock Valley, Nevada.

113 Whereas the relocation of the Kashmir aftershocks involved a significant repicking of arrivals from

114 raw waveform data, it is important to note here that all Bayesloc solutions presented use exactly the

115 same set of arrivals as the AEC network location estimates. A 1D velocity model was prescribed

116 based upon profiles presented in Fuis et al. (1997) and travel time tables were calculated for Pg, Pn,

117 Pb, Sg, Sn, Sb phases (see Storchak et al., 2003) for distances up to around 15 degrees, as applicable,

118   for input to the Bayesloc program. Additional travel time tables containing the travel time for the

119   first arriving P and first arriving S phase were also calculated and labelled P1 and S1. Following the

120   practice of Gibbons et al. (2017), relocating seismicity along the North Atlantic spreading ridge, we

121   performed a parallel calculation using a different basis velocity model (in this case AK135, Kennett et

122   al., 1995) to confirm that the final joint probability distribution of event hypocenters was largely

123   stable to small changes in the underlying 1D velocity model. As seen in Figure 1, there are stations

124   ranging from a few tens of kilometers to many hundreds of kilometers and so the identification of

125   the first arriving phase will change with distance. There may be uncertainty regarding the

126   identification of the first arriving phase in some regions. All first P and S arrivals from the AEC bulletin

127   were initially labelled P1 and S1 and we exploit the Bayesloc probabilistic identification of phase

128   labels (Myers et al., 2009) to attribute the most likely label to each arrival given the most probable

129   location.

130   Figure 2b) shows the distribution of mean event hypocenters from a run of Bayesloc with no priors

131   on the event locations and a total of 40000 iterations. The diffuse southern boundary of the network

132   solutions becomes a sharper edge with an ESE strike direction, a few kilometers north of the

133   southernmost epicenters from the AEC catalog. The contrast between the two sets of event locations

134   is more easily seen in Figure 2c) in which the relocations are plotted on top of the catalog location

135   estimates. The northern boundary of the aftershock cloud remains diffuse and largely unchanged in

136   the relocations. We display the surface projections of the InSAR-modelled western and eastern fault

137   segments from Gaudreau et al. (2019) in each of panels a), b) and c). In panel a), the network

138   location estimates almost all lie to the south of these two lines. In panel b), the southern extent of

139   the relocated events is approximately parallel to the western fault and the northern extent of the

140   relocated events is approximately parallel to the eastern fault. In Figure 2d) we illustrate how the

141   events in different regions of the aftershock zone are moved. Essentially all events are shifted in a

142   northeasterly direction. Events in the western part of the aftershock zone may be relocated more in

143   a northerly direction, and events in the eastern part of the aftershock zone in a more easterly

144   direction, although the pattern is quite consistent. The relocations obtained using the AK135 model

145   as a basis are essentially identical to those displayed in Figure 2.

146   In Figure 3 we display both the distance and direction of each relocation. The majority of the larger

147   events are relocated to the northeast by between 2 and 10 km. Events which are relocated in a

148   significantly different direction are low magnitude events and may be subject to far poorer location

149   constraints to begin with due to fewer phase-arrival readings and poorer azimuthal coverage. Figure

150   3 demonstrates that, whereas the overall change of shape of the aftershock cloud is significant, the

151   relocations of the individual events are modest. Given the station geometry, the relocated epicenters

152   lie well within the formal uncertainty ellipses of the AEC catalog locations. The elliptical distribution

153   of the relocation vector end-points provides an indication of consistency between the two sets of

154   location estimates. Whereas an identical set of phase arrival times is used to construct both sets of

155   origin estimates, the two location procedures are entirely independent; no information about the

156   catalog event locations is used as prior information for the Bayesloc calculation.

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VALIDATING AND INTERPRETING PROBABILISTIC EARTHQUAKE RELOCATIONS

163 The underlying algorithm in Bayesloc is iterative. It is instructive to examine the progress of the

165 solution from start to end understand why the resulting pattern of hypocenter estimates may

166 provide a higher confidence image of the seismicity. The latitude, longitude, depth, and origin times

167 of the events, the uncertainties associated with the arrival time estimates, and corrections to the

168 travel time estimates for each of the arrivals form a large parameter space for a given input. The

169 Monte Carlo Markov Chains in the Bayesloc algorithm explore this parameter space to try to

170 converge to a solution which best supports the full set of observations. The process starts with no

171 knowledge of the true parameters (unless prior information is available and provided) and probes

172 stochastically through different alternatives, identifying favorable choices.

173 In Figure 4a) we see as plain white symbols the final mean epicenters of all the events. Superimposed

174 onto this image are the location estimates at each iteration for a single selected event, displayed as

175 small colored dots to indicate the iteration number. (Only the first 10000 iterations are displayed

176 since changes in the epicenter estimates do not change significantly beyond that number.) Blue dots

177 in Figure 4a) indicate trial epicenters for this event in the earlier iterations and red dots indicate trial

178 epicenters towards the end. The most important features in the model parameter space in the

179 presence of geologic or velocity structure heterogeneity are the corrections to travel time

180 predictions. Gibbons et al. (2017) demonstrated very large travel time residuals for individual

181 regional station-phase combinations that were consistent from event-to-event over wide

182 geographical regions: biases far larger than the uncertainty in the arrival time estimates themselves.

183 This is why we plot (in Figure 4b) the observed minus predicted travel time residual of a given phase

184 arrival at a given station for every hypocenter and origin time estimate for this event as a function of

185 the iteration number. The convergence (or otherwise) of this parameter, and the corresponding

186 parameters for other phase/station combinations, provides an indicator as to whether the process

187 has converged on a solution. This offers an insight into how the event locations might relate to local

188 velocity structure.

189   The station and phase combination displayed in Figure 4b) is the first P-arrival at station D25K, the

190   closest station southwest of the aftershock zone. Before describing the evolution of this time residual

191   with iteration number, it is worth taking the time to consider what values of this parameter would

192   imply about the velocity structure between the aftershock zone and this station. How would the

193   values be affected by an analyst reading error, or a clock error? If we assume that the analyst placed

194   the arrival time estimate very accurately, and that the instrumental time-stamp is correct, then a

195   zero value of the observed minus predicted travel time residual means that our baseline 1D velocity

196   model provides an accurate representation of the geologic structure along these paths. A negative

197   value of this residual would mean that the picked arrival time is before the predicted arrival time,

198   and therefore that the seismic waves travel faster along the path than the model predicts. Similarly, a

199   positive value would imply slower rock than the model predicts. If the analyst placed the arrival time

200   estimate too late on the seismogram, this would move the curve up uniformly; this offset would be

201   constant for all hypocenter and origin time estimates. A too-early arrival time estimate would move

202   the curve down uniformly. We have a corresponding curve for every event in our dataset for which a

203   first P-arrival at station D25K has been picked: potentially several thousand such curves. The travel

204   time prediction correction for this phase and station combination, as part of the final joint probability

205   distribution, would consider all the curves generated. A timing error on the station would lift the P-

206   and S- time residuals for the station up or down by the same amount. It is important to note that the

207   earthquakes relocated in these two sequences occurred over time-intervals of many months (see

208   Ruppert and West, 2020, for details). A timing error typically covers a limited time-span, or is very

209   variable with time, and would likely be detected.

210   At the very start of the Bayesloc run, the time-residual in Figure 4b) takes on extreme values (often

211   greatly exceeding the actual travel time from the true event location to the station) as the trial

212   hypocenters and origin times for the event lie far from the true values. Few iterations pass before

213   epicenter estimates begin to stabilize in the region of the map where the blue dots in Figure 4a) are

214   observed. The time-residuals in Figure 4b) oscillate around a mean value of around

215   -0.8 seconds. At iteration 1000, corrections to model-based travel time predictions are activated

216   within Bayesloc. At this point, a rapid change in the evolution of this travel time-residual is observed,

217   decreasing to around -2 seconds. The corresponding trial hypocenters move northeast. A more

218   negative observed minus predicted time-residual means that the seismic wavefront is travelling

219   further than the basis model expects in a given time, and the event hypocenter moves further away

220   from the station to accommodate this. The time-residuals for stations in other locations will evolve in

221   different ways. Over the next 9000 iterations, the D25K-P time-residual continues to decrease but

222   flattens off to a value of around -2.8 seconds. Note that the spread of time-residual estimates for

223   different trial hypocenters and origin times does not appear to decrease further. Similarly, the cloud

224   of trial hypocenters for the later iterations (the red dots in Figure 4a) cover an elliptical region about

225   4 by 7 km, elongated in a direction with a NNE strike. The size of this ellipse, together with the spread

226   in the time-residuals, provide a visual uncertainty estimate for the event displayed.

227   Figure 4b) displays the time-residual for the one event for every single trial hypocenter and origin

228   time. The most typically used parameters from Bayesloc output are the mean values for latitude,

229   longitude, depth, and origin time (once the so-called burn-in phase, in which the location estimates

230   may be qualitatively different to the end solutions, is removed). In Figure 5, we instead evaluate the

231   time-residual for mean hypocenter and origin time for each event for the six station-phase

232   combinations indicated. This plot indicates both the internal consistency within the aftershock zone

233   of the travel time residual for a given phase, and how the values vary from station to station. We see

234   in Figure 5e) that the large negative time residual we converge towards in Figure 4b) is typical for

235   almost all events in the cluster and would confirm the hypothesis of fast crust to the southwest of

236   the aftershock zone. The consistency of this residual term over the full population of events, covering

237   many months, essentially eliminates the hypothesis of a timing error on the station. The variability of

238   S-wave travel time residuals is generally somewhat higher than for P-wave travel time residuals. This

239   is likely related to the increased difficulty in picking the arrival time for the secondary phases.

240   The output from Bayesloc provides uncertainty statistics for the hypocenter distributions both

241   laterally and in depth. The median over Kaktovik events of the standard deviation for location in the

242   East-West direction was 4.2 km, while the median standard deviation in the North-South direction

243   was 6.2 km. This is consistent with the distribution of trial hypocenters displayed for the event in

244   Figure 4 and is a function of the network geometry. The median standard deviation in the depth was

245   3.8 km and the median standard deviation in the origin time was 0.65 seconds. The travel time from

246   hypocenter to station has a trade-off with depth and the travel time residuals, as displayed in Figure

247   5, are relatively insensitive to depth.

248   We focus here on the three closest stations to the aftershock zone to give maximum insight into the

249   northeasterly shift of the hypocenters. The Bayesloc solutions include all arrivals used in the AEC

250   catalog and therefore many hundreds of stations at far larger distances; the time-residuals further

251   from the source will be discussed later. The parallel calculation using a different baseline 1D velocity

252   model is a valuable check on robustness of the hypocenters. We increase the confidence in the

253   spatial distribution of hypocenters obtained if essentially the same distribution is obtained using a

254   somewhat different set of travel time tables; if the solution is robust, the solutions obtained from the

255   different baseline models should differ primarily only in the correction terms to travel time

256   predictions. We note also that only stations within regional distances are used in the AEC bulletin.

257   Given the magnitude distribution of the Kaktovik events (Ruppert and West, 2020) there are many

258   aftershocks that will be well recorded with good global coverage at teleseismic distances. Teleseismic

259   travel times are less susceptible to crustal heterogeneity (e.g. Myers et al., 2015) and augmenting the

260   bulletin with high quality teleseismic phases, with a wide azimuthal distribution, for the largest

261   events may provide additional constraints and reduce the sensitivity of the hypocenters to local

262   geologic heterogeneity.

263

264 THE 2018/2019 EASTERN BROOKS RANGE EARTHQUAKE SWARM

265 To the southwest of the aftershock zone considered in the previous sections is a distinct earthquake

266 swarm, referred to by Gaudreau et al. (2019) as the Niviak cluster. Ruppert and West (2020) describe

267 the temporal and magnitude distributions of both sequences; the Niviak cluster consists only of

268 events below magnitude 4.5 but is more enigmatic given the spatial distribution, the long duration,

269 and the absence of a causative mainshock. The swarm intensified in July 2018 (shortly prior to the

270 large Kaktovik earthquakes and their aftershocks), reached a peak in October 2018, before

271 decreasing over the fall of 2018. A new intensification of seismicity started in July/August 2019.

272 Figure 6a) displays the locations of the events throughout 2018 and 2019 from the AEC bulletin. We

273 have better azimuthal coverage for recording this swarm than for the Kaktovik earthquakes, with

274 multiple stations observing the sequence in all directions. This is especially true to the north where

275 the Kaktovik sequence relied on a single station, C26K. Bayesloc was run using the same arrivals as

276 were used to compile the AEC catalog; the results are displayed in Figure 6b). The large-scale

277 features are unchanged although many features can be identified which appear better resolved or

278 more cleanly separated in the multiple event location estimates. The most south easterly cluster at

279 68.55°N, -145.5°E becomes significantly more compact in the relocations. A double cluster in the AEC

280 network solutions at 68.8°N, -148.2°E resolves into two distinct clusters elongated in the direction of

281 the topographic features. The cluster at 69.2°N, -147.5°E migrates a few kilometers to the northwest

282 and appears to split into two; the change is easier to identify in Figure 6c) where the relocated event

283 positions are superimposed on top of the network solutions. The spatial separation between each of

284 the clusters in the northeast is a little more pronounced in the relocations than in the AEC catalog.

285 Given the fine structures and complex cluster patterns visible in the relocations, there is motivation

286 to perform full-waveform cluster analysis using cross-correlation or other signal semblance analysis.

287 A given arrival measurement can contribute to a location error in two ways: error in travel time

288 prediction and error in the arrival time measurement. Bayesloc mitigates the first of these in a way

289   that event-by-event network solutions cannot, although we are still only using analyst arrival picks in

290   this study and are still vulnerable to the uncertainty in the human-estimated arrival times. Using

291   relative time-delay measurements and double-difference location methods (e.g. Shearer, 1997;

292   Waldhauser and Ellsworth, 2000) may reveal geometrical structure at finer spatial scales not

293   resolvable using only absolute arrival time estimates; such a study is however beyond the scope of

294   this paper. Given that the maximum event magnitude is below 4.5, we are unlikely to be able to

295   exploit teleseismic data to improve location accuracy.

296

297   **DISCUSSION AND FUTURE PERSPECTIVES**

298   We have applied the probabilistic multiple event location algorithm Bayesloc to two seismic

299   sequences in northern Alaska for which most of the phase arrivals were provided by stations of the

300   EarthScope USArray Transportable Array. In the first, aftershocks of the 12 August 2018 Kaktovik

301   earthquakes, Bayesloc made a small but significant relocation of the entire cluster. The relocated

302   event cluster has a far sharper southernmost boundary with a strike angle consistent with non-

303   seismological constraints on the fault plane. In the second, the Niviak cluster, the probabilistic event

304   locations are significantly more clustered and indicate clearer separation between localized zones of

305   seismicity. Without the TA stations, we would not have the detection threshold or the station

306   coverage to be able to resolve these sequences.

307   Full-waveform cluster analysis, using correlation methods to measure both signal similarity and

308   enhanced time-delay estimates, is likely to provide improved local scale resolution of the seismicity

309   in both sequences. The feature of Bayesloc which appears to be most powerful in these cases is the

310   ability to solve for corrections to travel time predictions for given paths. The exploitation of readings

311   from multiple events to account for, or to eliminate, bias in travel time estimates is a cornerstone of

312   many advanced seismic event location algorithms (e.g. Douglas, 1967; Richards-Dinger and Shearer,

313   2000; Nooshiri et al., 2017). The solutions obtained using Bayesloc indicate that failure to account for

314   anomalously fast propagation to the southwest of the Kaktovik aftershock is the primary reason that

315   the network locations in many cases lie to the south of the InSAR-inferred fault line.

316   In Figure 5 we display spatially consistent time-residuals for P- and S- phases at the three stations

317   closest to the Kaktovik aftershocks. In Figure 7, instead of a single travel time residual per event for a

318   given phase, we display the median travel-time residual for all events in the Kaktovik sequence for P-

319   and S- arrivals at each station. The blue symbols to the southwest of the earthquakes (the yellow

320   square) are of similar colors to the symbols in panels e) and f) of Figure 5 and indicate the faster

321   propagation along these paths. It should be noted that the geological heterogeneity over this short

322   path is not necessarily more extreme than elsewhere in Alaska. The waves arriving at more distant

323   stations from the Kaktovik earthquakes have travelled longer paths over which the contribution to

324   the travel time from regions with anomalously fast propagation will cancel with the contributions

325   from regions with anomalously slow propagation.

326   The travel time residuals displayed in Figure 7 are relative to one specific 1-dimensional velocity

327   model. However, the location calculations were repeated using alternative velocity models and we

328   confirm that the large-scale features of the relocated clusters of seismicity are largely unchanged.

329   The travel time residual plots for AK135 (corresponding to Figures 5 and 7) look somewhat different

330   as different corrections are required to compensate for the deficiencies of the baseline model along

331   the different paths. Relative insensitivity to the details of the underlying 1-D model was also

332   demonstrated by Gibbons et al. (2017). Another feature of Figure 7 that increases our confidence

333   that the residuals are related to 3-dimensional geologic properties and not a simple inapplicability of

334   the underlying 1D model is the distribution of high positive P-wave time-residuals for stations to the

335   south of the map. The size of the residuals does not increase simply with distance from the source;

336   the highest residuals are found to the South of the Chugach Mountains and indicate slow

337   propagation along these specific paths.

338   Repeating the procedure applied here to clusters of seismicity across Alaska would generate

339   corresponding maps which could be used to validate existing 3-dimensional tomographic images and

340   provide input for large scale evaluations of 3-d velocity maps. Similar studies have been performed

341   both globally and regionally (e.g. Myers et al., 2011, and Simmons et al., 2012) and applying such a

342   procedure to Alaska now would benefit from the recently improved station coverage. There is no

343   limit, in principle, as to how large the datasets for the Bayesloc program can be. In practice, the

344   computational cost of calculating the joint probability distributions increases greatly with the number

345   of events and phases; the 40000-iteration calculation for the Kaktovik aftershock sequence with 4192

346   events and 109905 phases took approximately 11.5 hours on a high-end Linux workstation. Simply

347   covering all historical seismicity over all of Alaska and adding new events with all readings as they

348   occur is not a viable strategy for near real-time event location with current technology. Bayesloc,

349   however, can take prior information regarding both uncertainty in event hypocenters and origin

350   times and travel time predictions; results from previous runs can be used to constrain subsequent

351   runs without needing to include all the raw inputs. Whereas only a subset of Alaska TA stations will

352   be transitioned into longer-term operation, the contribution of any of the TA stations that are

353   removed will always be valuable in the framework of probabilistic multiple event location algorithms.

ACKNOWLEDGEMENTS

DATA AND RESOURCES

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371 Earthquake relocations were performed using the Bayesloc program, available for download from

372 https://www-gs.llnl.gov/nuclear-threat-reduction/nuclear-explosion-monitoring/bayesloc

373 (last accessed June 6, 2020).

374 The website of the EarthScope USArray is www.usarray.org (last accessed June 6, 2020)

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Figure Captions

466

467 **Figure 1 Subset of the earthquake catalog from the Alaska Earthquake Center (2017-2019)**

468 **including the aftershocks of the 12 August 2018 Kaktovik sequence and the 2018 Eastern Brooks**

469 **Range swarm together with the closest available stations. BMAR is the Burnt Mountain seismic**

470 **array, consisting of 5 short-period vertical component seismometers within an aperture of**

471 **approximately 5 km. The M_w 6.0 and M_w 6.4 earthquakes on 12 August 2018 are marked with five**

472 **and six-sided polygons respectively.**

473

474 **Figure 2 All events in the catalog of the Alaska Earthquake Center for the region displayed in the**

475 **time period 2018-2019 (a) as reported in the AEC catalog, (b) as relocated by Bayesloc using only**

476 **the arrival picks from the AEC catalog, and (c) with the relocated hypocenters plotted over the**

477 **catalog hypocenters with the same color scales. The symbols in (d) are drawn at the locations of**

478 **the relocated hypocenters with a color indicating the direction from the relocated epicenter to the**

479 **catalog epicenter. The blue colors indicate that the catalog locations for almost all events lie to the**

480 **southwest of the relocated events. The M_w 6.0 and M_w 6.4 earthquakes on 12 August 2018 are**

481 **marked with five and six-sided polygons respectively. In panel c) the catalog location of the M_w 6.0**

482 **earthquake is marked with a black pentagon outline. The white lines in panels a), b) and c) indicate**

483 **the surface projections of the InSAR-modelled buried fault segments from Gaudreau et al. (2019).**

484

485 **Figure 3 Relocation vectors for all events displayed in Figure 2. We define the catalog location of**

486 **each event to be at the origin and plot the relocated hypocenter relative to the catalog**

487 **hypocenter. Size of the symbol is proportional to the event magnitude. The M_w 6.0 and M_w 6.4**

488 **earthquakes on 12 August 2018 are marked with five and six-sided polygons respectively.**

489

490   **Figure 4 Evolution of the location estimate for a single earthquake in the sequence as a function of**

491   **iteration number in the Monte Carlo Markov Chains of the Bayesloc program. The white symbols in**

492   **panel (a) display the mean epicenters for all events in the sequence and the small colored symbols**

493   **indicate the epicenter location for event 6155 colored according to the iteration. Panel (b) displays**

494   **the observed minus predicted travel time residual with respect to the 1D velocity model for the**

495   **first P-arrival at station D25K. The M_w 6.0 and M_w 6.4 earthquakes on 12 August 2018 are marked**

496   **with five and six-sided polygons respectively.**

497

498   **Figure 5 Observed minus predicted travel time residuals for relocated events in the Kaktovik**

499   **sequence for C26K P-phase (a), C26K S (b), C27K P (c), C27K S (d), D25K P (e), and D25K S (f) relative**

500   **to the 1D velocity model used to locate the events. The M_w 6.0 and M_w 6.4 earthquakes on 12**

501   **August 2018 are marked with five and six-sided polygons respectively.**

502

503   **Figure 6 Locations of earthquakes in the Eastern Brooks Range swarm (a) from the catalog of the**

504   **Alaska Earthquake Center, (b) from the Bayesloc relocations, and (c) with the two sets of**

505   **hypocenters superimposed with the same color code.**

506

507   **Figure 7 Median observed minus predicted travel time residuals for first P (a) and first S (b) arrivals**

508   **from events in the Kaktovik aftershock sequence given the hypocenters and origin times from the**

509   **Bayesloc relocation. Blue symbols indicate an earlier than predicted arrival and red symbols**

510   **indicate a later than predicted arrival. The yellow square indicates the location of the largest**

511   **earthquake on 12 August 2018. A symbol indicates that the phase and station combination**

512   **appeared in the catalog of the Alaska Earthquake Center for at least 25 events in the sequence.**

513

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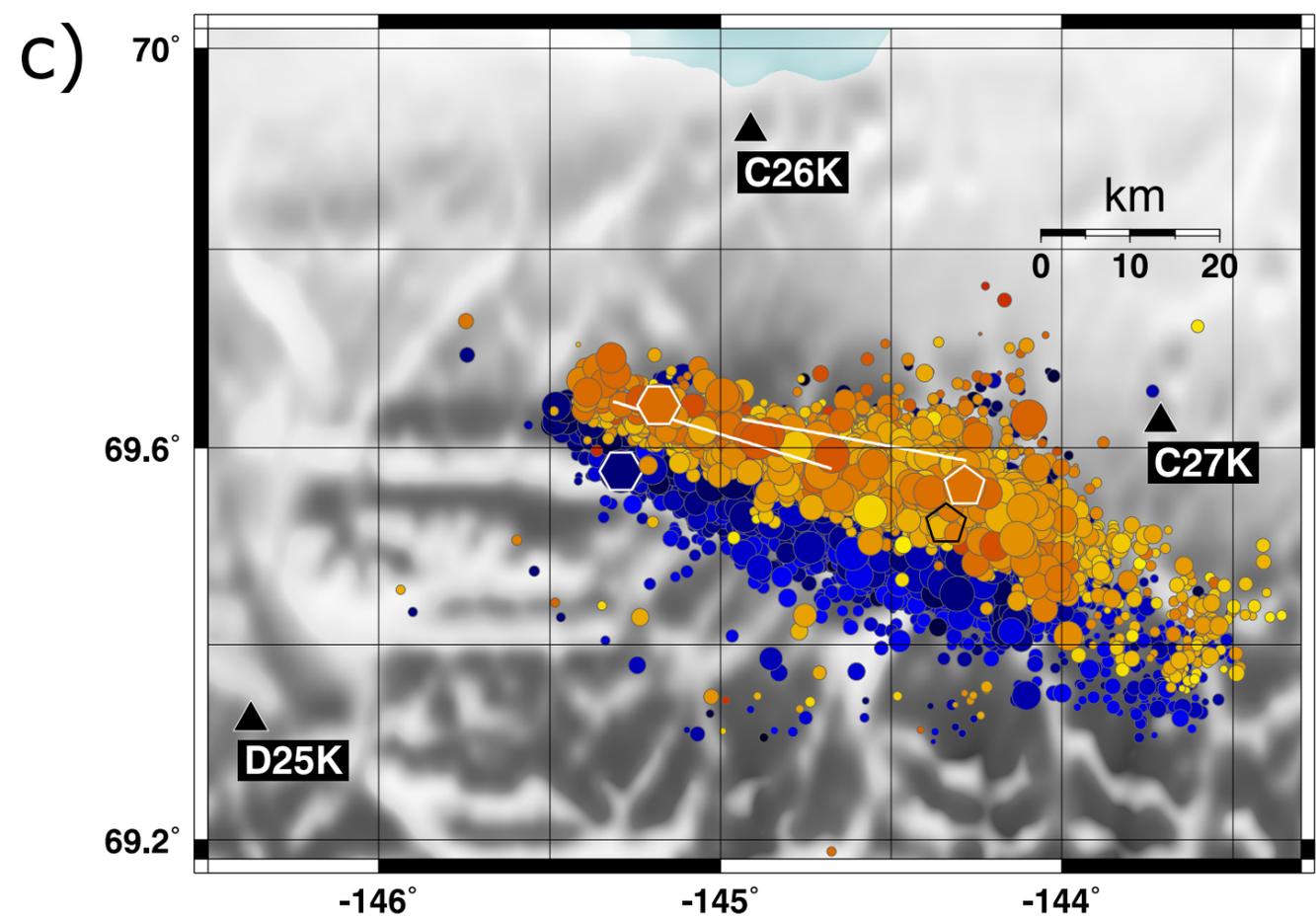517   2156 Koyukuk Drive, Fairbanks, Alaska 99775 U.S.A.

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Figure 1
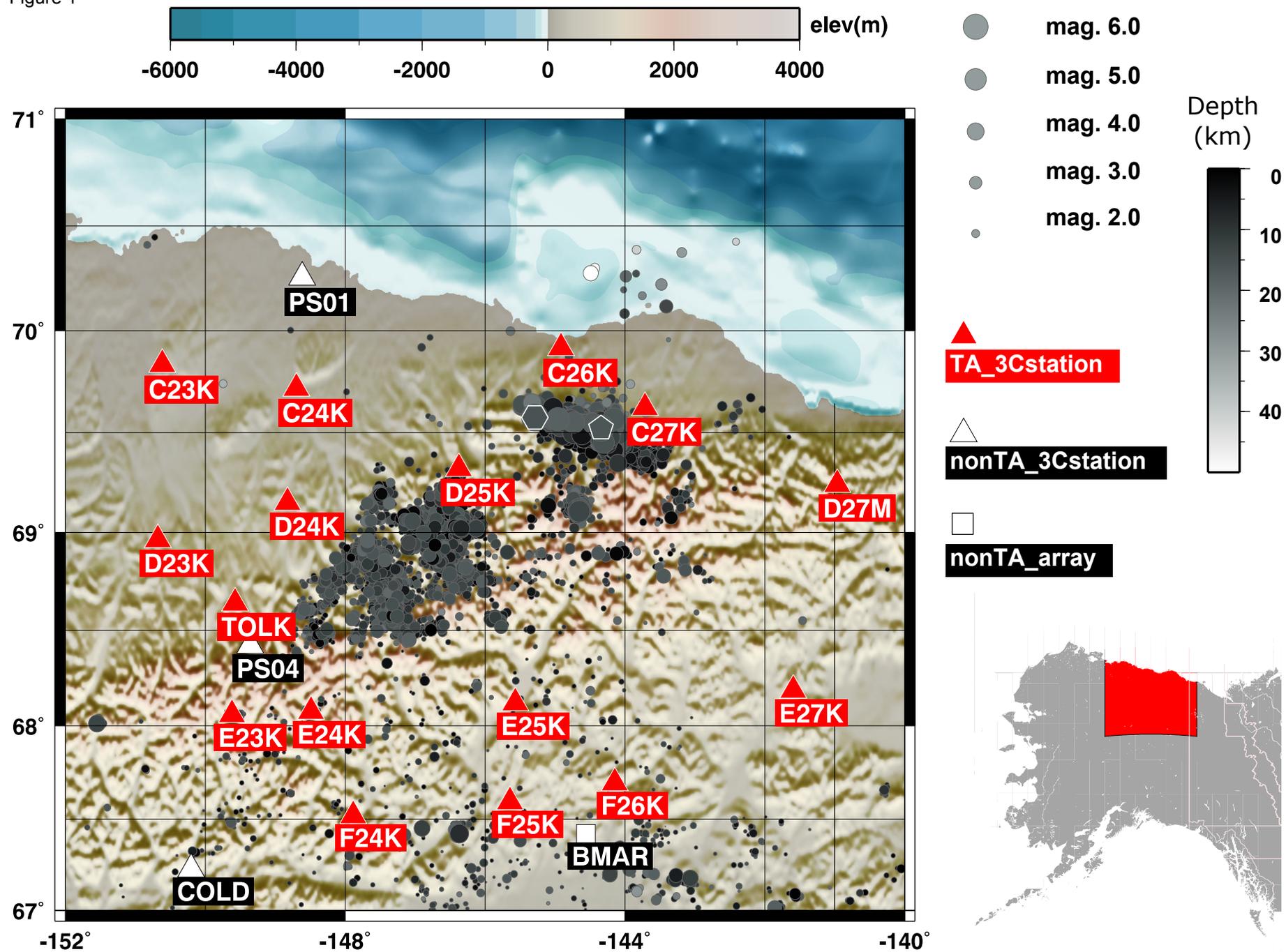
Figure 2

Figure 3

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