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1 **The variety of subaerial active salt deformations in the Kuqa fold-thrust belt**
2 **(China) constrained by InSAR**

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26 **ABSTRACT**

27 **Surface salt bodies in the western Kuqa fold-thrust belt of northwestern**
28 **China allow study of subaerial salt kinematics and its possible correlations with**
29 **weather variations. Ephemeral subaerial salt exposure during the evolution of a salt**
30 **structure can greatly impact the subsequent development and deformation of its**
31 **tectonic setting. Here, we present a quantitative time-lapse survey of surface salt**
32 **deformation measured from interferometric synthetic aperture radar (InSAR) using**
33 **Envisat radar imagery acquired between 2003 and 2010. Time series analysis and**
34 **inspection of individual interferograms confirm that the majority of the salt bodies**
35 **in western Kuqa are active, with significant InSAR observable displacements at 3 of**
36 **4 structures studied in the region. Subaerial salt motion toward and away from the**
37 **satellite at rates up to 5 mm/yr with respect to local references. Rainfall**
38 **measurements from the Tropical Rainfall Measuring Mission (TRMM) and**
39 **temperature from a local weather station are used to test the relationship between**
40 **seasonality and surface salt motion. We observe decoupling between surface salt**
41 **motion and seasonality and interpret these observations to indicate that regional**
42 **and local structural regimes exert primary control on surface salt displacement**
43 **rates.**

44

45 **Key words:** Kuqa fold-thrust belt, salt deformation, namakiers, InSAR

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49 **1. INTRODUCTION**

50 Analysis of subaerial salt behavior is limited because allochthonous salt outcrops
51 are rarely preserved on the Earth's surface, making subsurface imaging the primary
52 technique for observing salt deposits (Talbot and Pohjola, 2009). Few examples of salt
53 bodies outcrop at the surface today (Zagros, Iran; Salt Range, Pakistan), not including
54 submarine salt exposures. Interpretations of many subsurface salt bodies throughout the
55 world have indicate subaerial exposure during structural evolution (e.g., Canerot et al.,
56 2005). This subaerial exposure may be short-lived and yet have key impacts on the long-
57 term evolution because salt bodies interacting with surface processes may display sharply
58 distinct kinematics versus subsurface salt bodies. As a result, it is important for the
59 overall exploration of crustal salt to study the few available subaerial salt bodies. Many
60 structural systems dominated by salt deformation are commonly associated with major
61 hydrocarbon reservoirs. Additional compelling reasons to explore subaerial salt bodies
62 are (1) distinctive mechanical properties of salt make it one of the few solid Earth
63 materials able to flow at the surface, and (2) these represent Earth-surface deformation
64 systems that can be highly responsive to weather conditions (Talbot and Rogers, 1980).

65 Much of our current understanding of surface salt kinematics stems from
66 namakier (extrusive salt "glaciers", also called "salt fountains") studies predominantly in
67 the Alborz and Zagros Mountains in northern and southern Iran, respectively (e.g., Kent,
68 1979). Over one hundred Hormuz salt diapirs, fed from pipe-like conduits (point-
69 sourced), are known to exist in the Zagros Mountains (Kent, 1979). Of these salt bodies,
70 surface motion has been observed on twenty diapirs using a satellite-based remote
71 sensing technique called interferometry of synthetic aperture radar (InSAR) capable of

72 measuring millimeter-scale vertical displacements (Barnhart and Lohman, 2012). The
73 sheet-like Garmsar salt nappe of the Alborz Mountains extruded along a frontal thrust
74 before undergoing open-toed advance and is presently inactive; the motion detected by
75 InSAR is attributed to dissolution (Baikpour et al., 2010). Furthermore, InSAR has also
76 been used to detect continuous vertical, upward flow rates between 5.5-8.3 mm/yr across
77 the line-sourced Sedom diapir in the Dead Sea basin (Weinberger et al., 2006).

78 Recently recognized namakiers in the western Kuqa fold-thrust belt in
79 northwestern China provide a new natural laboratory to observe and constrain subaerial
80 salt kinematics (Li et al., 2014). Four active point-sourced namakiers exist in western
81 Kuqa fold-thrust belt (**Figure 1**). An active line-sourced diapir, the Tuzimazha salt wall,
82 is comparable to the Sedom diapir with vertical, upward flow. Quele namakier, exposed
83 in western Kuqa fold-thrust belt, is an active open-toed, line-sourced subaerial salt
84 structure extruded from a surface-breaching thrust fault on Earth's surface. Kuqa fold-
85 thrust belt provides an invaluable opportunity to study the behavior of a variety of
86 subaerial salt bodies within the same geologic setting. Furthermore, the Kuqa fold-thrust
87 belt is more accessible than other examples of subaerial salt extrusion like the Salt Range
88 of Pakistan.

89 Existing work concludes that the presence of meteoric water and fluctuating
90 temperatures are the principal factors enabling salt recrystallization and/or dissolution
91 after surface extrusion (Talbot and Rogers, 1980; Urai et al., 1986; Desbois et al., 2010).
92 In the present study, we use InSAR to measure the spatial and temporal deformation
93 patterns of namakiers in Kuqa fold-thrust belt. We compare these observations to rainfall

94 and temperature measurements in order to explore potential relationships between the
95 active surface salt kinematics and local weather conditions.

96 **2. BACKGROUND**

97 **2.1 Geologic setting**

98 The Kuqa foreland fold-thrust belt actively accommodates ~4-7 mm/yr of north-
99 south tectonic shortening between the Tian Shan to the north and the Tarim basin to the
100 south across a ~400 km long, ~20-65 km wide region (e.g., Allen et al., 1991).
101 Contractional tectonics have formed structural hydrocarbon traps across Kuqa fold-thrust
102 belt where the deformational style is controlled by the presence and varying thickness of
103 salt layers (e.g. Tang et al., 2004; Chen et al., 2004). The subsalt sequence (Upper
104 Permian-Cretaceous) includes Triassic-Jurassic coal and lacustrine mudstones that
105 matured into regional hydrocarbon source rocks (Hendrix et al., 1992; Tang et al., 2004;
106 Chen et al., 2004). Two salt dominated units control deformation across Kuqa (Li et al.,
107 2012): the Miocene Jidike Formation and Paleocene-Eocene Kumugeliemu Group
108 concentrated in eastern and western Kuqa, respectively. The Kumugeliemu Group
109 consists of halite and gypsum interbedded with mudstone, sandstone, conglomerate and
110 marl (Hendrix et al., 1992; Chen et al., 2004). These strata had an original thickness of
111 ~1100 m and the range of current thicknesses spans 110-3000 m (Hendrix et al., 1992;
112 Chen et al., 2004; Yixin and Pengwan, 2009). This dramatic thickness range testifies to
113 the importance of salt flow, which thinned and thickened the unit laterally. Where the salt
114 units thicken toward the south, deformation is concentrated in the suprasalt sequence.
115 From west to east, salt décollements in Kuqa fold-thrust belt have developed into salt
116 nappes exposed at the surface, triangle zones and pop-up structures (Chen et al., 2004;

117 Wang et al., 2011, Li et al., 2012). The suprasalt sequence (Oligocene-Quaternary)
118 reaches a thickness of ~7 km (Tang et al., 2004; Li et al., 2014). The salt-dominated
119 Kumugeliemu Group in western Kuqa fold-thrust belt (**Figure 1**) outcrops at line-sourced
120 and point-sourced salt structures. These surface salt structures display structural and
121 stratigraphic records of active vertical motion, exhumation and surface flow (Li et al.,
122 2014).

123 Point-sourced salt structures, like Awate namakier, Bozidun namakier and an
124 unspecified structure referred to hereafter as Daxiagu namakier, are fed from a salt source
125 via pipe-like feeders (i.e., stems) (e.g., Jackson and Talbot, 1986). Awate namakier
126 occurs at the western extent of the Quilitage anticline system, divided by a south-flowing
127 river. The eastern portion of Awate namakier is approximately 2.5 km long and 1.5 km
128 wide. The western portion may have the same salt source (Li et al., 2014). Salt mining at
129 the southern edge of Awate exposes freshly cut outcrop surfaces and reveals a mud-rich,
130 1-3 m thick carapace above the namakier. Bozidun namakier is located ~17 km north of
131 Awate with a length of ~2.2 km and 1.4 km width. Lastly, Daxiagu namakier is the
132 westernmost surface salt structure in Kuqa, located ~12 km west-northwest of Awate.
133 Daxiagu is ~4.5 km long and 3.4 km wide and we interpret it to be a point-sourced based
134 on its circumscribed surface geometry.

135 Line-sourced salt structures such as Quele namakier and Tuzimazha salt wall have
136 relatively thin, elongated salt feeders (e.g., Jackson and Talbot, 1986). The Quele salt
137 thrust propagates southward and the salt décollement is exhumed where the thrust fault
138 intersects the surface, forming the Quele namakier. Quele namakier is exposed across
139 ~32 km E-W with a vertical thickness generally ranging from ~50-200 m. The namakier

140 thins and locally pinches out toward the west and the salt thrust extends to a north-
141 trending, salt-lubricated strike-slip fault that appears to transfer slip to another E-W
142 trending thrust fault further north (Zhong and Xia, 1998a; Li et al., 2014). Quele
143 namakier broadens at its eastern extent and covers an area ~5km wide, called the
144 Chaerhan namakier, which also features an isolated salt dome (Li et al., 2014). Large,
145 siliciclastic rock bodies, of varying sizes reaching up to 2.5 km length, occur across
146 Quele namakier. These rock bodies may be considered rafts if that have been dislodged
147 from surrounding sedimentary units and incorporated into the namakier as it flows. These
148 sedimentary bodies may also be the more brittle, siliciclastic rocks that make up the
149 Kumugeliemu Group. Toward the north in the hinterland of Kuqa, the subvertical
150 Tuzimazha salt wall trends east-southeast and maintains an ~50 m thickness along its ~10
151 km long surface exposure.

152 **2.2 Subaerial salt deformation and the impact of weather conditions**

153 Relatively low viscosity and density as well as a strong resistance to compression
154 allows rock salt to flow as a non-Newtonian fluid that can pierce through surrounding
155 sedimentary layers in the Earth's upper crust (e.g., Weijermars et al., 1993).
156 Microstructural analysis shows that salt flow converges and accelerates as it moves from
157 a buried source layer into a diapiric feeder, or stem (Desbois et al., 2010). The principal
158 deformation mechanisms observed at the stem of the diapir are grain-boundary migration
159 (GBM) and sub-grain rotation (SGR) caused by increased differential stress (Desbois et
160 al., 2010). Exhumation of salt initially forms salt domes that later develop into salt
161 fountains as circumferential lateral spreading propagates away from the orifice (e.g.,
162 Kehle, 1988). Dominant deformation mechanisms shift from GBM and SGR to pressure-

163 solution accommodated grain-boundary sliding (GBS) from the top to the distal part of
164 the salt fountain (Desbois et al., 2010). This shift can be explained by the influx of
165 meteoric water and the decreased differential stress as salt flow divergences radially away
166 from the orifice (i.e., Jackson, 1985; Desbois et al., 2010). A ground-based geodetic
167 study, with hourly to daily sampling, of the Kuh-e-Namak namakier in southern Iran
168 proposed that the presence of meteoric water causes plastic deformation of the salt while
169 daily temperature variations cause elastic deformation (Talbot and Rogers, 1980).
170 Temporary surface salt flow rate of ~500 mm/day was observed at Kuh-e-Namak
171 namakier shortly after a large rain event (~330 mm average rainfall from October to
172 February) (Talbot and Rogers, 1980). Furthermore, it was observed that during dry
173 periods the surface salt shrunk, retreating and losing some of lateral extent attained
174 during the wet period (Talbot and Rogers, 1980).

175 Given the typical low-pressure stress conditions of subaerial salt bodies, the
176 namakier porosity is stimulated by joints formed as a result of diurnal/seasonal thermal
177 expansion and contraction (Merriam et al., 1962; Talbot and Aftabi, 2004; Desbois et al.,
178 2010). Vertical joints in subaerial salt bodies dilate as the salt carapace spreads in
179 response to continual growth of the viscous salt fountain, which permits infiltration of
180 meteoric water (Desbois et al., 2010). The carapace of a namakier is typically composed
181 of granular clastic material left behind after the shallower layers of salt have dissolved
182 (e.g., Walker 1973). An annual temperature range of -0.5°C to 37.8°C was enough to
183 facilitate the plastic deformation observed at Kuh-e-Namak (Talbot and Rogers, 1980).
184 However, surface motion during dry periods not only depends on temperature but also the
185 thermal gradient in the salt, which is dependent on the wetness of the salt (Talbot and

186 Rogers, 1980). The semi-arid climate of the Kuqa fold-thrust belt allows the preservation
187 of subaerial salt exposures. Here, annual rainfall averages ~74 mm (April-October) and
188 average temperatures can range from -13.3°C to 31.2°C.

189 **2.3 Models, predictions, and tests**

190 The rapid kinematic response of surface salt structures to temporary stimuli
191 requires subaerial salt evolution analysis to consider short-term (days to years)
192 deformation kinematics. The rates of salt supply, salt dissolution, sediment accumulation
193 of the overburden, erosion and regional tectonic strain influence the long-term evolution
194 of a namakier (i.e., Koyi, 1998; McGuinness and Hossack, 1993). Crustal shortening may
195 impede diapirism if lateral compression results in an obstruction of the salt feeder (Koyi,
196 1998). In other circumstances the compression of a diapir feeder may physically separate
197 the diapir from the source layer. This can produce a temporary pulse of increased salt
198 extrusion rates that would mark the onset of the final phases of namakier evolution (Koyi,
199 1998).

200 Extreme daily temperature variations in semi-arid climates, like Kuqa fold-thrust
201 belt, lead to oscillating inflation and deflation of a subaerial salt body on a sub-hourly to
202 daily scale (Talbot and Rogers 1980). We would expect the entire surface of the
203 namakiers to uplift during daylight hours, when surface temperatures can be very high,
204 under the influence of thermal expansion (Merriam et al., 1962). Similarly, we expect
205 subsidence across the namakier surfaces, as a result of thermal contraction, when
206 temperatures drop well below freezing. Hourly sampling, at minimum, of temperature
207 and surface motion would be necessary to detect the rate and degree of daily oscillations
208 across the namakier surfaces at Kuqa fold-thrust belt. Similar inflation and deflation

209 cycles in response to seasonal variations may also be detectable. However all these
210 variations due to the thermal expansion or contraction of the salt body are likely small
211 because the coefficient of the very low thermal expansion of NaCl, in the range of $5 \cdot 10^{-6}$
212 $^{\circ}\text{C}^{-1}$ (White, 1965). For example, in the idealized case of a homogeneous variation of
213 40°C on a 1 meter thick salt layer, these thermal effects would result in a vertical
214 displacement of the order of 200 micrometers.

215 The short-term deformation patterns of namakiers must consider moisture at the
216 surface. When sufficient quantities of meteoric water make contact with/infiltrate
217 namakiers, pressure-solution and grain boundary sliding allow accelerated salt flow. We
218 expect namakiers at Kuqa fold-thrust belt to flow faster within days after storm and rain
219 events. As salt flow accelerates the leading edge of the surface salt bodies should extend
220 further laterally. As a namakier spreads laterally, the surface should appear to subside.
221 This can be visualized for a static namakier by considering how a drop of molasses would
222 behave on a tabletop. As the drop spreads slowly in every direction, the surface will
223 flatten, bringing the top of the molasses closer to the table.

224 Two models suggest conflicting roles of the carapace in surface salt kinematics
225 during dry periods. One scenario is the dry-inflation model that suggests the carapace that
226 develops on a surface salt body inhibits lateral spreading and facilitates swelling at the
227 dome (above the orifice) as the salt extrudes from the feeder (Talbot and Pohjola, 2009).
228 If this model holds for Kuqa fold-thrust belt then we should see a relative surface uplift
229 above the orifice during dry periods. Alternatively, dry-deflation model suggests that the
230 carapace hinders uplift of the central dome and instead promotes lateral spreading (Aftabi
231 et al., 2010). With a constant salt supply rate, this model suggests a continual surface

232 subsidence of the namakier as it spreads laterally. To test these models we must record
233 time-lapse surface motions of the Kuqa fold-thrust belt namakiers during wet and dry
234 periods as well as document the occurrences of rain events.

235 The resistance supplied by a load overlying the orifice of a namakier is another
236 factor that can potentially impact subaerial salt. Emergent, surface breaching, diapirs rise
237 faster than pre-emergent diapirs because of the reduced confinement and load when the
238 overburden is removed (e.g., Weinberg, 1993). Strain rates from microstructural analysis
239 for pre-emergent diapirs range from 10^{-15} to 10^{-13} s^{-1} while higher strain rates from 10^{-11}
240 to 10^{-9} s^{-1} have been observed for emergent diapirs (Talbot and Jackson, 1987). This
241 aligns with flow velocity estimates that show pre-emergent diapirs in Germany rise ~ 0.3
242 mm/yr while emergent diapirs in Iran can exceed 10 mm/yr (e.g., Trusheim, 1960; Talbot
243 and Aftabi, 2004). Strain and velocity rates of pre-emergent and emergent diapirs
244 reasonably suggest that the rate of salt extrusion can increase if enough material above
245 the orifice of a namakier is removed. The salt above the orifice is a load, and this load is
246 reduced by salt spreading away from the orifice at the surface.

247 Removal of material above the orifice can occur via erosion and salt dissolution.
248 During periodic large storm events, the shallow, relatively uncompact layers of the
249 namakier carapace can erode considerably (Wenkert, 1979). Furthermore, significant salt
250 dissolution can occur during storm events if the carapace thickness allows sufficient
251 meteoric water to infiltrate the namakier. In the event that the removal of material above
252 the orifice is large enough, we expect acceleration of salt extrusion resulting in an overall
253 rise of the namakier surface. Conversely, if the load above the namakier orifice controls

254 the salt extrusion rate, a thickening carapace would cause a deceleration of salt extrusion
255 that would also lead to a deceleration of lateral spreading.

256 **3. METHODS**

257 To better understand the complex set of processes that govern deformation in salt
258 bodies, we examine several different bodies using a diverse set of data, including space-
259 based constraints on ground deformation and weather information from both ground
260 stations and remote sensing. Surface salt deformation is accessed using a remote sensing
261 technique called interferometry of synthetic aperture. To perform the InSAR analysis we
262 utilize Envisat ASAR (Advanced Synthetic Aperture Radar) imagery acquired between
263 June 2003 and October 2010. To access the relationship between subaerial salt motions
264 and weather conditions we use Tropical Rainfall Measuring Mission (TRMM) data and
265 local weather station data during the same period of Envisat acquisitions. The temporal
266 resolution of the Envisat imagery available must be less than the temporal range of
267 surface salt motion to detect the salts' kinematic responses to weather variations (**Figure**
268 **3**). Because of this it is unlikely that our Envisat dataset could resolve the impact of
269 individual storm events as our best temporal resolution is 36 days. However, it is possible
270 to detect the impact of seasonal weather variations. The combination of these disparate
271 datasets, which have very different spatial and temporal resolutions and degrees of
272 uncertainty, presents some challenges, but also allows a more complete analysis of the
273 setting.

274 **3.1 Weather estimates**

275 The TRMM satellite has utilized microwave and radar instruments since late 1997
276 with a spatial coverage between latitude 50°S to 50° (Huffman, 2011). The Daily TRMM

277 Rainfall Estimate (3B42 v7) used for our analysis is a product derived from rain gauge
278 and multiple TRMM satellite measurements. First, independent precipitation estimates
279 from various microwave instruments are calibrated to TRMM Combined Instrument
280 (TCI) precipitation estimates (Huffman, 2011). The 3-hourly multi-satellite
281 measurements are combined with the accumulated monthly Global Precipitation
282 Climatology Centre (GPCC) rain gauge analysis using inverse-error-variance weighting
283 to form a monthly best-estimate precipitation rate (Huffman, 2011). Lastly, the 3-hourly
284 estimates are scaled for the month then summed to the monthly value for each individual
285 grid box (Huffman, 2011). The final data set has precipitation estimates with a 3-hourly
286 temporal resolution and a $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution (Huffman, 2011). This temporal
287 resolution is sufficient to observe storms that can occur in the span of a few hours across
288 the surface salt structures in Kuqa fold-thrust belt.

289 Another dataset we have used includes daily humidity, temperature, and rainfall
290 measurements from a meteorological weather station in Kuqa, Xinjiang Province, China
291 (Tutiempo Network). We utilize this station, despite its location over 150 km away,
292 because it is the closest ground truth. When we compare the rainfall estimates from the
293 weather station and the TRMM dataset we look at the cumulative measurements for the
294 time periods between each Envisat image acquisition. Similarly, we compare the average
295 surface temperature and humidity during each time period between image acquisitions.

296 **3.2 Interferometry of synthetic aperture radar (InSAR)**

297 We constructed an InSAR time series to constrain the surface displacements of
298 active extruded salt structures in western Kuqa fold-thrust belt as well as several surface
299 displacements associated with hydrocarbon withdrawal and subsurface fluid injection.

300 InSAR is a remote sensing technique that uses radar imagery to provide spatially dense
301 measurements of surface displacements in the satellite line of sight (LOS) with millimeter
302 to centimeter accuracy (e.g., Zebker et al., 1994; Massonnet and Feigl, 1998; Bürgmann
303 et al., 2000). Multiple SAR images are used to generate sets of interferograms to form a
304 time series after a joint inversion (e.g., Berardino et al., 2002). InSAR time series analysis
305 helps reduce the impact of several noise sources (decorrelation, orbital and DEM errors,
306 atmospheric delays, phase unwrapping errors) on displacement rates estimates during the
307 time period spanned by the full dataset (e.g., Grandin et al., 2012) with an accuracy for
308 surface displacement velocity at the mm/yr scale. The time series analysis also allows
309 identification of time variable deformation including seasonal signals and response to
310 earthquakes or anthropogenic activity.

311 We use 40 ESA ASAR C-band radar images acquired by the Envisat satellite
312 between June 2003 and October 2010 from Track 291 (along descending orbits). A small-
313 baseline approach (e.g., Berardino et al., 2002) was used to process interferograms and
314 invert for average displacement rates and evolution through time with the New Small
315 Baseline Algorithm Subset (NSBAS) chain, as described in detail by Doin et al. (2011)
316 and Jolivet et al. (2013). 85 individual interferograms were generated using a modified
317 version of the Caltech/JPL Repeat Orbit Interferometry Package (ROI_PAC, Rosen et al.,
318 2004) and the STRM 90-global DEM. Interferograms were corrected from DEM errors
319 (Ducret et al., 2013) and stratified tropospheric delays (based on the ERA-Interim global
320 atmospheric model, Doin et al., 2009; Jolivet et al., 2011), multi-looked by a factor of 4
321 in the range direction and 20 in the azimuth direction, flattened and filtered before
322 unwrapping. Individual interferogram coherence was used to determine the optimal

323 unwrapping path for each interferograms. The phase unwrapping was achieved
324 iteratively, beginning in areas of high coherence then incrementally reducing the
325 coherence threshold for each iteration (Grandin et al., 2012). The InSAR inversion
326 process does not allow for a direct measurement of the error margin of the LOS
327 displacement measurements, however we estimate the noise level is on the order of ~1
328 mm/year. Radar amplitude images were used to interpret the namakiers' boundaries,
329 outlined on the velocity maps.

330 We present average velocity (mm to cm/yr) and displacement maps with a spatial
331 resolution of 80 x 80 m. The velocity and displacement maps are displayed in line of
332 sight (LOS) with positive (red) and negative (blue) values corresponding to movement
333 toward and away from the sensor that we furthermore interpret as uplift and subsidence,
334 respectively, due to the dominant sensitivity of InSAR to vertical motion. Differential
335 incremental displacement maps and time series are used to track the temporal phase
336 evolution. To isolate relative displacements, we generate these differential maps and time
337 series computing the difference between time series from points within deforming areas
338 and times series from local reference points. This helps minimizing the effect of spatially
339 coherent noise. The remaining, relative, correlated temporal fluctuations observed and
340 comparisons to weather conditions are discussed in the following section.

341 The present study uses three datasets that were processed to obtain a time-series
342 that cover the period June 2003 to October 2010 where InSAR data provide estimates of
343 surface displacement at a pixel size of ~30 m and time resolution of 36 to 210 days, with
344 an average of 75 days. From the nearest weather station, average temperatures and
345 precipitations are obtained. Finally, the TRMM data provide the same time-lapse series as

346 the weather station, at a pixel size resolution of 4 km and for the same periods at the
347 InSAR data. These three data sets are then processed to 1) analyze the surface
348 deformation of salt bodies, 2) correlate these deformations with weather conditions.

349 **4. RESULTS**

350 **4.1 Kinematic observations**

351 The overall distribution of LOS velocity at Bozidun namakier is relatively
352 uniform. From the average velocity map, minor subsidence is observed on the western
353 margin and localized uplift near the north and east (**Figure 4A**). The velocity distribution
354 across Bozidun namakier is nearly indistinguishable from its immediate surroundings
355 supporting field observations that suggest Bozidun namakier is not actively extruding
356 material to the surface, as shown in the time series of the **Figure 4**.

357 The distribution of positive and negative LOS velocities at Daxiagu is
358 asymmetrical and ranges from -4.5 to 5 mm/yr (**Figure 4B**). An area of uplift is observed
359 on the northeastern side of the structure, oriented toward the northwest. Areas of overall
360 subsidence occur predominately on the southwestern side of the structure as well as the
361 northwestern. The incremental displacements maps highlight deformation patterns that do
362 not reflect the long-term deformation patterns measured by the average displacement
363 velocity maps (**Figure 5**). Each incremental displacement map of Daxiagu displays
364 relatively uniform deformation across the namakier with fluctuations between surface
365 uplift and subsidence at different time intervals. Time series analysis of east and west
366 Daxiagu namakier inversely mirror each other; the east is uplifting at approximately the
367 same rate (~4.5 mm/yr) as the west is subsiding. The ribbed pattern that appears in both
368 the average velocity map and the incremental displacements maps do not correlate to

369 topographical variations but instead may reflect noisiness in the data likely due to the
370 namakiers' rugged surface.

371 Displacement velocities at Awate namakier are distributed asymmetrically
372 (**Figure 4C**). Awate namakier is divided in two by a major river with stronger subsidence
373 observed on the eastern segment, slight subsidence on the west, and uplift at the river
374 channel in between. On the eastern Awate namakier the displacement velocities decrease
375 radially away from the center and the maximum rate of displacement approaches -5
376 mm/yr. Incremental displacement maps show that the east Awate namakier has
377 experienced periods of uplift despite overall subsidence suggesting it is an active
378 structure. The areas of displacement at east Awate namakier have consistent shapes in the
379 incremental displacement maps for periods of a year to three, but gradually shift from a
380 central block to a more variegated area. These areas all subside and uplift more
381 dramatically than the surroundings. Minor subsidence and unvarying incremental
382 displacements are observed at west Awate namakier. Localized uplift at the river channel
383 approaches 4 mm/yr. The zone of uplift is broader than the river channel, extending
384 farther to the west. Incremental displacement maps show uplift at the riverbed, dividing
385 Awate namakier, initiated toward the western riverbank then propagated toward the
386 center. The time series analysis at the river channel is notably less noisy and fluctuating
387 than the time series from areas across the namakier, especially for east Awate namakier
388 (**Figure 4**). This observation indicates that uplift at the river channel is relatively regular
389 and constant while displacement of the namakier is relatively irregular.

390 The distribution of average displacement velocities across Quele namakier is
391 predominately uniform (**Figure 4D**). Relative subsidence is measured along the exhumed

392 thrust sheet but strong, localized subsidence is observed at the central segment of Quele
393 namakier where the average displacement velocity approaches ~ 4 mm/yr. Velocities
394 measured at Chaerhan namakier and the isolated salt dome at the eastern extent of Quele
395 are within the noise level of background velocity measurements. A few periods of minor
396 uplift are observed in the incremental displacement maps at the central segment despite
397 the overall subsidence suggesting an actively extruding structure (**Figure 4**). Time series
398 analysis shows the displacement trends of two areas in the central segment partially
399 mirror each other, from 2003 to 2006. After 2006, higher rates of subsidence are
400 concentrated toward the east suggesting heterogeneities along the salt thrust.

401 **4.2 Correlation between kinematics and weather conditions**

402 To test the relationship between weather conditions and surface displacements of
403 namakiers in Kuqa fold-thrust belt we compare the incremental displacements between
404 each image acquisition to the average humidity, average temperature, and cumulative
405 rainfall during the respective time intervals (**Figure 6**). There is no clear correlation
406 between average humidity estimates and surface displacements for any of the studied
407 namakiers. Similarly, no correlation is observed between displacements and average
408 temperature for Quele namakier. Furthermore, correlation coefficients between surface
409 displacement measurements on across the 4 namakiers studied and average temperature
410 and humidity estimates yield a maximum correlation of 0.2. However, at Awate, Bozidun
411 and Daxiagu namakiers we see temperature extremes are associated with more surface
412 salt motion than intermediate temperatures. When we compare the displacements
413 observed at the namakiers to the cumulative rainfall values estimated by TRMM as well
414 as the distantly located weather station, we find a positive correlation. There is an

415 increased occurrence of surface salt displacements during time intervals that experienced
416 lower rainfall estimates suggesting that with less rainfall there is more surface motion.
417 The correlation observed is not simply an artifact of having more data during periods of
418 lower rainfall events because there are equal amounts of temporal coverage during the
419 rainy (April-October) and dry seasons (October-April).

420 Another way to test the correlation between observed surface displacements and
421 rainfall is to look at how the displacement residuals correlate to rainfall estimates. The
422 residuals of a dataset are the observed values minus the predicted (or average) values.
423 Residuals highlight the data points' deviation from the linear average, which are used to
424 test the correlation between rainfall and surface salt displacement response. When we
425 calculate the correlation coefficient between the residual time series displacements,
426 showing the deviation of each displacement data point from the average, at the namakiers
427 of interest and TRMM rainfall we find no correlation greater than 0.1. The low
428 correlation coefficient is likely due to the occurrence of both positive and negative
429 motion with hot and cold temperatures.

430 **5. DISCUSSION**

431 InSAR analysis uncovers a variety of ground motions across the subaerial salt
432 structures of the Kuqa fold-thrust belt. While the majority of the namakiers studied show
433 surface motion, InSAR estimates of surface motion at Bozidun and Chaerhan namakiers
434 are relatively indistinct from the surrounding area. The lack of observable deformation at
435 the Tuzimazha salt wall could mean that (1) the salt wall has recently become inactive,
436 (2) it is deforming at rates below our detection threshold (<1 mm/yr), or (3) the activity is
437 confined to a small area that is more challenging to resolve. We favor the third

438 interpretation because the thickness of the Tuzimazha salt wall (~50 m) cannot be
439 adequately resolved by the 80 x 80 m spatial resolution of our InSAR dataset (Figure S4).
440 The namakiers exhibit asymmetrical spatial displacement patterns with fluctuating
441 deformation rates over varying temporal scales (weeks to months). Average velocity
442 estimates in addition to the incremental displacement steps allow us to explore the
443 seasonality of subaerial salt deformation and its link to weather conditions.

444 **5.1 Daxiagu namakier**

445 The asymmetric displacement patterns observed at Daxiagu namakier (**Figure**
446 **7A**) do not conform to the expected radial flow pattern of a salt fountain. The irregular
447 shape and flow kinematics is likely controlled by the surrounding topography and sub-
448 salt morphology beyond the feeder, beneath the namakier. A river east of Daxiagu has
449 eroded steep channel walls, and likely rapidly dissolves salt that flows toward the east.

450 Because surface uplift is expected directly above the feeder (orifice) of a point-
451 source namakier, we interpret the area of overall uplift, on the eastern side of the
452 namakier, to indicate the location of the salt feeder. Long-term average uplift also
453 suggests that the rate of salt extrusion into the namakier exceeds the rate of salt
454 dissolution/erosion. The similarity in magnitude of surface displacement on the east and
455 west may indicate the two sides of the namakier are not mutually exclusive (**Figure 4**).
456 Diminutive subsidence at the northwestern margin could also indicate partial flow toward
457 the northwest from the namakiers' feeder. Eastward flow is expected, where a river
458 passes, but the material that flows toward the river is likely dissolved relatively rapidly.
459 The subsidence is interpreted to reflect an approximate volume balance as the namakier
460 spreads farther out. This interpretation suggests that the dominant direction of flow is

461 toward the west and that lateral spreading is faster than the rate of supply. The
462 southwestern lobe of Daxiagu is subsiding on average, but does not appear in the time-
463 lapse data in any one time-step. However, we find no statistical correlation to suggest
464 weather conditions control the surface motion patterns measured. Furthermore, this
465 observation is not likely to be climatically driven because we do not see it in incremental
466 displacement maps. The north-south tectonic shortening (~4-7 mm/yr) accommodated
467 across the Kuqa fold-thrust belt is likely to have a greater influence on the exhumation
468 rates and subsequent surface displacement patterns (e.g., Allen et al., 1991; Zhong and
469 Xia, 1998; Yang et al., 2010; Zubovich et al., 2010). However, to positively discriminate
470 the precise influence of regional shortening on subaerial salt motion, spatially dense GPS
471 observations are necessary across the area.

472 **5.2 Awate namakier**

473 Subsidence is concentrated at the center of the eastern Awate namakier (**Figure**
474 **7B**). The broad, long-term deformation pattern of centralized subsidence is indicative of
475 a mature namakier that is experiencing a dissolution / erosion rate which exceeds the rate
476 at which salt is fed into the structure. Distinct anthropogenic forcing may play a role: salt
477 mining operations spray water along the southwestern margin of the eastern Awate
478 namakier branch, which may influence the observed long-term subsidence by locally
479 increasing salt dissolution.

480 Incremental displacement maps do not entirely correspond with observations from
481 the average displacement velocity map, thereby revealing different deformation patterns
482 at different temporal scales. Unlike the long-term displacement pattern, four intervals of
483 incremental surface uplift at eastern Awate namakier occur between January and March

484 (colder/drier months) confirming that new material (salt) is being fed into the namakier.
485 We observe uplift when our temperature-kinematic salt models predict Awate would
486 experience overall surface subsidence during colder periods in response to thermal
487 contraction. Calculated correlation coefficients between incremental displacements and
488 temperature variations show no statistical correlation. Temperature variations do not
489 appear to control periods of wide spread uplift and subsidence. The intervals of uplift do,
490 however, support the dry-inflation model. The dry-inflation kinematic salt model predicts
491 a namakier will inflate during dry periods because the carapace inhibits lateral spreading.
492 At Awate namakier, we observe uplift above a central location (dome) during periods of
493 low rainfall implying that the carapace restricts lateral spreading and prefers dome
494 inflation during dry periods. Furthermore, periods of increased rainfall do not correspond
495 to increased surface salt uplift.

496 The average, long-term (~7.3 years) uplift signal measured at the river channel
497 between the east and west segments is not notably observed in the incremental
498 displacement maps. If river deposition were responsible for the rise of the river channel
499 surface between the Awate namakier branches, the area of uplift would not be as
500 localized as observed. Instead, the rise would continue as the river does, toward the south.
501 It is more likely that the concentrated uplift observed at the river channel is due the rise
502 of salt from the source layer through the stem of the diapir that feeds Awate namakier. If
503 the river cuts off the salt feeder that sources Awate, the observed uplift could be the result
504 of accumulating strain in the overburden of a partially buried, active salt feeder.
505 However, the estimated long-term rate of uplift here is not likely to persist for time scales
506 of >100 years because that would significantly perturb the long-term equilibrium

507 topography by developing a hill in the very place there is a river. It is possible to perturb
508 the equilibrium topography if the diapir is new or suddenly changing character, but it is
509 not new because the namakier is well established. Thus, we interpret the equilibrium to
510 be controlled by the regular frequency of large flooding events allowing this area to
511 neither rise nor fall with respect to regional baseline for longer periods than ~7 years.
512 Alternatively, the surface of the river channel in between the Awate namakier can be
513 controlled by a natural equilibrium between the diapir extrusion rate and river erosion. A
514 study of climatic conditions from 1951 to 2009 in Xinjiang, China reveals that the
515 average precipitation has increased by 15 mm since 1990 (Kong and Pang, 2012). To our
516 knowledge, a detailed study of this particular river does not exist, however, work done on
517 the proximal Tailan River, west of Awate, found that glacial melt-water accounts for 60%
518 of its $7.5 \times 10^8 \text{ m}^3$ annual river discharge (Zhao et al., 2015). The combination of
519 increased rainfall and possible glacial melt-water, due to the 1°C raise in average annual
520 temperature, would facilitate flash-floods every 10 to 100 years that removes a lot of
521 material through erosion, maintaining a topographic equilibrium (Kong and Pang, 2012).

522 **5.3 Quele namakier**

523 Quele namakier (**Figure 7C**) is the exhumed portion of a significant salt thrust
524 and its surface kinematic patterns vary from typical salt fountains. Because it is a line-
525 source structure, we do not expect to see radial flow comparable to a point-sourced
526 structure. Unlike a salt fountain, if the exhumation rate of Quele namakier increases the
527 surface is not likely to uplift significantly because it is confined by its overburden, the
528 hanging wall of the Quele salt thrust. Instead we would see increased subsidence due to
529 amplified southward spreading. Decreased exhumation would result in stagnant to

530 minimal lateral spreading. The overall subsidence observed across Quele namakier is
531 within the range of the data resolution. However, one area of the structure has
532 experienced a higher rate of subsidence. Weather conditions are unlikely to be
533 responsible because we see no statistical relationship between surface motion and
534 weather variations (temperature and moisture). Furthermore, it is unlikely that weather
535 conditions would exclusively and consistently affect only one spot along a relatively
536 smooth hill-front. Alternatively, the isolated subsidence at Quele namakier may be
537 structurally controlled. The subsidence could be the result of a pinched salt source
538 because analog models by Cotton and Koyi (2000) show that an overriding hanging wall
539 can pinch a salt décollement during shortening. A possible indicator of a pinched salt
540 décollement includes the left-lateral tear fault that occurs in the hanging wall, coincident
541 with the area of concentrated subsidence (**Figure 7E**). The tear fault could have resulted
542 from lateral variations along the salt décollement, such as thickness, which could indicate
543 a pinched salt source for Quele namakier. Alternatively, the tear fault may be the result of
544 differential shortening of the thrust sheet. A large siliciclastic rock body, which appears
545 to be a raft, is located along Quele namakier and south of the tear fault (**Figure 7E**). If
546 this siliciclastic rock body acted as a structural barrier, limiting southward propagation of
547 the exposed Quele salt décollement (namakier), then it may have caused sufficient
548 differential shortening rates to generate a tear fault. This alternative suggests that the
549 localized, increased subsidence at Quele is the result of differential shortening across one
550 portion of the Quele thrust.

551 **5.4 Limitations**

552 Across Kuqa fold-thrust belt, we discovered that subaerial salt motion is
553 decoupled from weather conditions. The sparse temporal sampling of this Envisat dataset
554 is significantly limited when compared to the daily sampling rate of temperature and
555 rainfall from spaceborne satellites or ground-based weather stations. Additionally, the
556 restricted spatial rainfall resolution of ~4 km estimates from spaceborne satellites may
557 also preclude correlation with meter-scale InSAR sampling resolution. Looking forward,
558 the association of the European Space Agency's Sentinel 1A and 1B could provide
559 improved temporal coverage after several years of observation and better quantify the
560 temporal fluctuations that may reveal the weather dependence we expected

561 **6. CONCLUSIONS**

562 In this study we present quantitative estimates of sub-aerial salt displacement
563 rates of surface salt bodies in Kuqa fold-thrust belt of northwest China. We predicted
564 strong dependence of surface salt motion on weather conditions based on previous
565 surface salt studies but discovered weather conditions do not control surface kinematics
566 here. Although the namakiers occur in the same fold-thrust belt, none of the salt bodies
567 share the same short-term kinematic displacement pattern, which suggests contrasting
568 subsurface geometries between the salt bodies. We measure the dominant vertical
569 displacement and identify asymmetric deformation patterns of uplift and subsidence at
570 Daxiagu and Awate, likely controlled by local tectonics and topography. At Quele
571 namakier we identify an area of concentrated subsidence that is coincident with
572 surrounding structural features that may indicate a pinched salt thrust. Li et al., 2014
573 detailed the geometries of the Awate, Bozidun, Quele and Daxiagu namakiers. Our study

574 furthers our understanding of the Kuqa fold-thrust belt namakiers by providing a
575 kinematic description of the active subaerial salt motion.

576

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726 **FIGURE CAPTIONS**

727 **Colón et al., Figure 1** (Top) Geologic map of the western Kuqa fold-thrust belt, adapted
728 from Li et al., 2014, located south of Tian Shan Mountain Range and northern Tarim
729 Basin. Blue and green units toward the north represent Tian Shan bedrock. Yellow and
730 orange units represent Cenozoic basin deposits. (Bottom) Cross section (adapted from Li
731 et al., 2012) from the southern Tian Shan through the Kuqa fold-thrust belt, toward the
732 Tarim basin and dissects the Quele salt nappe and the Misikantage anticline. The
733 schematic cross section of Quele namakier is more representative of the central portion of
734 Quele namakier.

735

736 **Colón et al., Figure 2** Chart highlights variables that may control subaerial salt motion,
737 their temporal and spatial ranges, and an illustration and description of the predicted
738 kinematic impact. White arrows represent dominant salt flow direction. Black arrows
739 represent surface displacement direction. Swelling of the salt in hot weather due to
740 thermal expansion and deflation during cold weather because of thermal contraction may
741 occur however the range of motion may be very small. During and shortly after rainfall
742 events surface salt flow is predicted to accelerate significantly albeit short lived. During
743 dry periods, 2 opposing models explain surface salt behavior: Dryness (a) predicts the
744 strong carapace that develops during dry periods inhibits lateral spreading and facilitates
745 swelling at the dome (above the orifice) as the salt extrudes from the feeder. Dryness (b)
746 predicts that the thick carapace hinders uplift of the central dome and instead promotes
747 lateral spreading. The presence of a thin weak overburden/carapace can potentially

748 reduce overburden stress and accelerate salt extrusion. A thick, strong
749 overburden/carapace may apply enough overburden stress to reduce salt extrusion rates.
750
751 **Colón et al., Figure 3** Logarithmic plot with spatial range in meters over temporal range
752 in days. The yellow, green and blue regions represent the range of temporal and spatial
753 scales that deformation in response to respective variables could be observed. The purple
754 highlights possible GPS sampling resolution. The dashed black rectangle represents the
755 range of spatial and temporal sample of our Envisat dataset. Satellites like the Sentinel
756 1A and 1B have potential to reach temporal resolution of up to 5 days. The dashed gray
757 rectangle represents the maximum Tropical Rainfall Measuring Mission (TRMM)
758 resolution used in this study.

759

760 **Colón et al., Figure 4** (Top) Average surface velocity maps for Bozidun namakier (A),
761 Daxiagu namakier (B), Awate namakier (C), and Quele namakier (D) displayed in
762 satellite line of sight (LOS) and saturated to the color scale 0.5 to -0.5 cm/yr. Surface
763 movement toward (uplift) and away (subsidence) from the satellite is represented by
764 warm and cool colors, respectively. (Bottom) Differential time series analysis of select
765 points on Bozidun, Daxiagu, Awate, and Quele namakiers (locations are highlighted by
766 black circles on the velocity maps above) is displayed in LOS displacement (cm) across
767 time (from June 2003 to October 2010). The displacement measurements are relative to
768 local references represented by the label “Ref”.

769

770 **Colón et al., Figure 5** Line-of-sight (LOS) differential incremental displacement maps of
771 Daxiagu (1A-33A), Awate (1B-33B), and Quele namakiers (1C-33C), saturated to the
772 color scale 5 to -5 cm. Displacement values of the local reference points (labeled in
773 Figure 4) were removed from each incremental displacement map (*Ref1* was used for
774 Quele namakier) to reduce spatially coherent noise and highlight relative motion. Each
775 incremental map spans the time between 2 successive acquisitions, the temporal coverage
776 is represented by the shaded red area on each timeline.

777

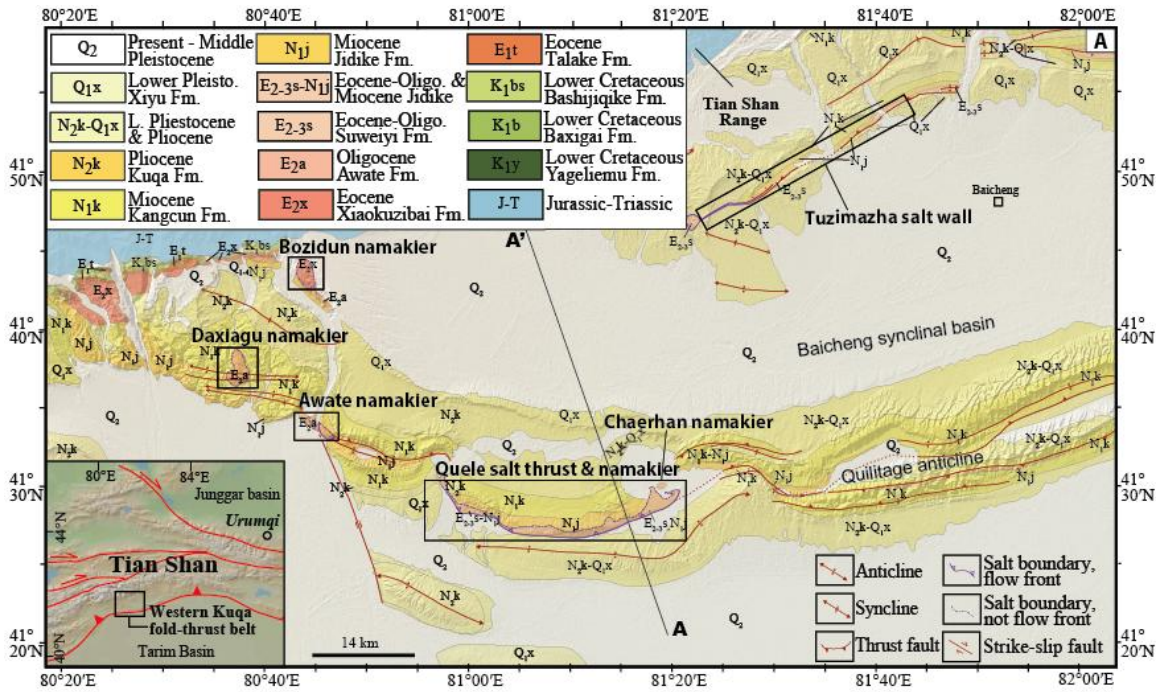
778 **Colón et al., Figure 6** Comparison between surface displacements at Kuqa fold-thrust
779 belt and weather conditions. We evaluate the dependence of incremental LOS
780 displacement rates (cm) from each structure (Bozidun, Daxiagu, Awate, and Quele
781 namakiers) to daily humidity (left), temperature (center left), and rainfall/snowmelt
782 measurements (center right) at a meteorological weather station in Kuqa (Xinjiang
783 Province, China) from Tutiempo Network and daily cumulative rainfall estimates from
784 the Tropical Rainfall Measuring Mission (right).

785

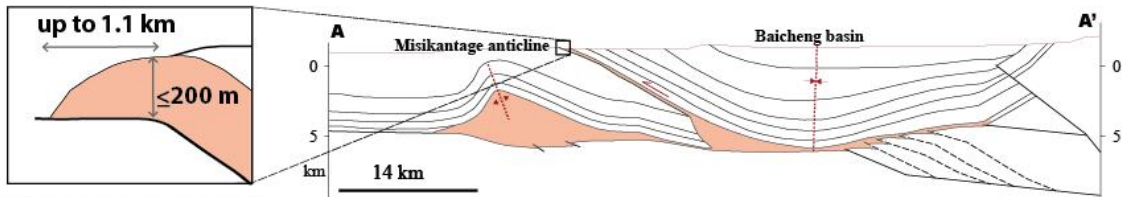
786 **Colón et al., Figure 7 (Top)** Schematic cross-section and overview of displacement
787 patterns across Daxiagu, Awate and Quele namakiers and kinematic interpretations.
788 Daxiagu is interpreted to have an inflating dome that actively extrudes from salt feeder on
789 the eastern side. Similarly, Awate is interpreted to flow predominantly toward the east to
790 southeast. Awate is interpreted to have a salt feeder on the eastern segment that may be
791 partially buried by the adjacent river channel causing the localized uplift. Unlike Awate
792 and Bozidun namakiers, Quele namakier does not have a central dome because it is an

793 exhumed salt thrust décollement. We interpret the dominant flow direction of Quele
794 namakier to be toward the south. (Bottom) The average displacement map (displayed in
795 radians) overlaid on top of Google Earth. The concentrated area subsidence at Quele
796 corresponds precisely to a large raft immediately to the east of the area of deformation.
797 The local left-lateral tear fault may also have created a structure barrier between this part
798 and the rest of the namakier.

FIGURES

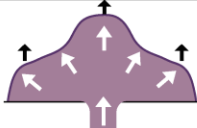
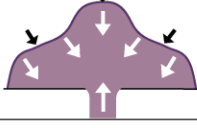
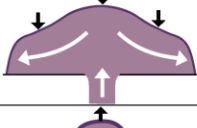
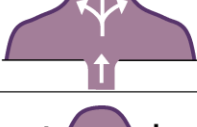
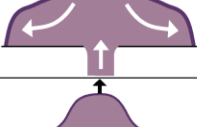
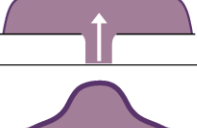



(B) Kuqa fold-thrust cross-section



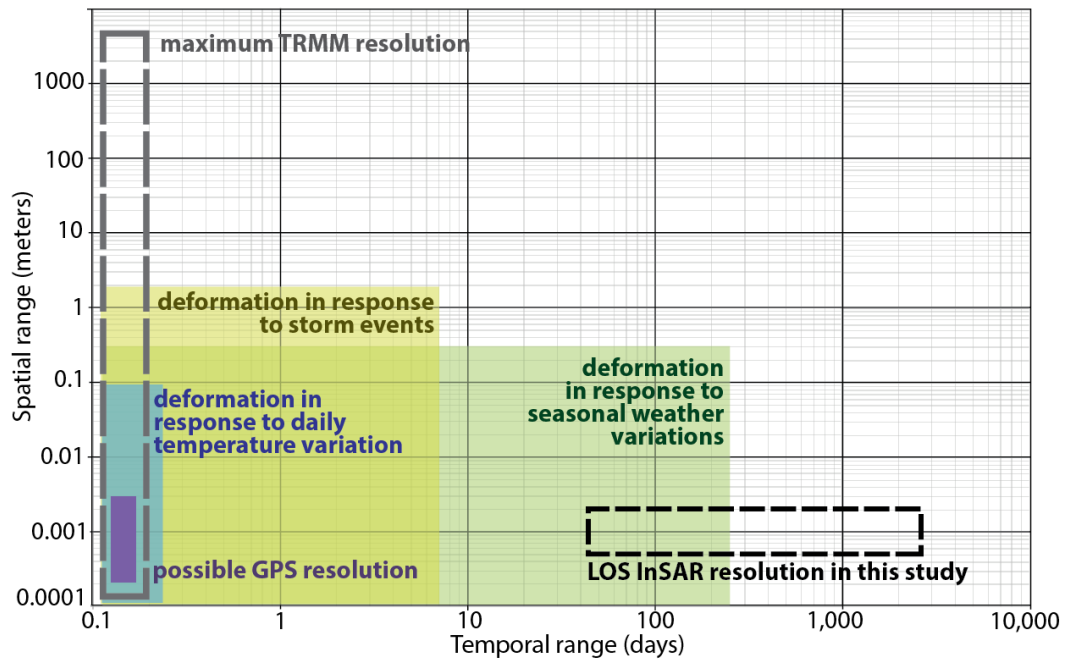
Colón et al., Figure 1

Factors impacting subaerial salt structure motion

Variable	Temporal range	Spatial flow range	Kinematic response to external condition
Hot (surface temp.)	hourly, daily, seasonal	<mm to cm	 <p>Thermal expansion may cause inflation and overall relative surface uplift of the namakiers when surface temperatures are high</p>
Cold (surface temp.)	hourly, daily, seasonal	<mm to cm	 <p>Thermal contraction may cause deflation and overall relative surface subsidence of the namakier when temperatures are low</p>
Wetness	daily, seasonal	<mm to meters	 <p>Meteoric waters facilitates pressure-solution GBS which accelerates salt flow. As salt spreads faster and further laterally, the namakiers' surface appears to subside</p>
Dryness (a)	seasonal	<mm to cm	 <p>Dry-inflation scenario suggests the carapace, developed during dry periods, inhibits lateral spreading and facilitates swelling above the orifice resulting in relative surface uplift above the orifice</p>
Dryness (b)	seasonal	<mm to cm	 <p>Dry-deflation scenario suggests the carapace, developed during dry periods, hinders uplift of the central dome and promotes lateral spreading resulting in surface subsidence of the namakier as it spreads laterally</p>
Thin Overburden	seasonal, annually	<mm to cm	 <p>If enough material is removed from the top of a namakier, thereby reducing the overburden above the orifice, and causing an increase salt extrusion rate which results in surface uplift above the orifice</p>
Thick Overburden	>annually	<mm to cm	 <p>If a namakier carapace thickens significantly then the additional load from may cause enough resistance to decrease the salt extrusion rate resulting in reduced namakier growth</p>

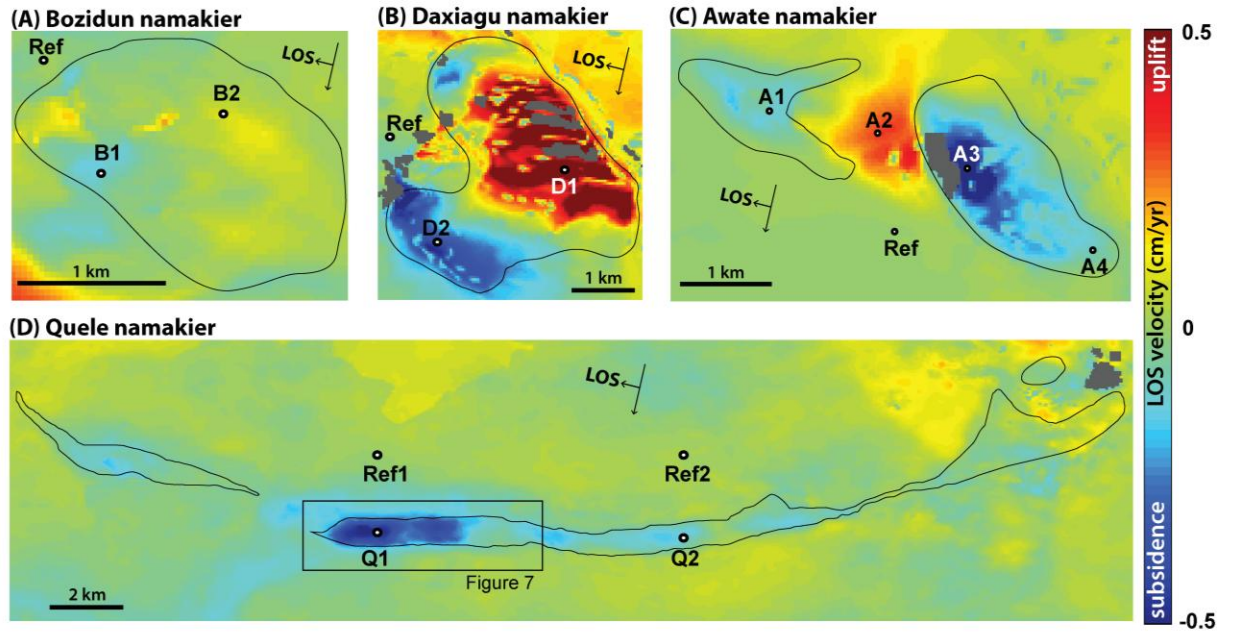
↓ = vertical surface motion ↘ = dominant salt flow direction

Colón et al., Figure 2

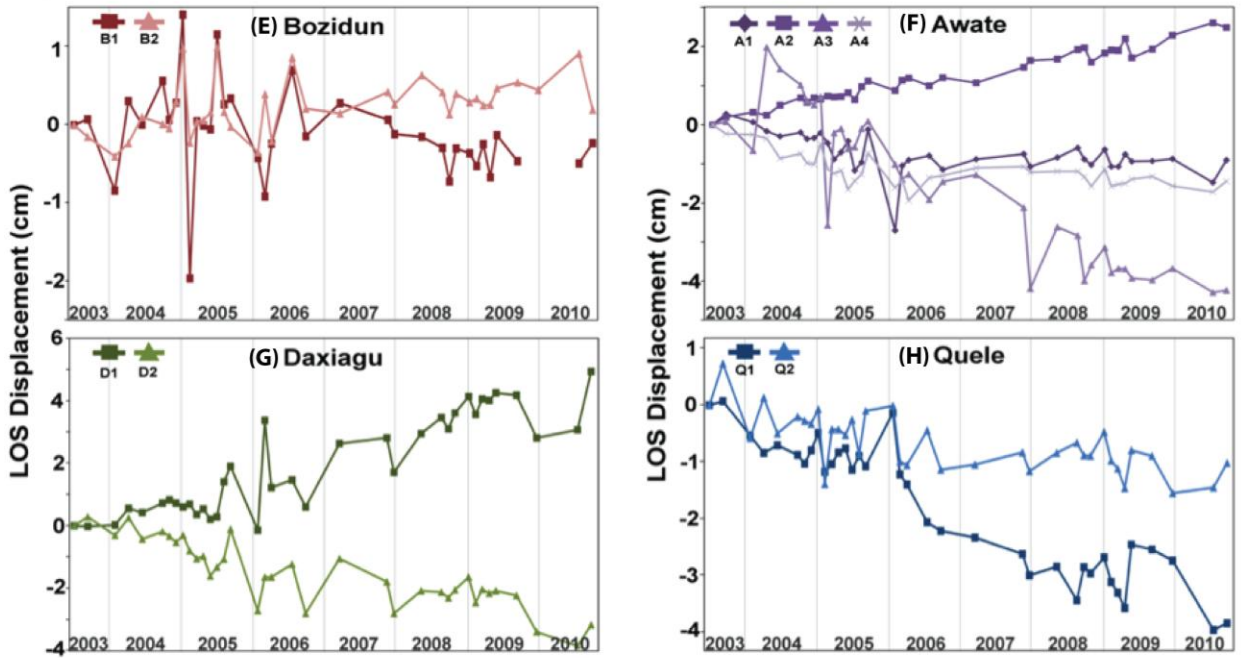


Colón et al., Figure 3

Average surface displacement rate maps

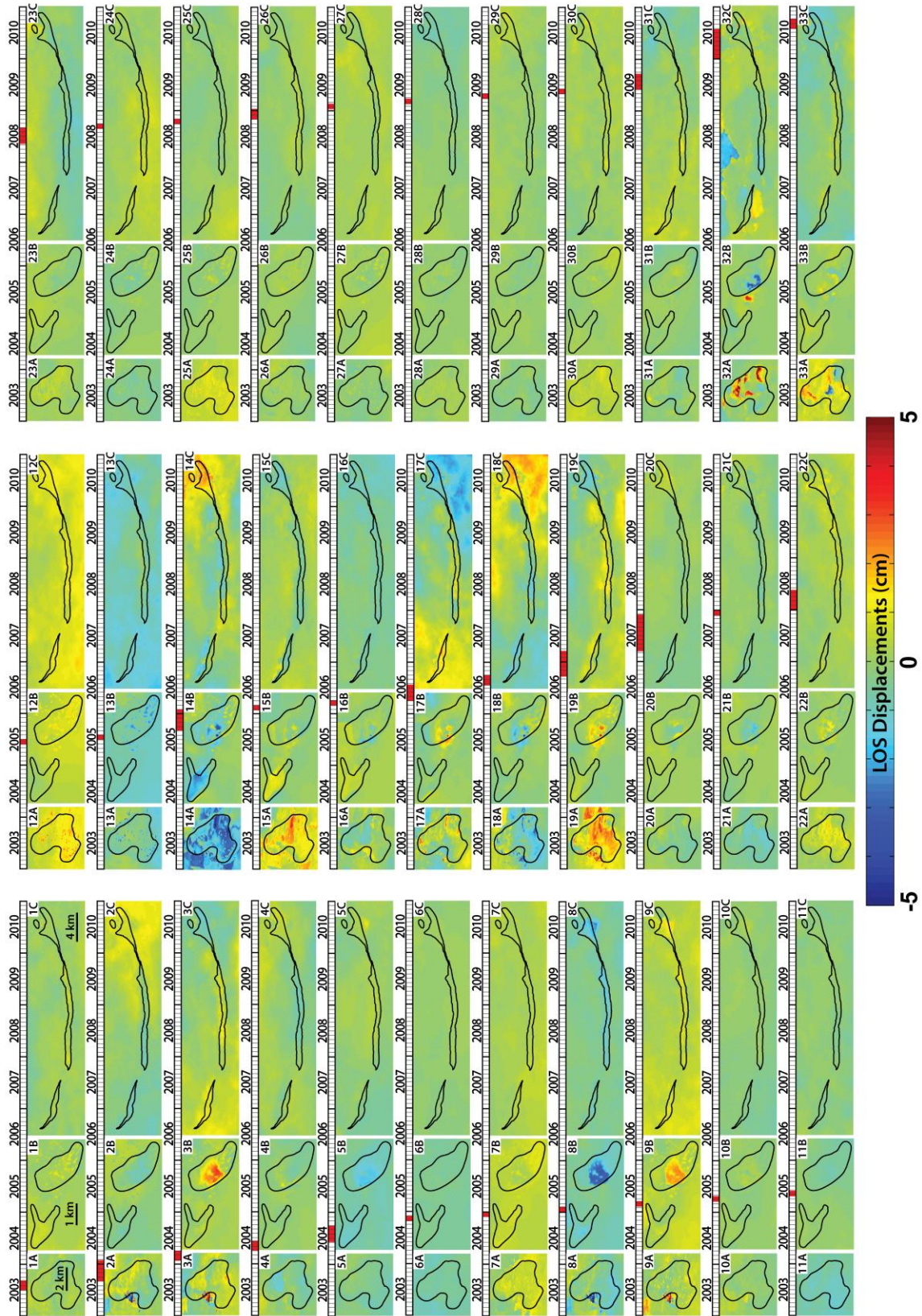


Time series analysis of surface salt structures

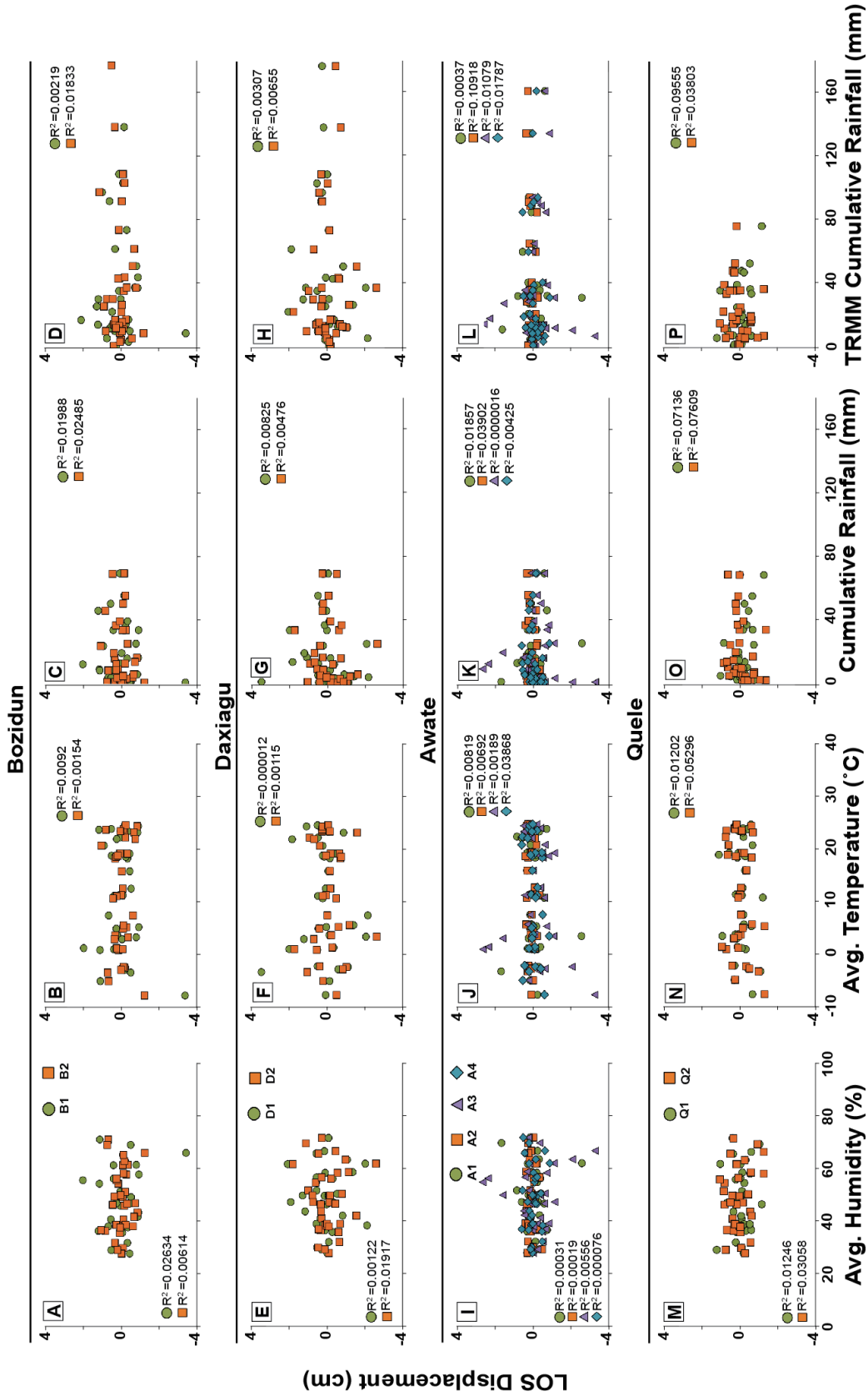


Colón et al., Figure 4

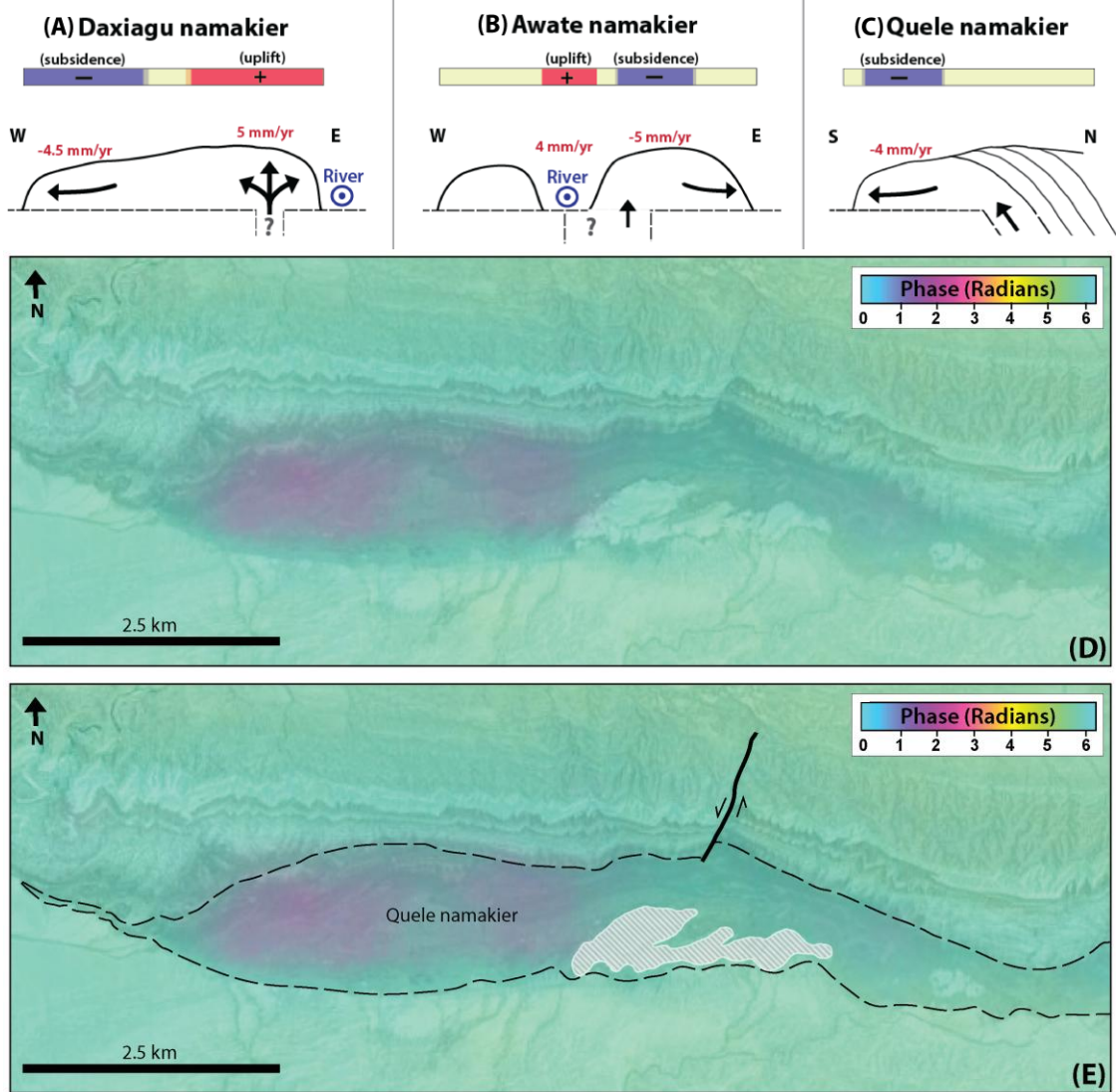
Colón et al., Figure 5



Colón et al., Figure 6



InSAR surface displacement rates and kinematic interpretations



Colón et al., Figure 7