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Land uplift due to subsurface fluid injection

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1 **Abstract**

2 The subsurface injection of fluid (water, gas, vapour) occurs worldwide for a variety of
3 purposes, e.g. to enhance oil production (EOR), store gas in depleted gas/oil fields,
4 recharge overdrafted aquifer systems (ASR), and mitigate anthropogenic land
5 subsidence. Irrespective of the injection target, some areas have experienced an
6 observed land uplift ranging from a few millimetres to tens of centimetres over a time
7 period of a few months to several years depending on the quantity and spatial
8 distribution of the fluid used, pore pressure increase, geological setting (depth,
9 thickness, and area extent), and hydro-geomechanical properties of the injected
10 formation. The present paper reviews the fundamental geomechanical processes that
11 govern land upheaval due to fluid injection in the subsurface and presents a survey of
12 some interesting examples of anthropogenic uplift measured in the past by the
13 traditional levelling technique and in recent times with the aid of satellite technology.
14 The examples addressed include Long Beach, Santa Clara Valley, and Santa Ana basin,
15 California; Las Vegas Valley, Nevada; Cold Lake and other similar sites, Canada;
16 Tokyo and Osaka, Japan; Taipei, Taiwan; Krechba, Algeria; Upper Palatinate,
17 Germany; Chioggia and Ravenna, Italy.

18 *Keywords:* land uplift; subsurface fluid injection; ground- and satellite-based
19 measurements; hydro-geomechanical properties; case studies

20

20 1. INTRODUCTION

21 It is well known that subsurface fluid (groundwater, gas, oil, thermal water) removal
22 induces a land settlement commonly called land subsidence. Magnitude, time of
23 occurrence, and extent of the area involved depend on a large number of factors
24 including the amount of the fluid withdrawn, the pore pressure decline, the depth,
25 volume, and permeability of the pumped formation, and the geomechanical properties
26 of the reservoir and the overburden. For a review of some famous anthropogenically
27 subsiding sites worldwide see Gambolati et al. (2005). The reverse, namely land uplift
28 due to underground fluid injection, is a much less observed and recognized event
29 although the practice of injecting fluids underground is more than a half century old.
30 Injection technology has been advancing continuously since it began to be widely used
31 in the 1950s-1960s to re-inject formation water extracted along with the hydrocarbons,
32 or to dispose of industrial wastes (Donaldson, 1964). The number of injection wells has
33 grown exponentially to the point that EPA (the U.S. Environmental Protection Agency)
34 has identified about 400,000 injection boreholes in the USA alone (USEPA, 2002). The
35 injection of water-based solutions, hydrocarbons, CO₂ or N₂ to enhance oil production
36 (EOR) started in the 1940s and soon became an accepted technique to recover
37 additional oil from reservoirs that were already depleted or waterflooded. Thermal
38 recovery processes, used in reservoirs containing heavy (viscous) oil or bitumen, can
39 also be classified as EOR. There are also examples of water pumped into an oil field to
40 mitigate land subsidence caused by oil production, including, for example, the case of
41 Long Beach, California, where the mitigation programme started in 1958 and was
42 carefully controlled and monitored (Rintoul, 1981).

43 Land motion related to subsurface fluid injection went unnoticed for a long time in
44 the vast majority of cases. There are a number of reasons for this. First, in most cases

45 the disposal of fluids occurred in deserted or sparsely inhabited areas where measuring
46 surface displacements was not a priority, in part due to the large cost of levelling
47 surveys. In other instances uplift was so small that no environmental hazards were
48 created and that no monitoring programme was really needed, or the area involved was
49 quite limited with no damages to the engineered structures and infrastructures reported
50 or even expected. Only in recent times satellite technology has offered a relatively
51 inexpensive, spatially distributed, and accurate methodology to detect ground
52 movements practically worldwide and has revealed anthropogenic uplifts of some
53 interest in terms of magnitude, size of the area involved and time of occurrence. The use
54 of Interferometric Synthetic Aperture Radar (InSAR) techniques has grown rapidly over
55 the last decade, thus facilitating immensely the detection and measurement of rising
56 areas. This is particularly true for surface movements connected with natural
57 fluctuations of the groundwater head and in areas of aquifer storage (ASR), which have
58 been systematically monitored, e.g. Galloway et al. (1998), Amelung et al. (1999),
59 Hoffmann et al. (2001), Watson et al. (2002), Hoffman and Zebker (2003), Schmidt and
60 Bürgmann (2003), Ferretti et al. (2004), Galloway and Hoffmann (2007), Bell et al.
61 (2008). Also surface and borehole tiltmeters have been widely used in recent years to
62 monitor ground heave within relatively small areas.

63 This paper provides a survey of some interesting areas in the world where
64 appreciable heave has been observed mostly as a “by-product” of fluid (water, gas,
65 vapour) injection in geological formations. The mechanics of land rebound is first
66 briefly addressed. The case studies are presented on the basis of the injection purpose,
67 i.e. EOR, ASR, gas storage, land subsidence mitigation, and geomechanical
68 characterization of the geologic formations. The focus is on the magnitude, spatial
69 distribution, and extent of the anthropogenic uplift, with some effort also devoted to
70 describing the geometry of the injected formation, fluid used, depth of disposal,

71 duration of the action, and increase of the fluid pore pressure, i.e., the factors controlling
 72 the observed displacement field. Finally, two projects on land subsidence mitigation by
 73 seawater injection in the Northern Adriatic are described and discussed.

74 2. MECHANICS OF LAND UPLIFT DUE TO FLUID INJECTION

75 Generally speaking, uplift is caused by the migration to the ground surface of the
 76 expansion of the geological formation where the fluid is injected. The deformation of
 77 the injected porous medium is mainly driven by the in situ pore pressure p and
 78 temperature T variations, with the amount of the total displacement mainly controlled
 79 by the rock compressibility and thermal expansion coefficient. Based on classical
 80 thermo-poro-elastic theory (Coussy, 1995), the partial differential equations governing
 81 the rock deformation can be expressed as:

$$82 \quad G\nabla^2\mathbf{u} + (G + \lambda)\nabla\text{div}\mathbf{u} = \alpha\nabla p + \frac{\theta_s}{c_b}\nabla T + \mathbf{b} \quad (1)$$

83 where ∇ and ∇^2 are the gradient and the Laplace operators, respectively, G and λ are
 84 the Lamé coefficients generally dependent on the stress path, \mathbf{u} is the displacement
 85 vector, α is the Biot coefficient, θ_s is the volumetric thermal expansion coefficient for
 86 the solid phase, c_b is the volumetric bulk compressibility, and \mathbf{b} is the vector of body
 87 forces. Well-known relationships link the mechanical coefficients in equation (1) to the
 88 soil uniaxial vertical compressibility c_M . This is the fundamental geomechanical
 89 parameter which basically controls the amount of vertical soil deformation caused by p
 90 change and can be acquired from in-situ measurements and lab tests.

91 Different types of fluids can be pumped underground, most commonly water, e.g., to
 92 recharge an aquifer system, arrest or mitigate the anthropogenic land subsidence
 93 accompanying the development and depletion of aquifers and hydrocarbon fields; but
 94 also gas, e.g., steam for EOR, CO₂ for long-term sequestration, or natural gas (methane)

95 for gas storage operations. Regardless of the fluid injected, the basic mechanism
96 underlying the geomechanical response is similar with the major differences related to
97 the framework where the operation takes place, i.e. the basin geology, the magnitude of
98 the p and T variations, and therefore the stress path that ultimately controls the
99 deformation. For instance, recharged aquifers are typically shallow, wide, and
100 unconsolidated with the p rise smaller than the previous decline, while gas/oil reservoirs
101 are deeper and more consolidated with a generally lower porosity, permeability and
102 compressibility. In this case the pressure build up can be, at least potentially, much
103 larger than the one experienced by an aquifer. The above factors can generate a very
104 different land surface response in terms of both magnitude and areal distribution
105 according to the specific case at hand.

106 The pore pressure increase in the injected formation may induce new geomechanical
107 processes which are not encountered when fluid is withdrawn. These mechanisms can
108 be more easily understood with the aid of the schematic Mohr representation of the
109 stress state shown in Figure 1 where compressive stresses are taken with the positive
110 sign. When fluid is removed p decreases with respect to the original value ($p < p_0$) and
111 the effective stress, according to Terzaghi's principle, increases. Hence Mohr's circle of
112 Figure 1 moves rightward, i.e. farther from the failure line bounding the envelope of the
113 allowable stress states. By contrast, when fluid is injected p rises and possibly exceeds
114 p_0 . In this case the effective stress decreases under the original in situ value with Mohr's
115 circle moving leftward, i.e. toward the failure line. Two failure mechanisms can be
116 experienced: (a) if Mohr's circle touches the envelope line a shear failure may occur; (b)
117 if Mohr's circle crosses the τ -axis a tensile failure takes place. Moreover, a dilation (or
118 dilatancy) phenomenon, i.e. an increase of volumetric strain due to shear, could be
119 induced, thus contributing to the magnitude of the injected formation expansion. Shear
120 dilation accompanies yield and strain weakening with a permanent alteration of the

121 fabric of the gas/oil or water bearing stratum through irreversible deformation, grain
122 rearrangement, permeability change and porosity increase, thus causing a potential
123 contribution to a measurable rebound of the land surface (Dusseault and Rothenburg,
124 1988; Settari et al., 1989, 1993). On summary, expansion of the injected formation is
125 primarily caused by a vertical effective stress release due to the pore pressure increase,
126 with the shear stress possibly contributing to deformation through dilation.

127 An additional source of deformation can be of thermal origin. If the temperature of
128 the injected fluids are lower than in-situ temperature, poroelastic and thermal effects on
129 stresses and deformations tend to counteract and may cancel each other. However, in
130 thermal EOR, where the formations involved are usually shallow, both thermal and
131 pressure effects cause expansion and are additive, resulting in appreciable surface
132 heave. According to Wang and Kry (1997) in an analysis of Cyclic Steam Stimulation
133 (CSS) operations conducted in an oil sand at Cold Lake, Alberta, Canada, the pressure
134 effects can dominate because of high injection pressures reached in the CSS process.
135 Conversely, in the Steam Assisted Gravity Drainage (SAGD) process, which uses
136 relatively lower steam injection pressure, experience in modelling (Walters, 2007)
137 shows that the thermal effects can account for 50% or more of the total heave, if the
138 nonlinearity of the geomechanical properties is taken into account.

139 It must be kept in mind that rocks typically exhibit a hysteretic mechanical behaviour
140 with stiffer properties in unloading conditions. For instance, the expansion induced by
141 pore pressure rise in the Northern Adriatic basin is only a third of that of the compaction
142 for a similar pressure decline (Baù et al., 2002; Ferronato et al., 2003).

143 In the survey of uplifted sites that follows it will be shown that anthropogenic land
144 heave can vary from a few millimetres to tens of centimetres depending on the
145 mechanism of deformation (mechanical expansion, dilatancy, thermal deformation) and
146 the several geological and geomechanical factors mentioned above.

147 **3. CASE STUDIES**

148 **3.1. Injection for EOR**

149 *3.1.1. Cold Lake, Alberta, Canada*

150 Cold Lake is the oldest of the four developed oil sand production areas of northern
151 Alberta, Canada. It is producing from the 15-30 m thick Clearwater sand lying at a
152 depth of about 450 m. The sand is primarily quartz and in the best quality area is quite
153 homogeneous and densely packed; it exhibits dilation when sheared. Above the
154 Clearwater is the Grand Rapids formation consisting of interbedded shale/sand
155 sequences (often containing small gas reservoirs), and the Colorado shale group. A
156 fresh water sandy aquifer at a depth of 100-150 m overlies the Colorado shale. The
157 bitumen viscosity in the Clearwater varies between 50,000 and 100,000 cp at an in-situ
158 temperature close to 13 °C. The area was developed initially by Imperial Oil Ltd. using
159 CSS consisting of cycles of steam injection (30-40 days) at fracturing pressure followed
160 by a production period of several months. Currently, the SAGD process is favoured for
161 new projects.

162 In CSS, the deformations from the pressure cycles (typically between 10 MPa to 2
163 MPa or less) and thermal expansion combine to produce an overall heave of 10-35 cm.
164 Wang and Kry (1997) show the data and simulation results for an area of 3 well “pads”
165 (each consisting of 4 rows of 5 wells) for the period between January 6 and February
166 24, 1989. At the beginning of this period, injection and production was balanced, but
167 due to previous injections, the maximum heave was already about 20 cm, as shown by
168 the baseline on Figure 2a. During the period studied, most of the wells were injecting
169 and this resulted in an additional 5-7 cm of uplift. This magnitude is typical and the
170 heave generally increases with time as the area heats up and accumulates dilation strain.
171 Wong and Lau (2008) confirmed this magnitude by semi-analytical calculations using

172 the nucleus of strain concept. Satellite measurements of the Cold Lake project have
173 been described by Stancliffe and van der Kooij (2001). As shown in Figure 2b, large
174 deformation changes can occur over small periods of time (2-3 months). They stated
175 that their best data show that the total deformation can reach 36 cm during a single
176 month.

177 3.1.2. *Shell Peace River, Canada*

178 The Peace River oil sands deposits cover an area of about $47 \times 10^7 \text{ m}^2$ west of the
179 Cold Lake and Athabasca areas. The resource, containing bitumen of viscosity of
180 10,000 to 200,000 cp in a formation 30 m thick buried at a depth of 600 m, has been
181 developed by Shell Canada, using modifications of the CSS technology. Injection takes
182 place at pressures of above 13 MPa (the in-situ vertical stress), thereby producing
183 formation fracturing. An extensive monitoring program, consisting of microseismic,
184 surface time-lapse seismic, time-lapse 3D vertical seismic profiles, surface tiltmeters
185 and InSAR, was implemented to better understand the production mechanisms, and
186 determine the reservoir volume change. In particular, tiltmeter data were used
187 extensively. The data interpretation indicated a similar magnitude of heave as that as
188 Cold Lake, as shown in Figure 3 (Du et al., 2005). McGillivray et al. (2006) reported
189 that during the first year (Oct. 2002-Oct. 2003), the reservoir volume increased by
190 $400,000 \text{ m}^3$.

191 3.1.4. *Athabasca oil sands, Canada*

192 The Underground Test Facility (UTF), located in the Athabasca area, was the first
193 field scale project designed to test the SAGD recovery method for oil sands. UTF
194 operates at a depth of about 140 m. During the first phase, started in 1984, 3 pairs of
195 short horizontal wells were drilled from an underground tunnel accessed by a vertical
196 shaft. The second phase followed with 3 pairs of long (500 m) horizontal wells from

197 which commercial quantities of bitumen were produced (see O'Rourke et al., 1999, for
198 review). Flue gas was also injected at a later stage (Yee and Stroich, 2004) and the
199 project is now in a commercial stage. Separate vertical wells were drilled to monitor
200 temperature and deformations. About 5 cm of heave was recorded in the centre of the
201 deforming area from September 1993 to in April 1994, as shown in Figure 4. As the
202 project matured, the heave increased up to 30 cm in 2001.

203 Following the success of the UTF project, several commercial projects using SAGD
204 technology started, and are now producing in the Athabasca area. A complete set of
205 heave surveys is available for the MacKay River project of PetroCanada (Petro-Canada,
206 2008) and the Firebag project of Suncor (Suncor, 2008).

207 The MacKay River SAGD produces from the McMurry sand at a depth of about 100
208 m, at an operating pressure of 1.7 MPa and steam temperature of 205 °C. Deformations
209 were measured by repeated monitoring of 97 monuments (leveling) and supplemented
210 by an array of tiltmeters and microseismic monitoring. In December 2007, an additional
211 67 monuments were installed. The heave contours between the baseline surveys of
212 December 2002 and December 2007 are shown in Figure 5a. The overall heave pattern
213 follows the orientation of the injection/production well pairs running NE to SW. The
214 heave exceeds 30 cm in several areas and reaches a maximum of 37 cm over the field.
215 Heave along a profile oriented perpendicular to the well pairs is shown for three
216 different times in Figure 5b.

217 The Firebag project of Suncor also produces from the McMurry formation but it is in
218 an earlier stage of development. Heave surveys have been conducted yearly from 2004
219 to 2008 and the cumulative heave during this period has reached 15.3 cm, with the
220 incremental heave over the last year having a maximum of 4.9 cm. Coupled
221 geomechanical and thermal flow studies carried out by the authors on various Athabasca
222 sites confirm the range of uplift observed at the sites discussed above (i.e., 20-35 cm).

223 The main mechanisms contributing to heave include thermal expansion, decrease of the
224 effective stress, nonlinear decrease of stiffness associated with decrease of effective
225 stress and change in Poisson's ratio.

226 **3.2. Injection for ASR**

227 *3.2.1. Santa Clara Valley and Santa Ana Basin, California*

228 The Santa Clara Valley is a structural trough running 110 km southeast of San
229 Francisco. The valley is bounded on the southwest by the Santa Cruz Mountains and the
230 San Andreas fault, and on the northeast by the Diablo Range and the Hayward fault.
231 The fresh-water-bearing sediments forming the groundwater reservoir within the valley
232 were mainly deposited during the Quaternary. They include semi-consolidated deposits
233 of the Pliocene and Pleistocene epochs, and unconsolidated alluvial and bay deposits of
234 the Pleistocene and Holocene epochs consisting of poorly sorted conglomerate,
235 sandstone, siltstone, and clay as much as 600 m thick. Coarse-grained deposits
236 predominate in the alluvial fans near the valley margins where the stream gradients are
237 steeper. The proportion of clay and silt layers increases toward the San Francisco Bay
238 (Poland, 1984).

239 From the early 1900s agriculture depended heavily on groundwater for irrigation. As
240 farming was progressively replaced by urban and industrial development in the 1940s,
241 the withdrawal continued to increase as the population grew. A decrease in rainfall
242 during the first half of the twentieth century along with an increase in the pumping rate
243 resulted in a significant drop of the artesian head, by as much as 80 m between 1912
244 and 1966. The well depth ranges from 90 to 360 m. Total annual groundwater
245 withdrawal approached 250 Mm^3 by 1960 (Ingebritsen and Jones, 1999). The
246 piezometric head decline caused as much as 4 m of land subsidence (Poland, 1984).

247 The Santa Clara Valley was the first area in the United States where organized
248 remedial actions were undertaken against groundwater overdraft with land subsidence
249 substantially halted by about 1969. Importation of surface water reduced the subsurface
250 pumping and allowed for an effective program of aquifer recharge leading to a recovery
251 of groundwater levels. Such a program began in the 1960s and continues presently.
252 Using InSAR Schmidt and Bürgmann (2003) showed the regional uplift of the ground
253 surface in the Santa Clara Valley occurred from 1992 to 1999 (Figure 6a). A maximum
254 upheaval of about 4 cm, reflecting the poroelastic response of the confined aquifer
255 system, has been measured northward. In the south-eastern part of the valley a seasonal
256 uplift signal is superimposed onto the long-term trend (Figure 6b). The long-term and
257 seasonal displacements result from head changes in the aquifer system in the elastic
258 range of stress. Observed water level fluctuations and borehole extensometer records
259 provide evidence that the vertical compressibility of the confined aquifer system in the
260 virgin stress range is from 20 to 100 larger than the average c_M in the elastic range
261 (Poland and Ireland, 1988).

262 InSAR investigations (Bawden et al., 2001) show that the 20×40 km Santa Ana
263 Basin in the metropolitan area of Los Angeles displays a seasonal fluctuation with a 5
264 cm uplift during the late fall through mid-spring (Figure 7) and 6 cm subsidence during
265 the late spring through mid-fall. Seasonal water table changes of the order of 30 m
266 indicate a close relationship between aquifer management and land deformation as
267 measured by InSAR. The aquifer is recharged all year round and is pumped during May
268 - September to meet the summer water demand. Approximately 78% of the water
269 pumped from the basin in 1996-1997 came from artificial recharge through surface
270 spreading basins located in the proximity of the Santa Ana River and Santiago Creek.
271 The produced water-bearing units span the depth interval between 50 and 600 m below
272 the ground surface (MWDSC, 2007).

273 3.2.2. *Las Vegas Valley, Nevada*

274 The Las Vegas Valley is located in a structurally controlled alluvial basin containing
275 up to 1500 m of unconsolidated sediments during the Pliocene through Holocene age.
276 Coarse-grained (sand and gravel) alluvial-fan deposits derived from the surrounding
277 mountain ranges form broad piedmonts around the periphery of the valley, while
278 predominantly fine-grained (silt and clay) compressible materials underlie the central
279 part of the valley. Intervening sequences of both coarse- and fine-textured sediments
280 give rise to a well-developed multi-aquifer system cut by several Quaternary faults
281 extending from the underlying bedrock to the ground surface. Most of the groundwater
282 in the aquifer system originates from the precipitation in the Spring Mountains to the
283 west.

284 Groundwater has greatly promoted the development of Las Vegas since the early
285 1900s when the first wells were drilled in the area. The Las Vegas metropolitan area
286 increased in population from 0.8 million in 1990 to more than 1.5 million in 2000.
287 Although natural springs historically provided water to this arid valley (the average
288 precipitation in a year is about 12-20 cm), groundwater pumping was drastically
289 increased to help meet the rising demand. Total pumpage reached a peak of more than
290 100 Mm³/year in the late 1960s, remaining steadily above 70 Mm³/year until the 1990s.
291 Groundwater is mainly pumped from the upper 600 m of unconsolidated sediments. The
292 long-term effects of pumping produced a regional decline of water levels of as much as
293 90 m by 1990 with more than 1.7 m of land subsidence measured by levelling surveys
294 through 2000 (Bell et al., 2002).

295 Since 1988 the Las Vegas Valley Water District (LVVWD) has maintained a
296 groundwater recharge program in to augment the local water supply during periods of
297 high demand. Water is recharged primarily in the coolest months using treated surface
298 water imported from the nearby Lake Mead on the Colorado River. Since the beginning

299 of the artificial recharge program, water levels have stabilized and recovered by as
300 much 30 m from 1990 to 2005 (LVVWD, 2005). Persistent Scatterer InSAR for the
301 periods 1995-2000 and 2003-2005 show a general reduction of the subsidence rate and a
302 broad area of uplift with velocities as much as 1 cm/year adjacent to the easternmost
303 margin of the main artificial recharge zone (Figure 8). Seasonal displacements of the
304 order of 1 cm are superimposed on the larger uplift trend, indicating that there are both
305 short- and long-term components in the elastic response of the system. The maximum
306 seasonal uplift occurs during January through March each year during the peak period
307 of artificial recharge (Amelung et al., 1999; Bell et al., 2008).

308 Based on the available subsidence/uplift measurements, the records of water level
309 changes, and the thickness of the compacting/expanding geologic units, the ratio r
310 between the inelastic (virgin loading) and elastic (unloading/reloading) compressibility
311 of the aquifer system has been estimated to be in the interval of 3 to 20 (Hoffmann et
312 al., 2001; Bell et al., 2008).

313 **3.3. Injection for gas storage**

314 *3.3.1. Krechba field, Algeria*

315 The Krechba field is a gas reservoir located in the Algerian Sahara desert at a burial
316 depth of about 2000 m. The 20-m thick producing layer lies on a north-northwest
317 trending anticline and mainly consists of quartzose fine-grained sandstone of Early
318 Carboniferous period. The overburden comprises of a sequence of alternating
319 mudstones and sandstones. The horizontal stress field in the basin is highly anisotropic
320 with faults on the flanks of the anticline trending north-northwest. The gas produced
321 from the Krechba field contains a high mole fraction of CO₂ which must be separated
322 and disposed of for both economic and environmental reasons. The CO₂ is re-injected
323 into the reservoir through three nearby wells located at about 8 km northeast of the

324 cluster of the production wells. At the reservoir pressure the CO₂ behaves as a
325 supercritical fluid with a density of about 0.85 kg/dm³. The well-head injection pressure
326 varies during the operations with an average value of 15 MPa and peak values achieving
327 18 MPa.

328 As part of a CO₂ sequestration research project, the PSInSAR technique (Ferretti et
329 al., 2001; Colesanti et al., 2003) has been used to monitor the injection effects on the
330 ground surface (Vasco et al., 2010). The study is based on satellite radar images
331 obtained from July 12, 2003 to March 19, 2007. With this approach, stable scatterers are
332 identified using a statistically based analysis of the phase and amplitude characteristics
333 of the energy reflected by the earth surface. A subset of such scatterers is denoted as
334 permanent and used to estimate the atmospheric and orbital errors. In the Krechba field
335 case the quality of the data is particularly good because the rock outcrops in the desert
336 area are stable reflectors. The mean vertical ground velocity for the investigated 2003-
337 2007 time interval as provided by the PSInSAR data analysis is shown in Figure 9. The
338 areas shown in blue are increasing in elevation by more than 5 mm/year and are clearly
339 correlated with the location of the three injection wells. The cumulative upheaval
340 measured above the Krechba field amounts to about 2 cm with a rather uniform areal
341 distribution.

342 3.3.2. *Lombardia field, Italy*

343 To cope with the energy demand in the cold season, gas and oil companies dispose of
344 methane in exhausted reservoirs during summer and extract it during winter. In Italy
345 Stogit S.p.A. manages a number of depleted gas fields for storage purposes. The
346 Lombardia field, located in the Po river plain, Northern Italy, is one such reservoir,
347 consisting of three mineralized layers (named A, B and C) made of turbiditic sediments
348 deposited during the late Pliocene epoch with about 30-m thick shale caprocks. Layer C,

349 about 100-m thick and 1200-m deep, is the main pool containing about 93% of the
350 overall gas originally in place. About 2,700 MSm³ were produced from pool C between
351 1981 and 1986, and since 1986 pool C has been used for storage purposes. The largest
352 pore pressure drawdown achieved in 1986 was about 3 MPa. In the following years
353 water ingression from the surrounding aquifer led to a partial recovery of about 2 MPa.
354 Currently, the average operative pore pressure is about 1 MPa below the original value,
355 with a difference of 2.5 MPa between the maximum at the end of the storage phase and
356 the minimum at the end of withdrawal. The maximum pore pressure in the reservoir
357 exceeds the original in situ value by about 3% (IGU, 2003).

358 An integrated monitoring system has been implemented above the Lombardia field to
359 monitor the land movements induced by the cyclic injection-extraction activity operated
360 in the reservoir. From 2003 to 2007 traditional high-precision levelling surveys were
361 carried out yearly along with a much more frequent PSInSAR analysis. The levelling
362 surveys reveal that the region above the field exhibits a slight upheaval trend with a
363 positive vertical ground velocity of about 1 mm/year. The PSInSAR data do show
364 cyclic ups and downs phased with the pressure variation within the reservoir. An
365 example of the vertical displacements vs. time for a few pixels from the PSInSAR
366 analysis located above the field is given in Figure 10, with the magnitude of the
367 occurrence gradually dissipating on the observation points farther from the reservoir.
368 Apart from the general upheaval trend, that is most likely of tectonic origin, land motion
369 appears to be elastic with an average difference between the peak values of about 1 cm.
370 A spatial kriging interpolation of the satellite images was used to map the areal
371 distribution of the vertical displacements above the reservoir. As an example, Figure 11
372 shows maps over the periods November 2005 – April 2006 (a) and April 2006 –
373 November 2006 (b). In the former time interval gas is withdrawn and land subsides, and
374 in the latter gas is injected and the land rises by about the same magnitude. Moving

375 farther from the reservoir boundary the vertical displacements quickly vanish and
376 appear to be un-influenced by gas storage.

377 A modeling study by Castelletto et al. (2010) and Teatini et al. (2010) shows that the
378 PS records are successfully matched with a finite element model using a loading
379 unloading-reloading compressibility ratio of 4.

380 **3.4. Injection for land subsidence mitigation**

381 *3.4.1. Wilmington, Long Beach, California*

382 The Wilmington oil field is a broad asymmetrical anticline extending lengthwise
383 approximately 18 km in a SE-NW direction and about 5 km in the SW-NE direction
384 below Long Beach, in the southwestern part of the Los Angeles basin, California. The
385 reservoir is made of seven overlying oil-bearing formations of the Pliocene and
386 Miocene epoch spanning the depth range 600-2000 m below m.s.l. The pools are
387 divided into six structural blocks by five major faults that restrict the fluid flow between
388 the blocks. The sediments predominantly comprise rather loose and unconsolidated
389 sands and siltstones, with intervening shale layers (Mayuga and Allen, 1970).

390 Because of limited waterdrive activity, the pressure decline in the oil reservoir was
391 relatively fast. By the mid-1960s about 9 MPa. of drawdown at 900 m depth, and nearly
392 9 m of land subsidence had occurred since the onset of production (Allen and Mayuga,
393 1970). The subsidence above the field was clearly recognized in 1941 when the U.S.
394 Coast and Geodetic Survey surveyed the levelling lines between San Pedro and Long
395 Beach, which had been previously monitored in 1933-1934. Subsequent measurements
396 showed increasing subsidence up to the maximum 9 m value experienced in 1965
397 (Colazas and Olson, 1983). Results from precision casing collar surveys, i.e. the
398 periodic monitoring of the shortening (or lengthening) of well casing joints due to the

399 compaction (or expansion) of the oil-bearing formations (Law, 1950), provided
400 evidence that compaction occurred over the 650-1100 m depth interval.

401 In order to mitigate land settlement a massive water injection program was
402 implemented in the late 1950s. Approximately 175,000 m³/day of water were injected
403 into the field during the 1960s (Mayuga and Allen, 1970), declining to 90,000 m³/day
404 by the mid-1990s (Otott Jr and Clark, 1996). Both seawater withdrawn from shallow
405 beds directly connected with the ocean and formation water produced along with the oil
406 were used for injection. Subsidence stopped over a large portion of the field with the
407 subsiding area reduced from 50 km² to 8 km². The settlement rate at the historical centre
408 of the subsidence bowl was reduced from a maximum of 71 cm/year in 1951 to zero in
409 1968, and in certain areas a surface rebound up to 33 cm was observed (Figure 12a). In
410 the newest portions of the Wilmington field waterflooding and oil production began
411 almost simultaneously. No significant subsidence occurred in those areas with over-
412 injection generating a 20 cm increase of the original ground elevation (Figure 12b)
413 (Colazas and Olson, 1983).

414 In-situ measurements by casing joints (Allen and Mayuga, 1970), lab tests at high
415 confining pressures (Vesić and Clough, 1968) and numerical modelling (Kosloff et al.,
416 1980a, 1980b) suggest that the Wilmington sandy formations under unloading/reloading
417 are from 2 to 8 times stiffer than for virgin loading conditions.

418 3.4.2. *Tokyo and Osaka, Japan*

419 Over the 1950s-1960s a significant lowering of the groundwater level occurred in all
420 the major cities of Japan because of an uncontrolled overdraft of the shallow multi-
421 aquifer systems. For example, the resulting land settlement in Tokyo was reported to be
422 about 4.5 m relative to the ground elevation at the early 1920s (Yamamoto, 1995) with a
423 number of serious related social problems. Full scale development of the aquifer system

424 in Tokyo started in 1914. After that time, the number of deep wells increased very
425 quickly. The hydraulic head kept on falling year after year due to pumping from the
426 upper 300 m thick multi-aquifer, and after a temporary recovery during World War II, it
427 achieved its lowest value of about -70 m below the mean sea level of the Tokyo Bay
428 (Yamamoto, 1984).

429 To mitigate the anthropogenic settlement new regulations were established from the
430 early 1970s throughout Japan to control of the groundwater use. As a major
431 consequence groundwater level has increased over the last decades in all the major
432 Japanese cities, including Tokyo and Osaka, and this has been accompanied by a
433 general ground upheaval. This has been carefully monitored by local administrations in
434 order to prevent possible deformations of the underground structures. As an example,
435 Figure 13 shows the piezometric increase and the associated vertical uplift for the city
436 of Tokyo. Inspection of Figure 13a reveals the close relationship between aquifer
437 recovery occurring after the implementation of the 1970 regulations and land upheaval,
438 which amounts to about 20 cm. The areal distribution of the Tokyo uplift from 1991 to
439 2005 is shown in Figure 13b, with several zones experiencing an uplift of more than 5
440 cm and a slightly irregular pattern. Similar results are found for the city of Osaka where
441 several urban areas experienced uplift of about 3 cm in 5 years (Sreng et al., 2009).

442 3.4.3. *Taipei, Northern Taiwan*

443 Taipei City is the political and economical centre of Taiwan with a dense population
444 of about 3 million inhabitants plus several million people in the surrounding suburban
445 areas. Like many other big cities in the world, early development of the city was
446 enhanced by the development of the groundwater resources. The city centre lies on 300-
447 m thick late-Quaternary fluvial deposits laid down over deformed Miocene bedrock
448 starting from about 400,000 years ago.

449 Groundwater pumping mainly occurred from 1955 to 1970 from a confined aquifer
450 lying between 50 and 140 m depth below the ground surface. Piezometric head has
451 decreased by more than 40 m with the lowest value reached in 1975. The massive
452 pumping was accompanied by large land settlements amounting to as much as 2.2 m in
453 the city centre (Wu, 1977). In order to mitigate the subsidence and prevent any possible
454 associated damages, the government stopped the use of groundwater in the Taipei Basin
455 during the early 1970s. The settlement rate has significantly decreased as the hydraulic
456 head gradually recovered and stabilized after approximately the late 1990s. The
457 establishment of a fine network of levelling benchmarks has allowed for accurate
458 monitoring and control of the ground movements during the recovery. The behaviour of
459 the post-pumping ground elevation is characterized by a relatively long period of
460 declining subsidence followed by a period of uplift from 1989 to 2003. Most surface
461 rebound was observed in the central to eastern portion of the basin, roughly
462 corresponding to the area of maximum subsidence. From 1989 to 2003 most of the
463 Taipei Basin, except for its westernmost margin, experienced a rather homogeneous
464 uplift of 7 to 10 cm with a maximum of 17 cm (Figure 14a). The largest rate, more than
465 1 cm/year, was measured between 1989 and 1994 (Figure 14b). The observed elastic
466 rebound was used to quantify a ratio of about 10 between the aquifer-system
467 compressibility under virgin loading and unloading/reloading conditions (Chen et al.,
468 2007).

469 3.4.4. *Chioggia Mare, Northern Adriatic, Italy*

470 ENI-E&P, the Italian national oil company, has recently advanced a plan for the
471 development of a number of gas fields (about 15) located in the Northern Adriatic. The
472 largest field, named Chioggia Mare, is the closest to the coastline (the westernmost
473 margin of the field is 12 km from the city of Chioggia, south of Venice). Gas production

474 from Chioggia Mare raises some concerns about the risk of contributing to
475 anthropogenic settlement of Chioggia and the surrounding lagoon, including Venice. To
476 offset this environmental hazard ENI-E&P designed a project of land subsidence
477 mitigation using two deep seawater injection wells located halfway between the field
478 and the coastline. The Italian Ministry of Environment gave the University of Padova,
479 Department of Mathematical Models and Methods for the Scientific Applications
480 (DMMMSA), the task of checking the environmental sustainability of the ENI-E&P
481 mitigation programme, with the aid of ad hoc numerical models able to reliably predict
482 the expected land subsidence in the presence of the injection wells. The Chioggia Mare
483 gas field is seated at a 1100-1400 m depth and consists of four pools. The upper pools
484 (C and C2) are formed by a structural trap and the lower ones (E and Ea) pinch out
485 against a thick clayey formation (called Santerno), which represents a natural hydraulic
486 barrier. The estimated total gas withdrawn from Chioggia Mare over its 12-year
487 production life will be about 5,000 MSm³. Pools C and C2 are surrounded by a strong
488 lateral and bottom waterdrive. The lateral aquifer partially encompassing pools E and
489 Ea is much weaker. More detailed information about the geology and the properties of
490 Chioggia Mare are provided in Teatini et al. (2000).

491 Injection of seawater is planned to take place in pool C lateral aquifer at a rate of
492 5,000 m³/day for 25 years after the inception of gas production. The injected water will
493 be properly filtered to remove particles larger than 5-10 µm that could cause a reduction
494 of the aquifer permeability. It will be also chemically treated for compatibility with the
495 in situ water to avoid the activation of corrosion of the well intakes. Figures 15a and
496 15b show the simulated fluid pore pressure variation in pool C and the associated
497 waterdrive predicted at the end of the field production life without and with the injection
498 of water. It can be noted that the depressurization caused by gas pumping does not
499 propagate coastward because of the barrier effect exerted by the injection wells. Note

500 also the overpressure experienced by the waterdrive in the vicinity of the injection
501 boreholes. The simulated influence of injection on vertical ground displacement is
502 shown in Figures 15c and 15d. In the present case, water injection helps mitigate the
503 expected land subsidence and does not necessarily induce an appreciable anthropogenic
504 heave. Figure 16 shows the simulated vertical ground displacement in Chioggia without
505 and with the injection wells for the various plausible combinations of hydro-geo-
506 mechanical parameters investigated by Gambolati et al. (1998) in their report to the
507 Ministry. As an example, in the most favourable scenario using geomechanical
508 properties derived from lab tests, the predicted land uplift occurs 13 years after the
509 cessation of gas withdrawal and is on the order of 6 mm.

510 3.4.5. Ravenna, Adriatic coastline, Italy

511 The Ravenna Adriatic coastline is underlain by a major gas field, named Angela-
512 Angelina (Figure 17a), that extends down to 2900-4000 m depth and consists of a very
513 large number of gas pools (about 300) separated by intervening clayey layers and
514 crossed by a number of geological faults. Initially, the gas reserve was estimated to be
515 22,000 MSm³ of which about 12,000 were produced as of January 2002 and 10,000
516 more are planned to be pumped out over the following 25-30 years. In a few depleted
517 pools the maximum fluid pore pressure drawdown has amounted to as much as 35 MPa.
518 The land subsidence caused by gas production in the vicinity of Angela-Angelina has
519 received the attention of a number of studies (Teatini et al., 1998; Gambolati et al.,
520 1999; Schroot et al., 2005) and is a matter of concern regarding the stability of the
521 Ravenna coastland. To mitigate it, ENI-E&P has implemented an experimental project
522 called “Angela Pressure Maintenance” with the final objective to oppose the anticipated
523 coastland settlement through the injection of water in the aquifer connected to the

524 reservoir over the depth interval 3100-3700 m. The ENI-E&P injection project was
525 designed in 2001 and consists of three phases (Figure 17b):

- 526 1- re-injection of the formation water, i.e. the water extracted along with the gas
527 from Angela-Angelina and the nearby offshore fields Amelia, Antares and Porto
528 Corsini Mare. At the beginning of the operation in 2003, the injection rate was
529 $150 \text{ m}^3/\text{day}$ and soon increased to $300 \text{ m}^3/\text{day}$ with the addition of the seawater
530 obtained with the aid of the Beach Management System (BMS) (Ciavola, 2005;
531 Piccini et al., 2006) and chemically treated for compatibility with the situ water;
- 532 2- increase of the injection rate using additional wells from the cluster Angela;
- 533 3- further increase of the injection rate using the dismissed production wells from
534 the Angela-Angelina platform.

535 The cumulative water injected from March 2003 to April 2007 is shown in Figure
536 17c (ENI, 2007). Despite the very modest quantity of water injected underground some
537 benefits in terms of a delayed propagation of the depressurization below the coastline
538 have been observed. No evidence is so far available of any significant mitigation of land
539 subsidence. However, the ENI-E&P pressure maintenance experiment is of great
540 practical interest, and especially so in view of the planned progressively increased rate
541 of injection. Future modelling predictions and field measurements will help reveal the
542 hopefully effective impact of the above programme.

543 By the use of recent geophysical logs and marker measurements from deep offshore
544 boreholes drilled in the vicinity of Angela-Angelina, Baù et al. (2002) estimate a ratio r
545 between loading and unloading-reloading c_M ranging from 3 to 2 over the depth interval
546 3000–4000 m. However, because of the large injection depth, the medium
547 compressibility in expansion is expected to be about one order of magnitude smaller
548 than that of the shallower Chioggia Mare field.

549 **3.5. Injection for geomechanical characterization. Upper Palatinate, Bavaria,**
550 **Germany**

551 A water injection experiment intended to study deformation of the upper crust,
552 improve knowledge of coupled hydro-geomechanical processes and characterize the
553 affected subsurface porous medium was performed from June 2004 to April 2005 in the
554 Upper Palatinate, Eastern Bavaria, Germany (Kumpel et al., 2006). Water was injected
555 at a rate of about 290 m³/day to a total of 84,000 m³ through an open hole that was
556 3850-4000 m deep. Land deformation was monitored by high-resolution borehole
557 tiltmeters installed at 5 locations (Berg, Eiglasdrof, Stockau, Mittelberg and
558 Pullersreuth) at a variable 1.5-3.3 km distance from the injection well denoted as
559 Kontinentale Tiefbohrung der Bundesrepublik Deutschland (KTB) (Jahr et al., 2005,
560 2006). The pore pressure increase exceeded 10 MPa at KTB over the injection time and
561 induced a land deformation that was detected by the tiltmeter array. The measured tilts
562 were reproduced with the aid of a finite element model. The results (Jahr et al., 2008)
563 reveal a maximum anthropogenic uplift of approximately 3 mm above the injection
564 point which dissipates quickly as one moves far from it (Figure 18a). Figure 18b shows
565 the modelling reconstruction of the tiltmeter measurements around KTB.

566 **4. DISCUSSION AND CONCLUSIONS**

567 A survey of sites worldwide where underground fluid (water, gas, steam) injection
568 has caused a measurable land uplift (or heave) has been performed. Fluid is injected for
569 a variety of purposes, from enhancing oil production to storing gas in depleted gas/oil
570 fields, recharging pumped aquifers, disposing of industrial liquid wastes and mitigating
571 anthropogenic land subsidence. Vertical land displacement is measured using traditional
572 levelling, tiltmeters, or, most recently and relatively inexpensively, with the aid of the
573 satellite interferometry. Land may rise as a consequence of the migration to ground

574 surface of the injected formation expansion. This is due primarily to the release of the
575 effective intergranular stress and secondarily to the shear dilation (or dilatancy) on
576 condition that the induced fluid pore overpressure is large enough so as the yield surface
577 (or friction line) is intersected by the Mohr-Coulomb circles. Thermal expansion may
578 also contribute significantly to the observed heave. Careful inspection of each single
579 occurrence reveals that:

- 580 1- the observed land uplift may vary from a few millimetres to tens of centimetres
581 over a time interval of some months to several years according to the specific
582 location;
- 583 2- the largest uplift depends on a number of factors, including the fluid pore
584 pressure increase, the depth, thickness and areal extent of the pressurized and
585 heated geological formation, and the hydro-geo-thermo-mechanical properties of
586 the porous medium involved in the process.

587 The uniformity of uplift at the ground surface is basically related to the location,
588 arrangement, and strength of the injection sources and the depth of the injection that, in
589 turn, depend on the purpose of the disposal. If the injected formation is deep enough,
590 the uplift may be expected to be rather uniform for a regular distribution of the injection
591 wells. Conversely, if the injection is irregularly distributed and the injected formation is
592 shallow, the anthropogenic uplift may result in irregular patterns.

593 The case studies described above provide a clear affirmative answer to the question: is it
594 physically possible to appreciably raise the ground surface by injecting fluids
595 underground? This concern has been advanced by a few geotechnical and hydrological
596 experts (see Ferronato et al., 2008), in relation to a possible anthropogenic land uplift as
597 an innovative defence from periodical flooding that affect high-value coastal areas that
598 are experiencing land settlement and/or sea level rise due to climate changes. Recent
599 modeling studies (Comerlati et al., 2003, 2004) suggest that injecting seawater into a

600 600- to 800-meter-deep brackish aquifer underlying Venice, Italy, might induce an
601 upheaval of this much loved city by 25–30 cm over 10 years. Such an uplift would be
602 enough to offset the most likely scenario of relative sea level rise expected in 2100
603 (Carbognin et al., 2009).

604 A second point enlightened by the present survey regards the ratio r of virgin to second
605 cycle elastic compressibility c_M . The available data are summarized in Figure 19 and
606 show that, almost irrespectively of the site, r tends to increase for shallower depth. If at
607 very large depths the virgin c_M is only from two to three times the elastic c_M , in shallow
608 aquifer systems (~50-300 m) the former can be one order of magnitude larger than the
609 latter. The actual prediction of the expected medium expansion due to fluid injection,
610 and thus the related ground uplift, requires the knowledge of c_M in the unloading-
611 reloading cycle. On first approximation, it might be obtained from the more frequently
612 and easily known c_M in virgin loading and a r estimate based on the depth of the
613 injected formation. For sure, a more accurate evaluation requires a site-specific
614 investigation. This is why, concerning the project mentioned above of anthropogenic
615 Venice raising, a pilot ad hoc injection experiment has been recently advanced
616 (Castelletto et al., 2008).

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- 849

849 **FIGURE CAPTIONS**

850 **Figure 1.** Mohr-Coulomb circles. When the pore pressure p increases because of fluid
851 injection, the circles move leftward and may achieve the limiting yield surface or
852 friction line $\tau = c + \sigma_n \tan \phi$ where σ and τ are the normal and shear stress, respectively,
853 c is cohesion and ϕ the friction angle. τ_m and τ_m^* are the current largest and maximum
854 allowable shear stress, respectively, σ_1 and σ_3 the maximum and minimum principal
855 stress, respectively.

856 **Figure 2.** (a) Differential heave in 3 pads of the Cold Lake CSS during one steam
857 injection period (modified from Wong and Kry, 1997). The upper figure is the total
858 heave at the beginning of the period, and the lower figure is the incremental heave
859 between the beginning and the end of the one month period. (b) Deformations over a
860 time period of 86 days (August 5, 1996 – November 1, 1996) measured by InSAR in
861 Cold Lake CSS project (adapted from Stancliff and van der Kooij, 2001). Uplift is
862 positive.

863 **Figure 3.** Heave (a) over a one-year period and (b) from April 26, 2005 to June 5, 2005
864 calculated by tiltmeter data in the Shell Canada Peace River CSS project (modified from
865 Du et al., 2005).

866 **Figure 4.** Distribution of heave with depth from September 1993 to April 1994 at the
867 UTF BE2 extensometer site (adapted from Collins, 2007).

868 **Figure 5.** Heave (a) in the MacKay River SAGD project from December 2002 to
869 December 2007. The leveling monuments used to map the ground displacements are
870 shown. (b) Heave development in time along the cross section AB traced in (a)
871 (modified from Petro-Canada, 2008).

872 **Figure 6.** Vertical land displacement recorded by Differential InSAR in the Santa Clara
873 Valley, California. (a) Cumulative uplift measured from September 1992 to October
874 1999; (b) seasonal upheaval measured from August 1998 to March 1999. The bottom

875 insets shows the time series at two points illustrating the seasonal vs. long-term
876 deformation pattern partitioned by the Silver Creek (modified after Schmidt and
877 Bürgmann, 2003; Galloway and Hoffmann, 2007).

878 **Figure 7.** (a) Ground displacement in the Santa Ana Basin, California, detected by
879 Differential InSAR from July 1998 to January 1999. (b) Uplift behaviour along the A-
880 A' cross-section traced in (a) (modified after Bawden et al., 2001).

881 **Figure 8.** Velocity map for the northwest portion of Las Vegas Valley, Nevada,
882 obtained by Persistent Scatterer InSAR from ENVISAT data between April 2003 and
883 May 2005. The contour lines of the water-level change (m) recorded in the same
884 interval are shown. The inset on the right shows the time series of the vertical
885 displacement for the persistent scatterer indicated on the map (modified after Bell et al.,
886 2008).

887 **Figure 9.** Mean land vertical velocity above the Krechba field, Algeria, as detected by
888 the analysis of PSInSAR data in the period 2003-2007 (modified after Vasco et al.,
889 2010).

890 **Figure 10.** Vertical displacements (mm) vs. time for a few pixels monitored by InSAR
891 located above the Lombardia field, northern Italy.

892 **Figure 11.** Land vertical displacements above the Lombardia field between: (a)
893 November 2005 and April 2006; (b) April 2006 and November 2006. The maps are
894 obtained with a kriging interpolation of InSAR data. The reservoir outline is also
895 shown.

896 **Figure 12.** (a) Land uplift (inches) at Long Beach, California, from 1958 to 1975 as a
897 result of elastic unloading caused by repressurization of the producing field blocks
898 (modified after Kosloff et al., 1980b). (b) Increase in elevation (feet) measured at a
899 leveling benchmark above a eastern block of the Wilmington field (modified after
900 Colazas and Olson, 1983).

901 **Figure 13.** Ground upheaval in Tokyo: (a) groundwater level and vertical displacement
902 over period 1962-2005; (b) cumulative upheaval distribution in the urban area over the
903 period 1991-2005 (modified after Sreng et al., 2009).

904 **Figure 14.** (a) Map of land uplift in the Taipei basin from 1989 and 2003 as obtained by
905 interpolation of the leveling records. (b) Land upheaval rate over the period 1989-1994
906 (modified after Chen et al., 2007).

907 **Figure 15.** Fluid pore pressure change (10^{-1} MPa, above) and anthropogenic land
908 subsidence (cm, below) at the end of the Chioggia Mare gas field production life as
909 predicted with the aid of numerical models: (a) and (c) without, (b) and (d) with the
910 seawater injection wells. Negative values denote pressure decline, positive values
911 pressure increase. The outline of the Chioggia Mare reservoir is also shown (modified
912 after Teatini et al., 2000).

913 **Figure 16.** Anthropogenic land subsidence and land heave in Chioggia as predicted
914 with the aid of numerical models without (solid lines) and with (dashed lines) seawater
915 injection wells for the various hydro-geo-mechanical scenarios addressed by Gambolati
916 et al. (1998).

917 **Figure 17.** (a) Location of the Angela-Angelina gas field along the Northern Adriatic
918 coastline, Italy. The trace of the reservoir is highlighted in red. (b) Representation of the
919 three-phase ENI-E&P injection programme “Angela Pressure Maintenance”. (c)
920 Cumulative volume of water injected from March 2003 to April 2007 in the ENI-E&P
921 injection programme “Angela Pressure Maintenance”.

922 **Figure 18.** Results from the finite element interpretation and reconstruction of the
923 tiltmeter measurements: (a) land uplift; (b) tilts at the land surface (modified after Jahr
924 et al., 2008).

925 **Figure 19.** Ratio r between virgin and second cycle elastic compressibility versus depth
926 as derived from the case studies addressed in the present paper (1: Santa Clara Valley,

- 927 California; 2: Las Vegas Valley, Nevada; 3: Lombardia field, Italy; 4: Wilmington,
928 California; 5: Taipei, Taiwan; and 6: Ravenna, Italy).

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Figure 1

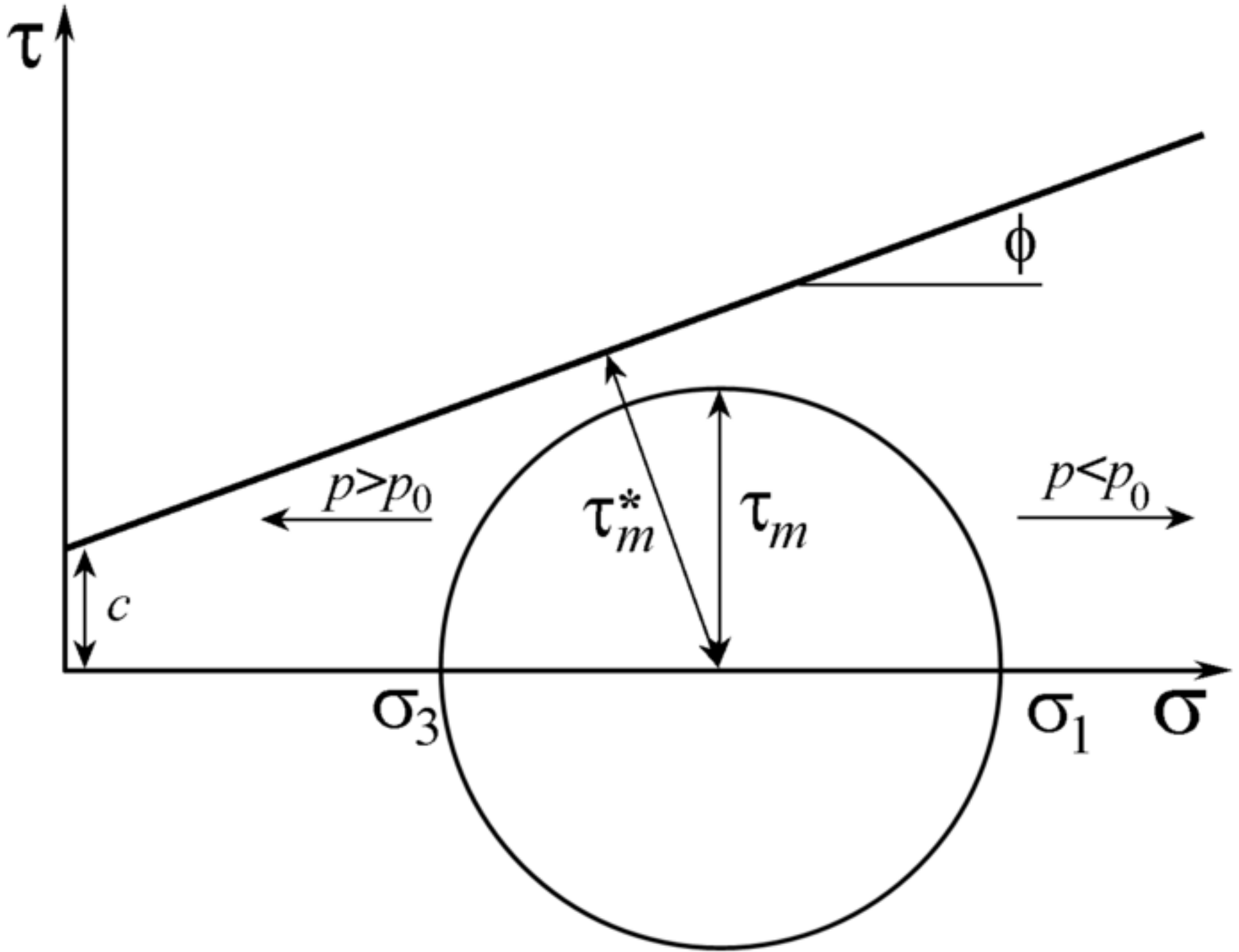


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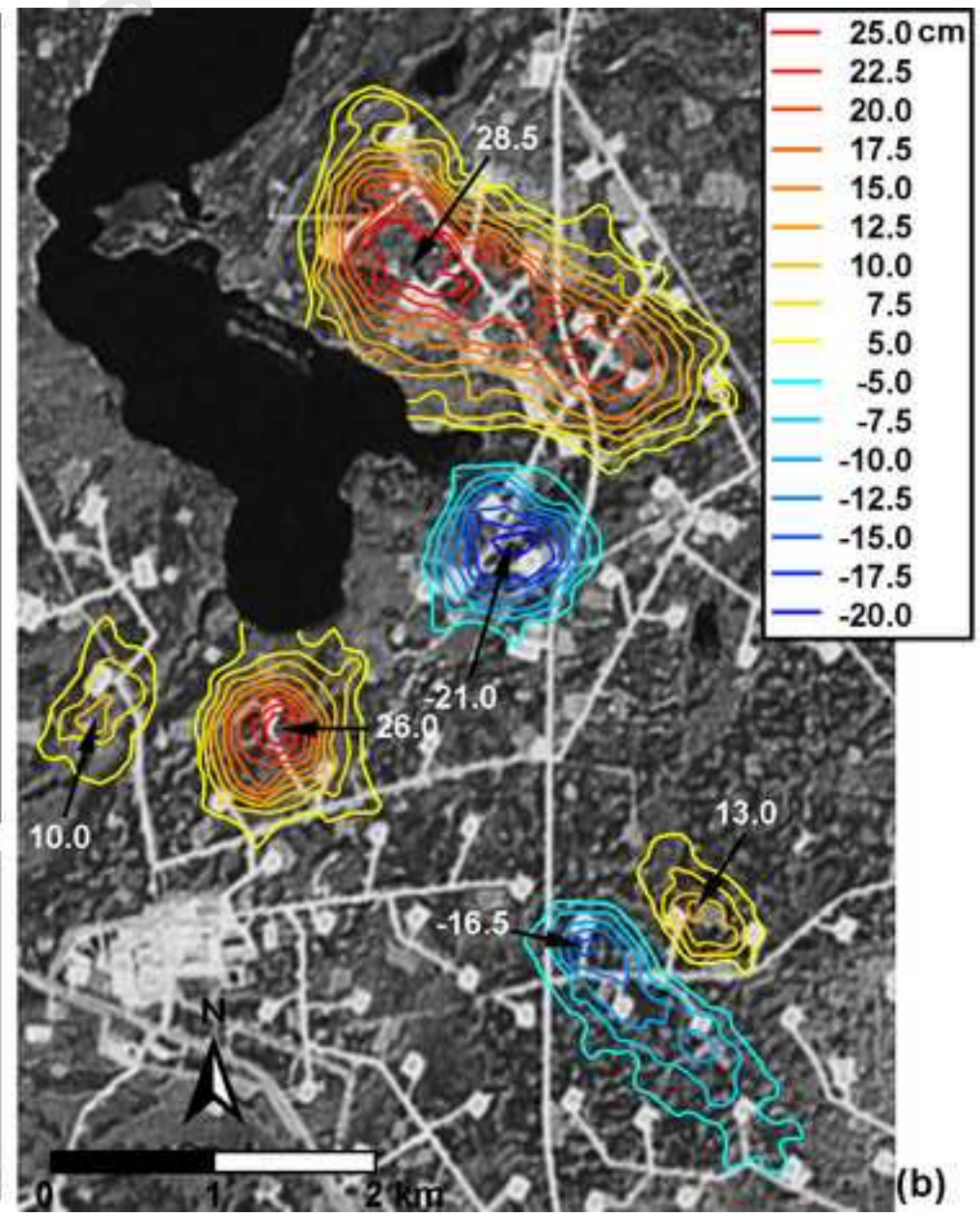
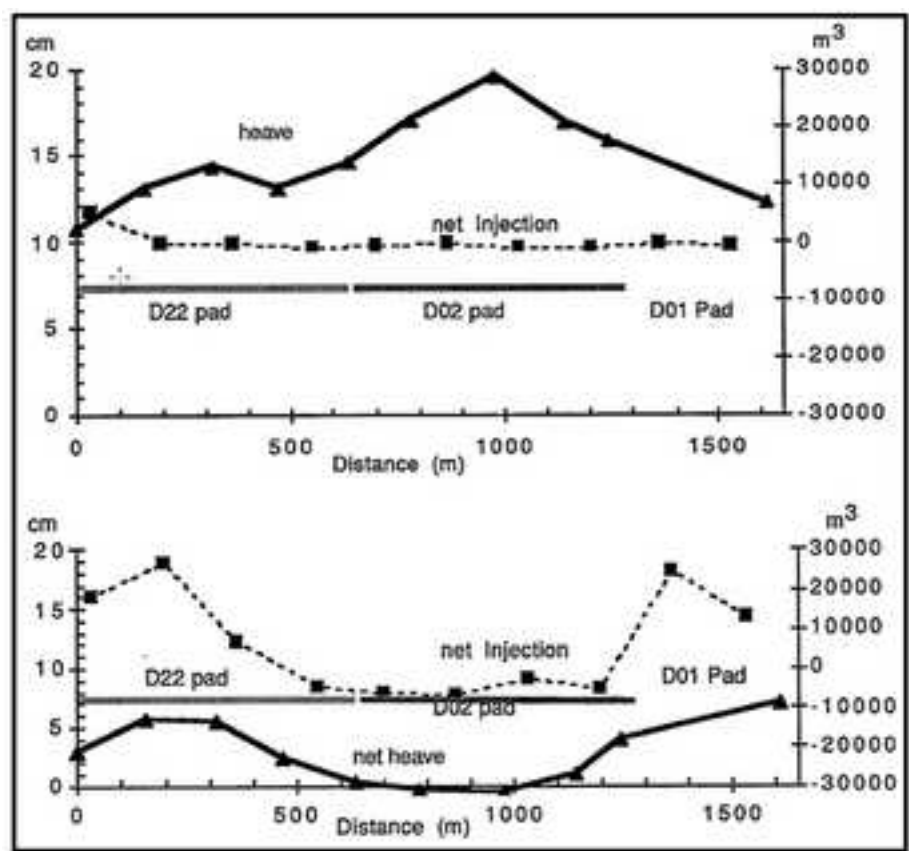


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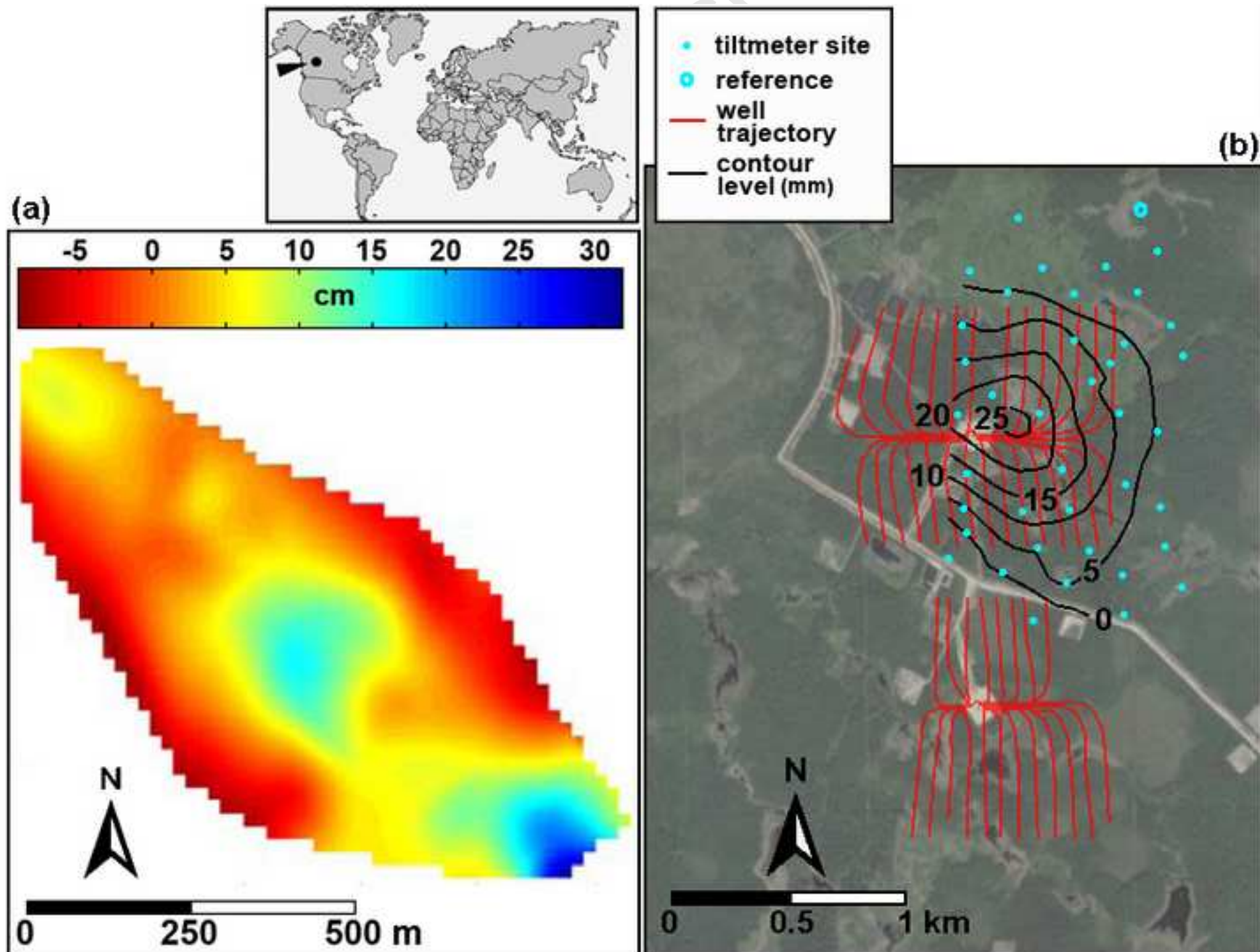


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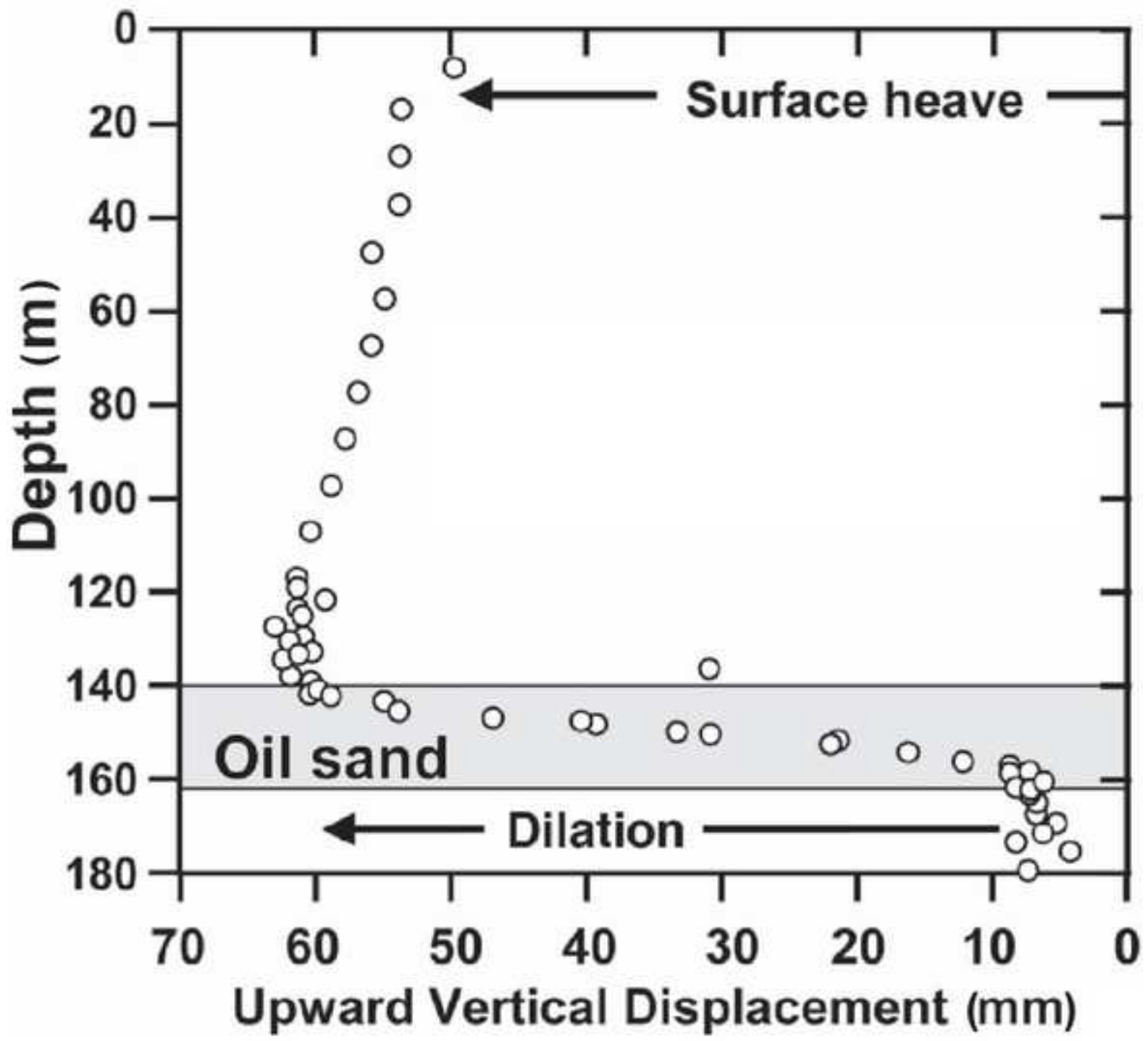


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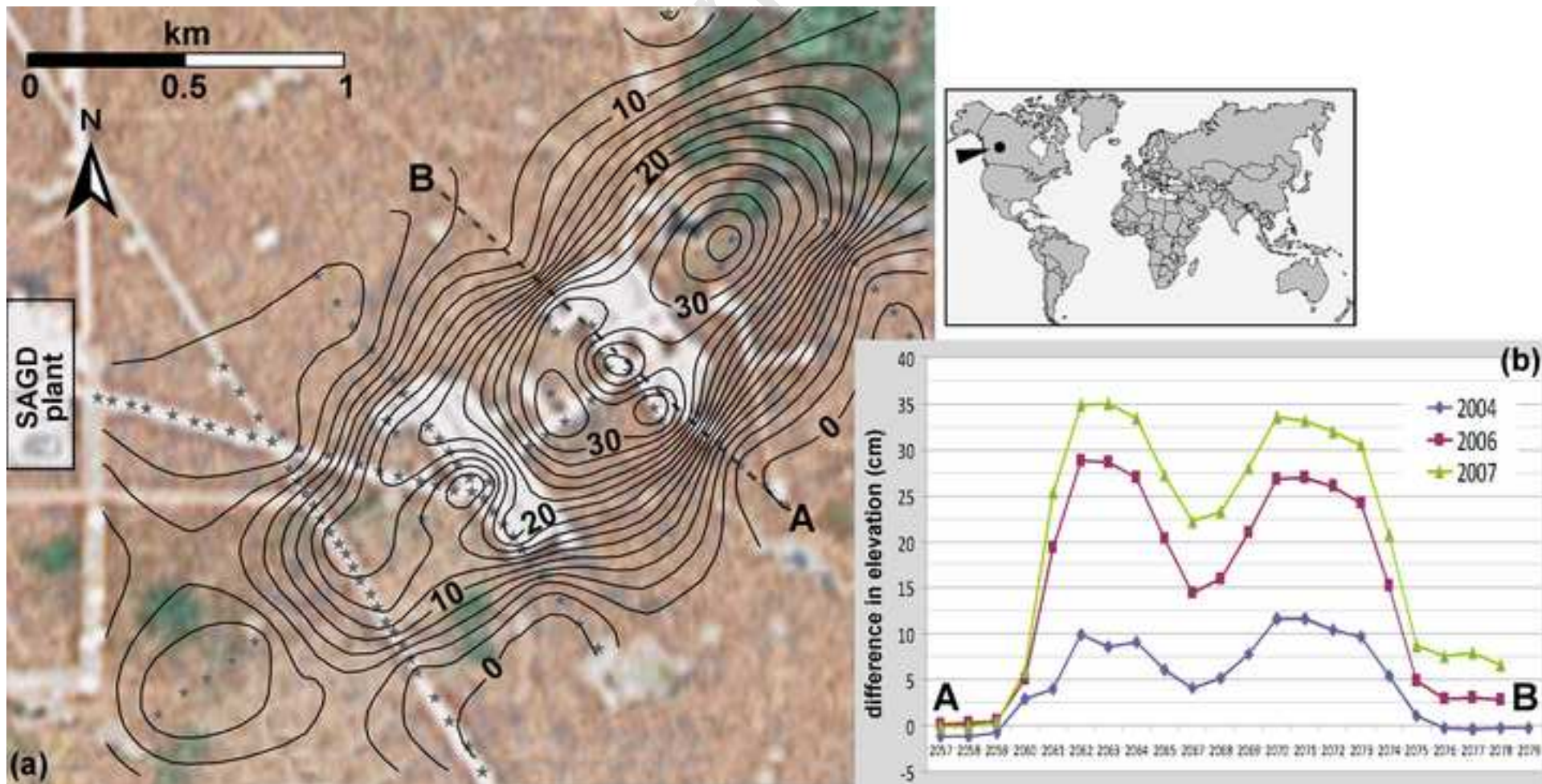


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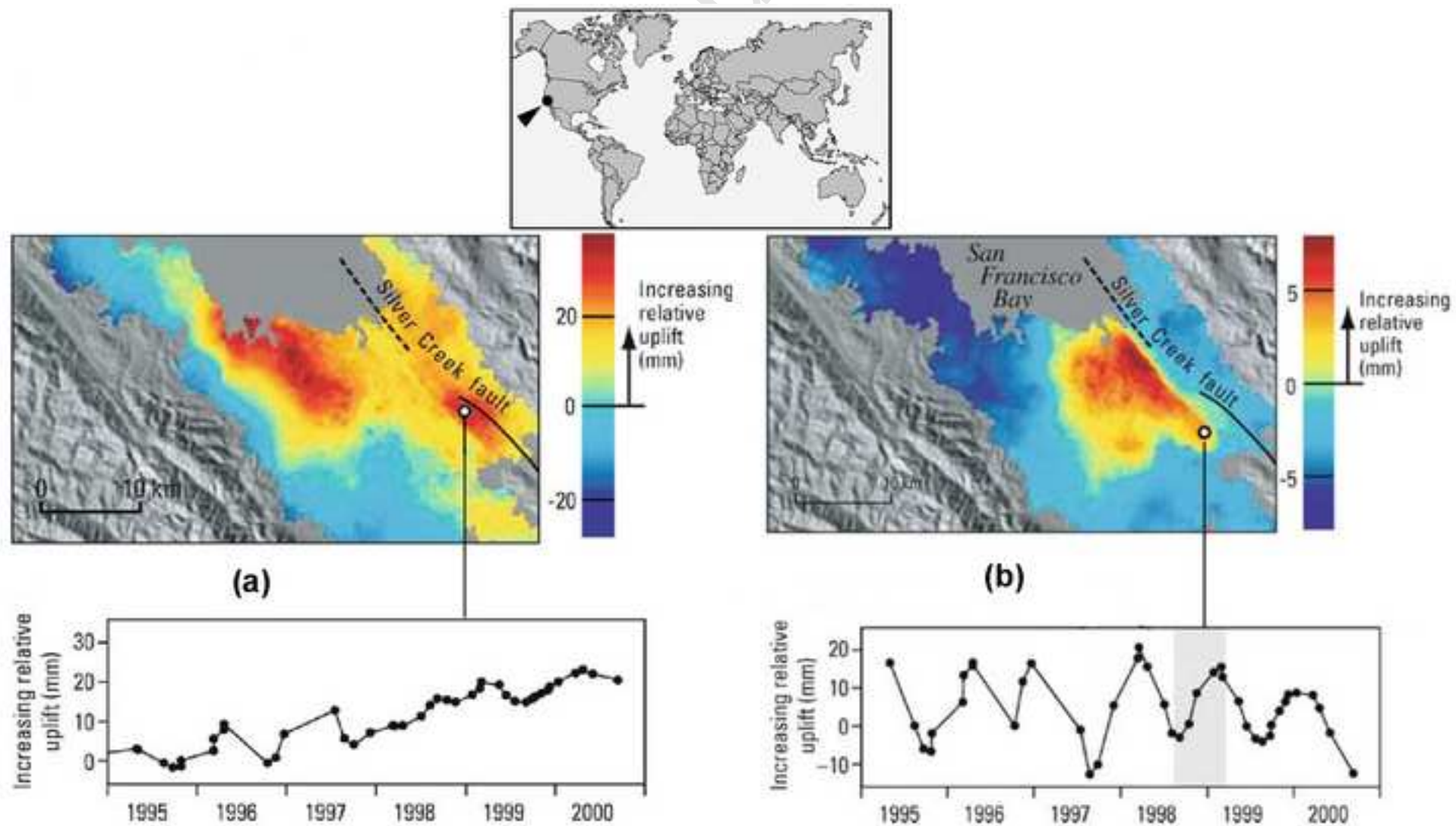


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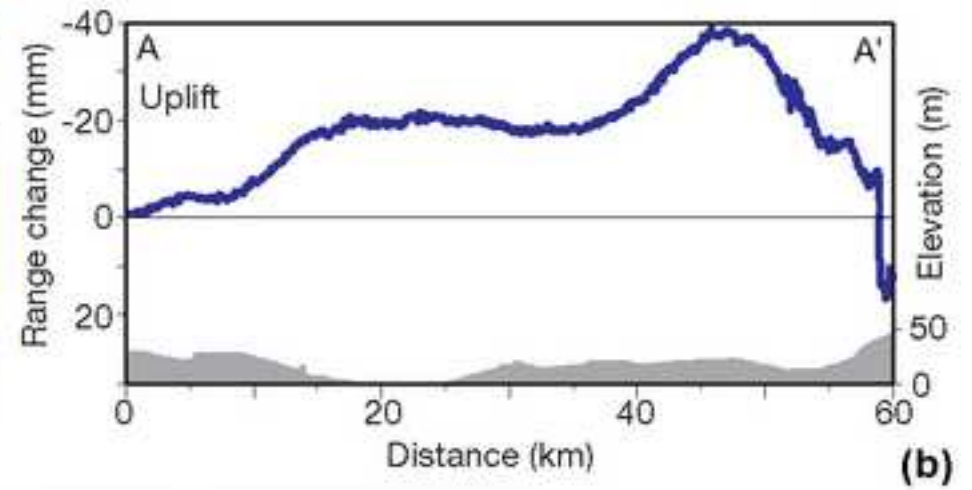
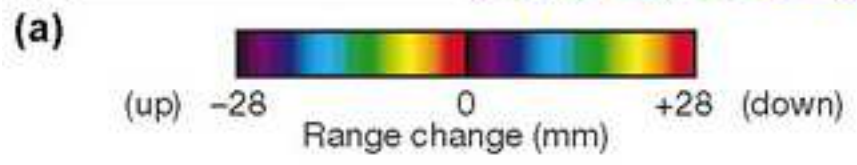
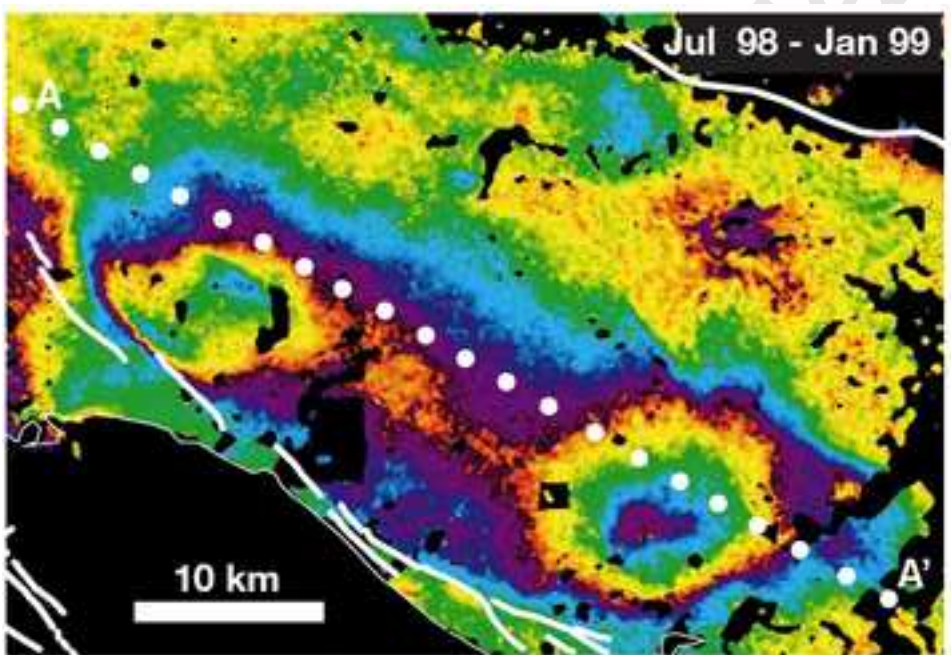


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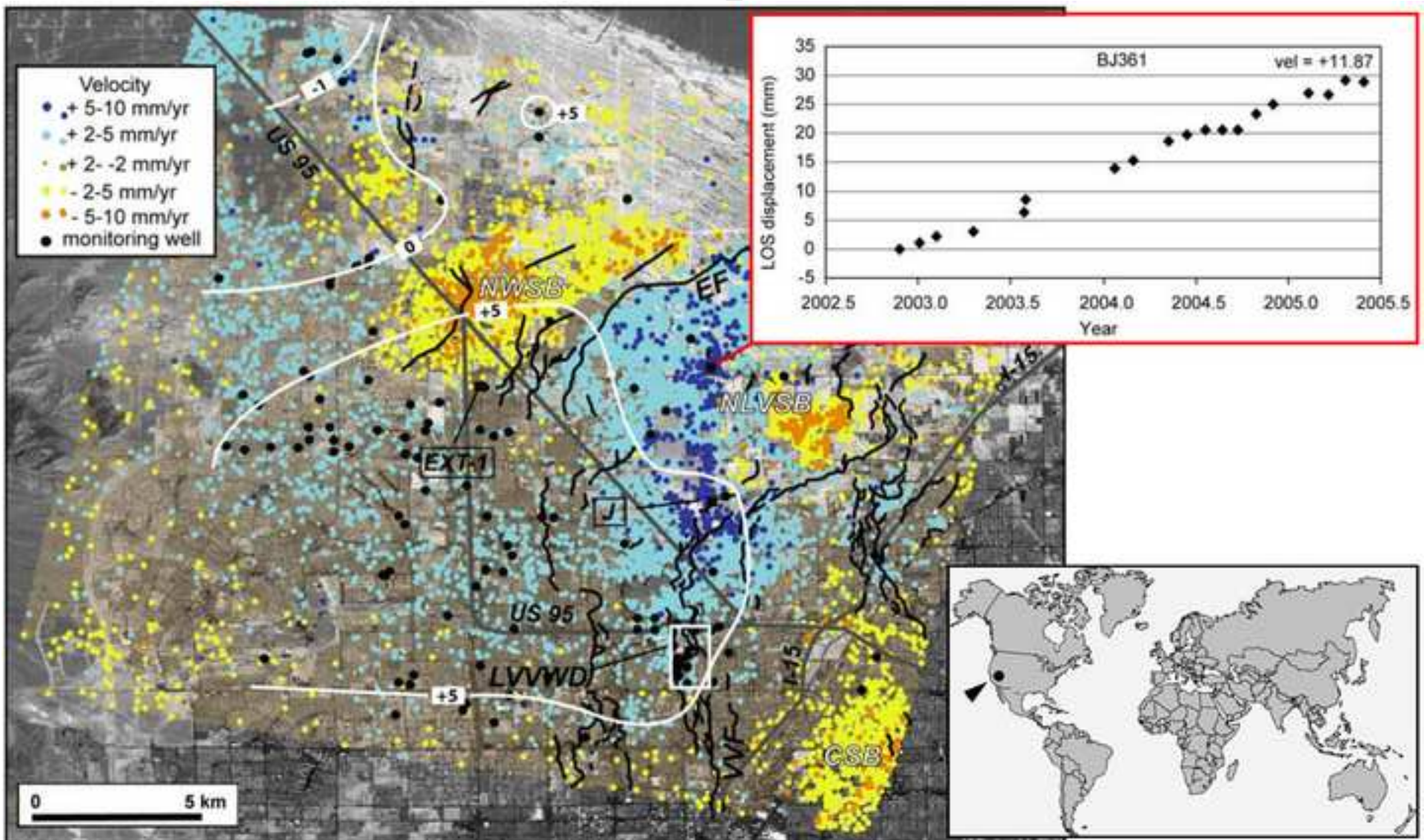


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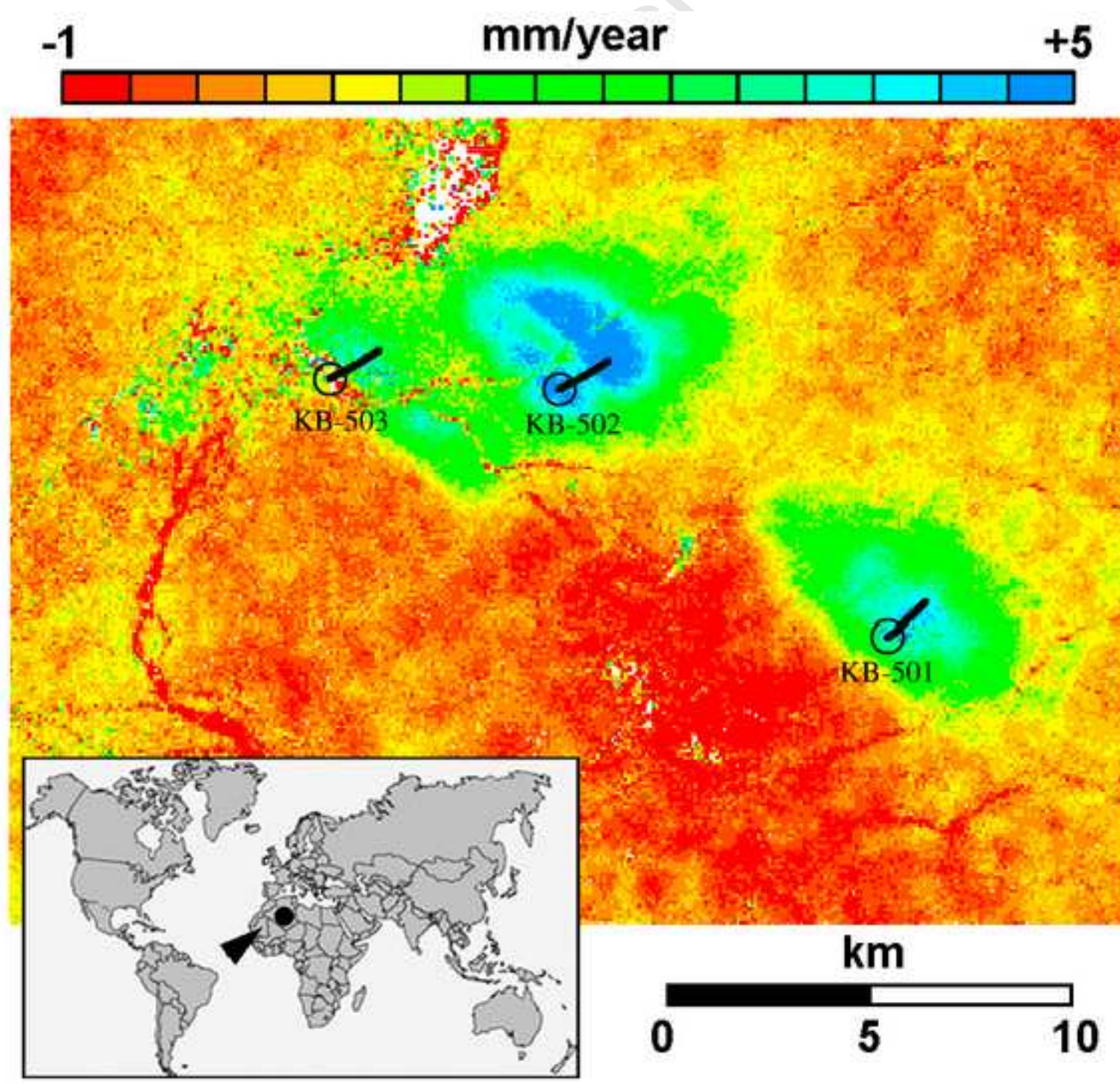
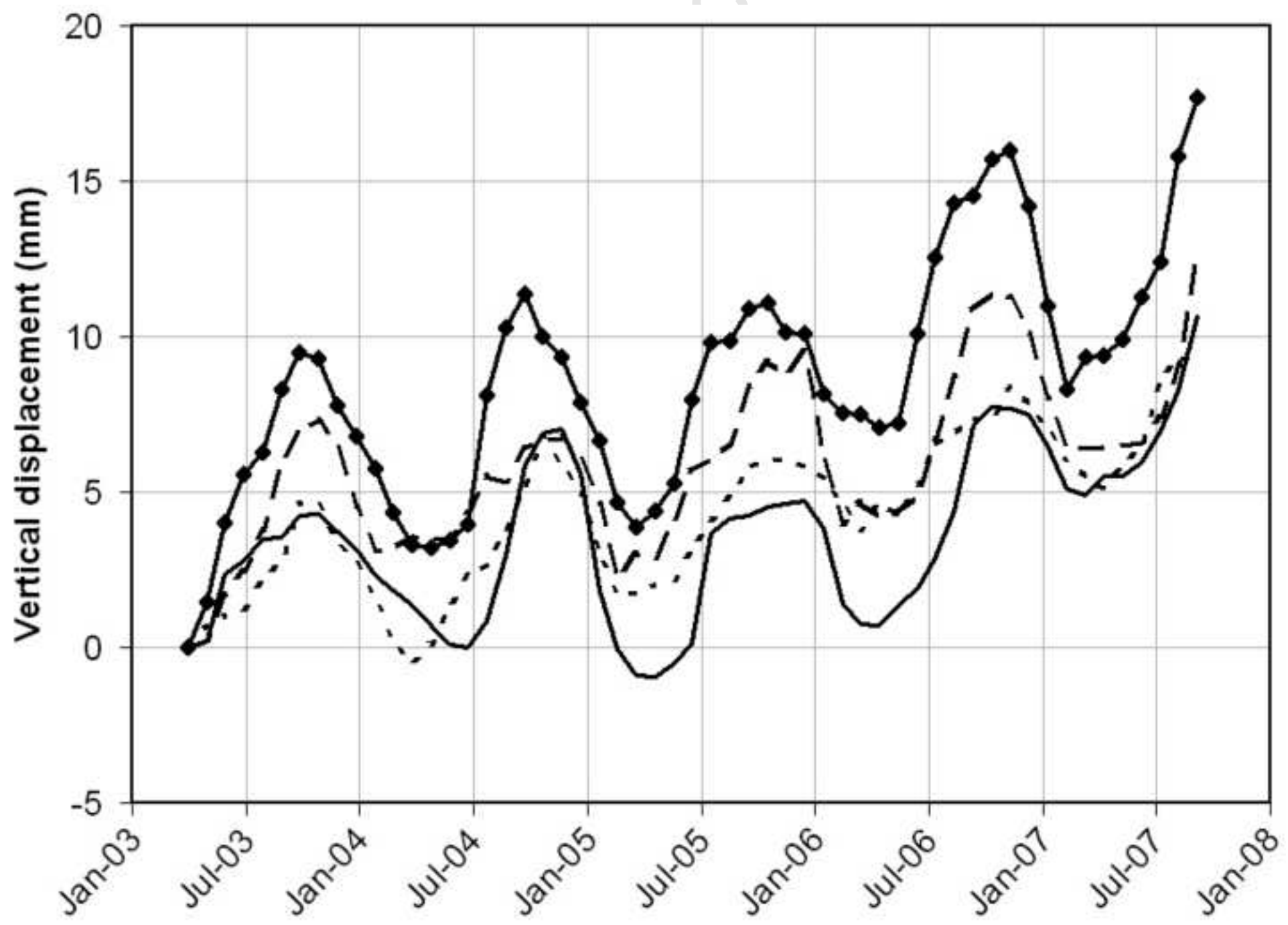


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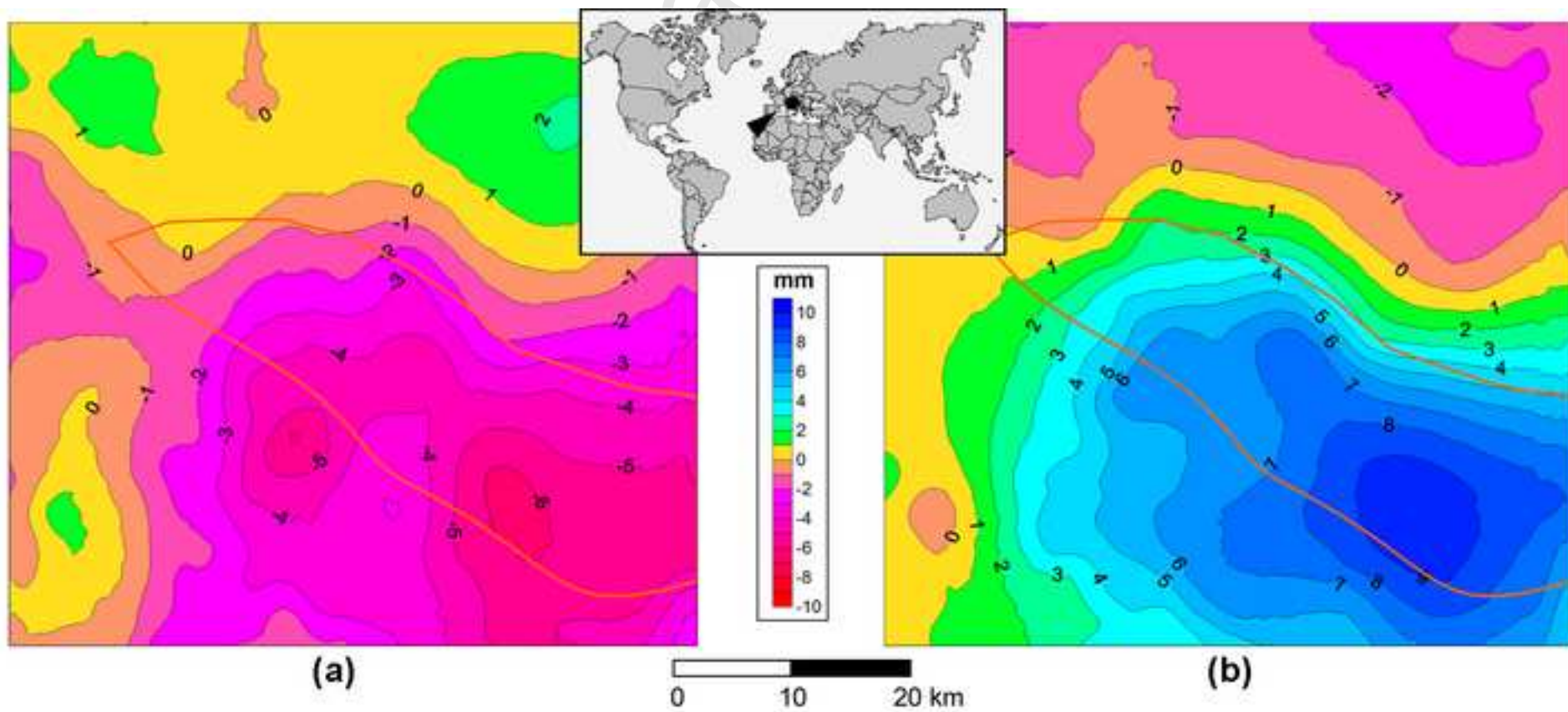
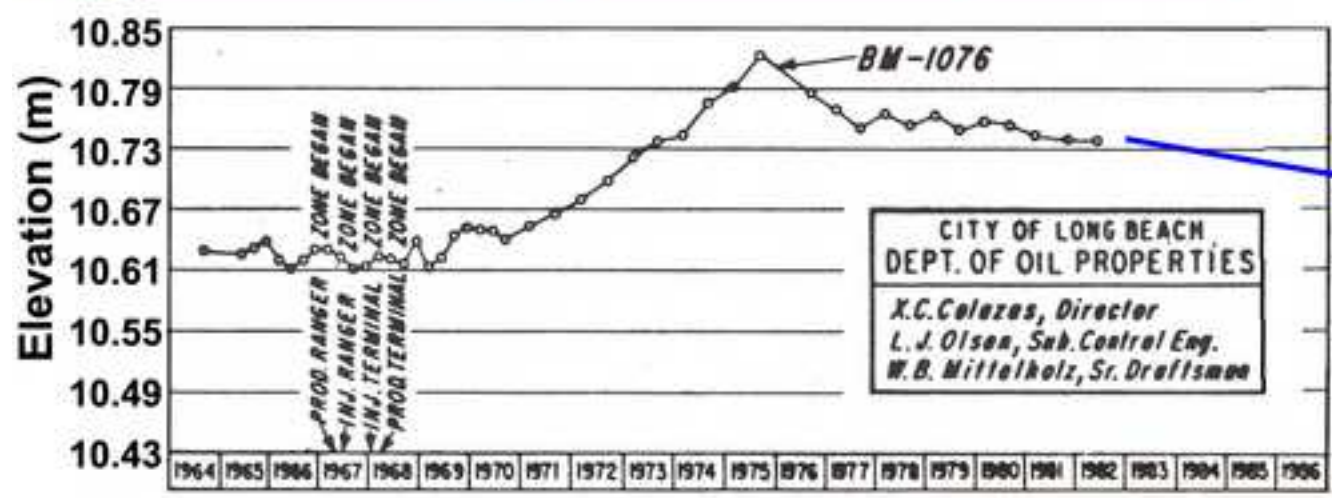
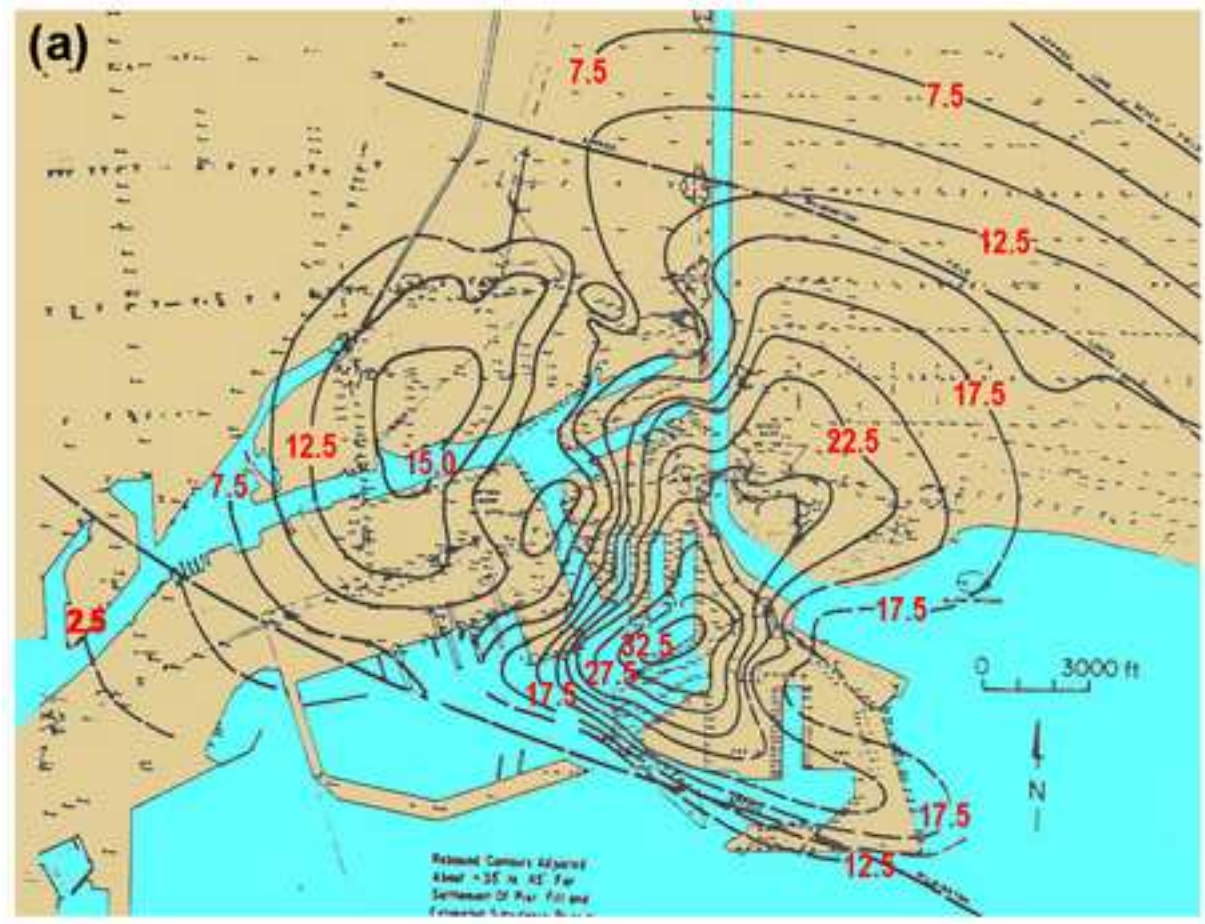


Figure 12



(b)

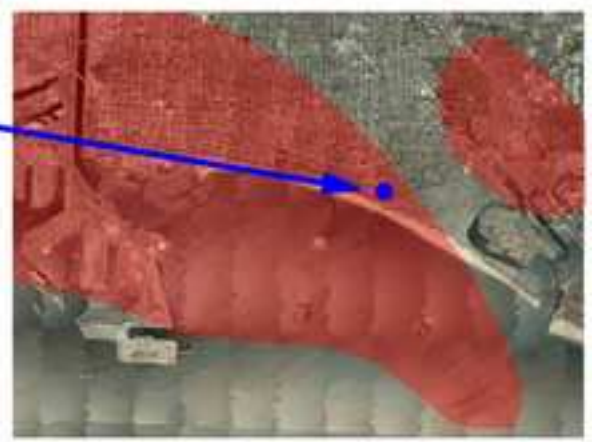


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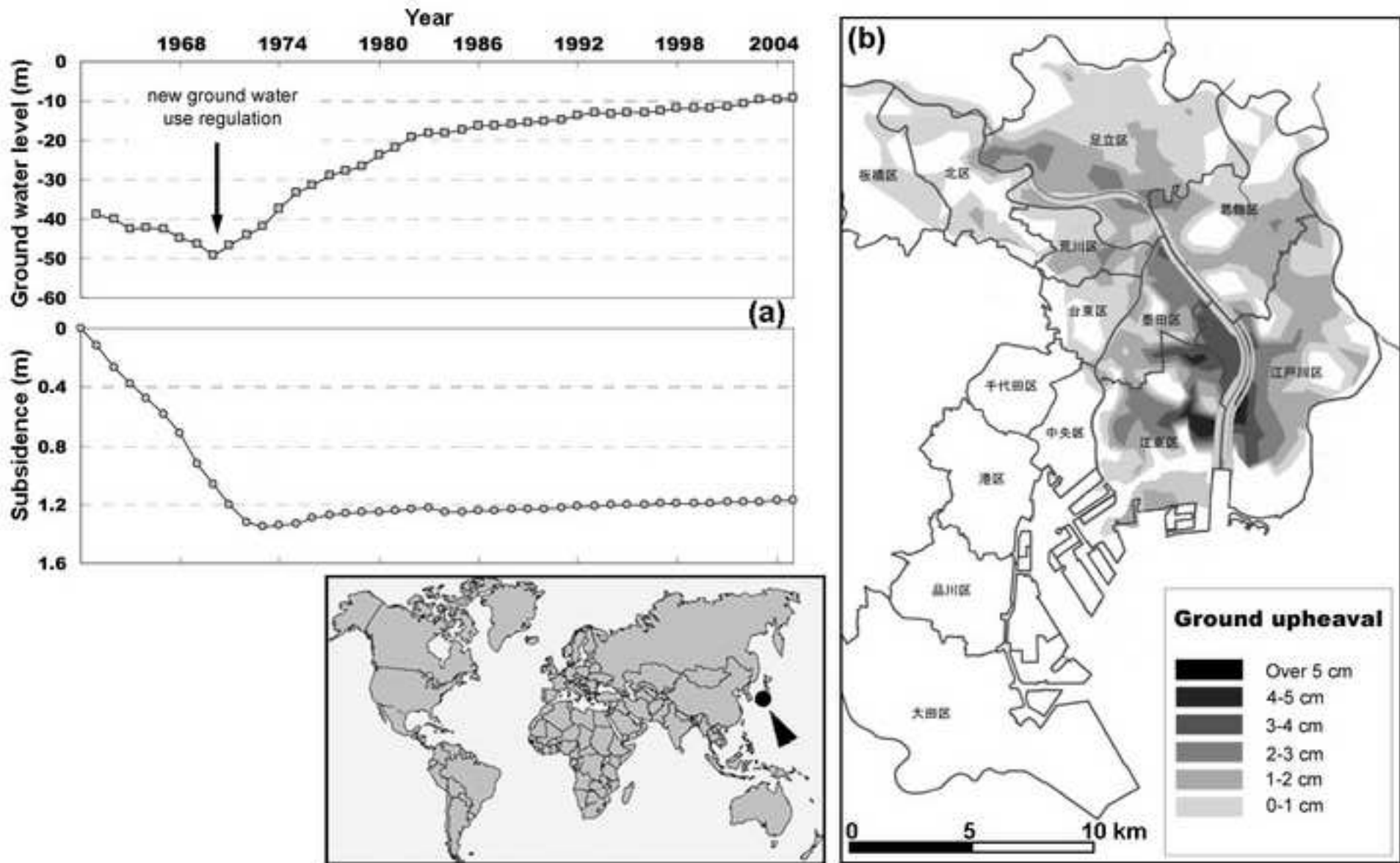
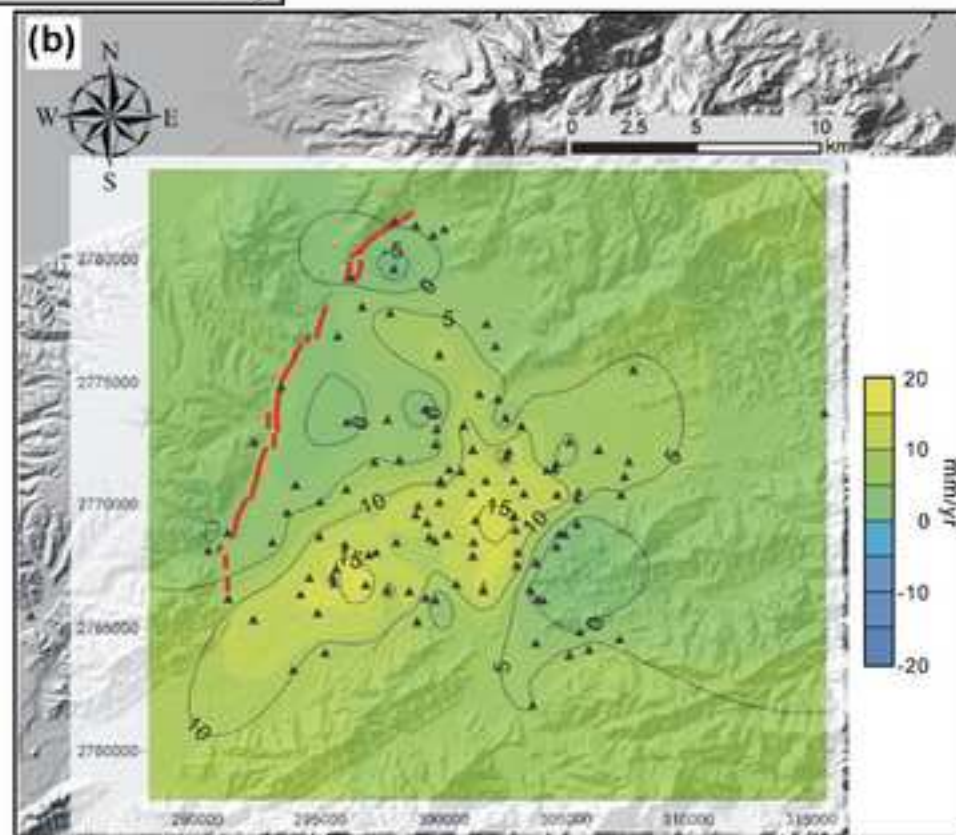
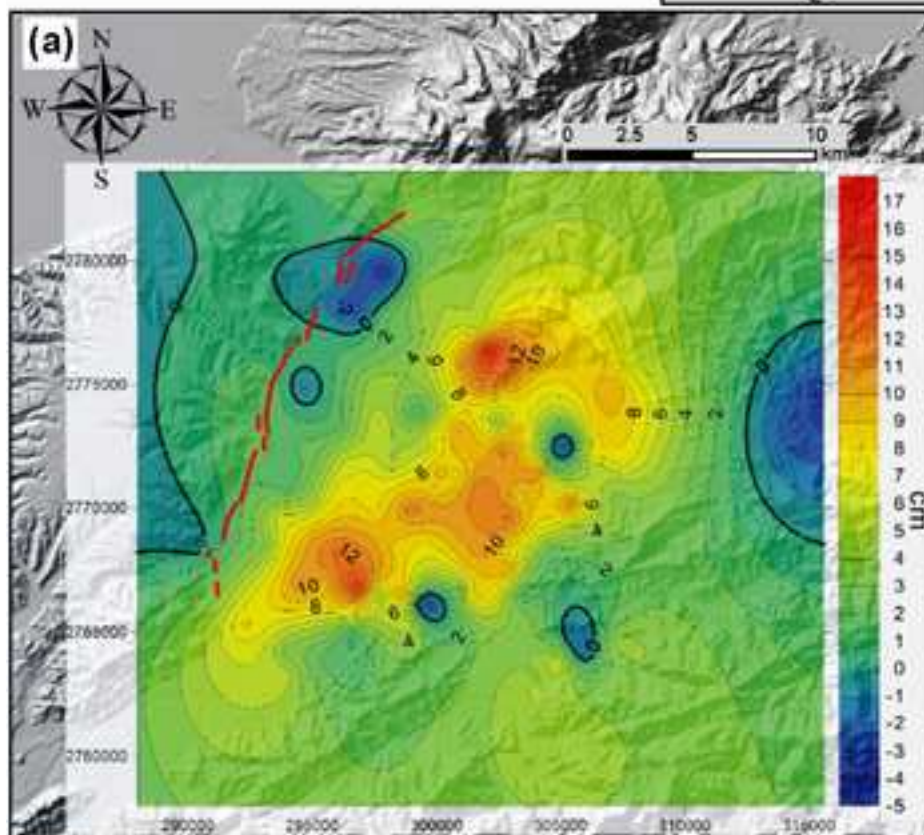


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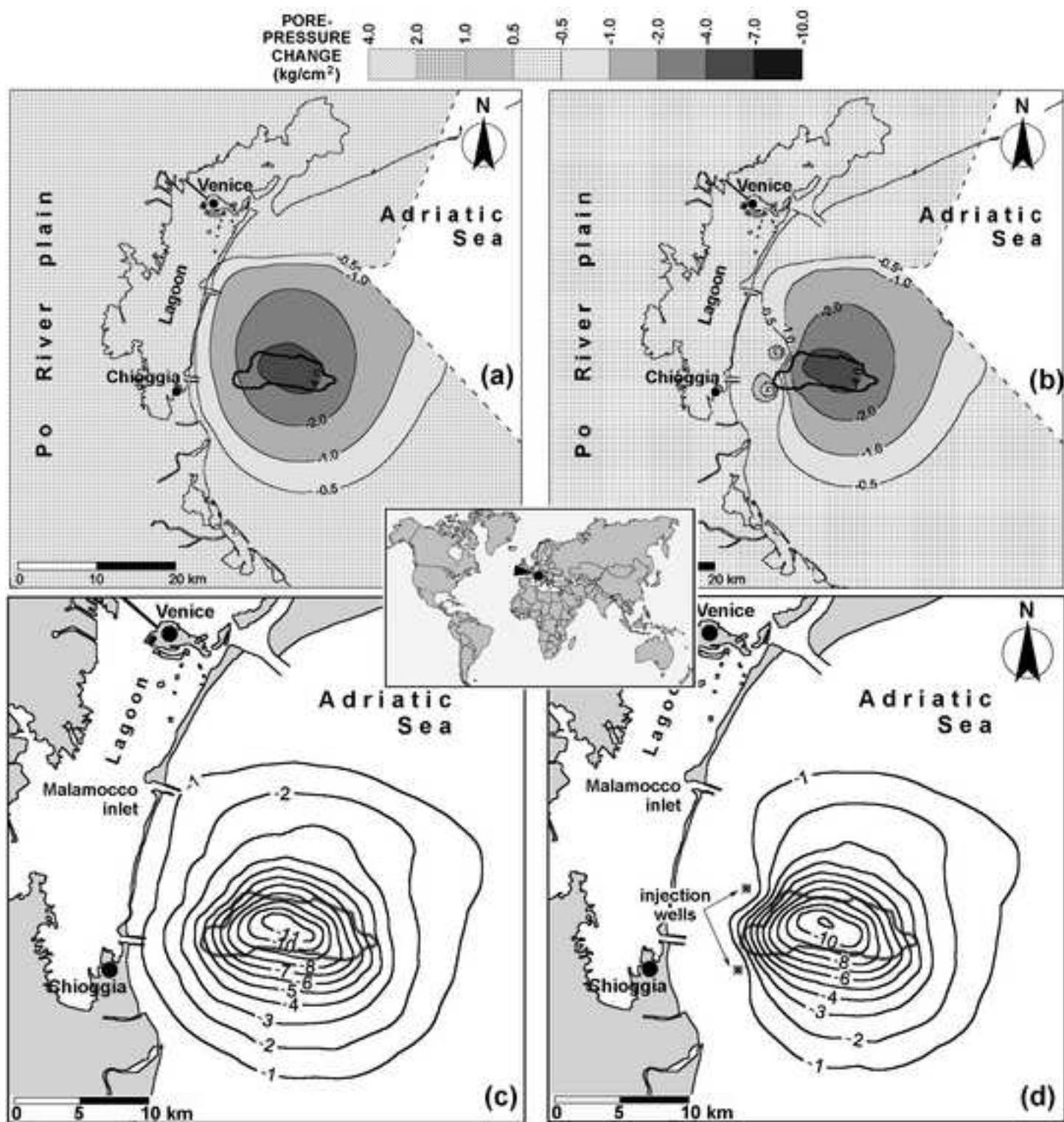


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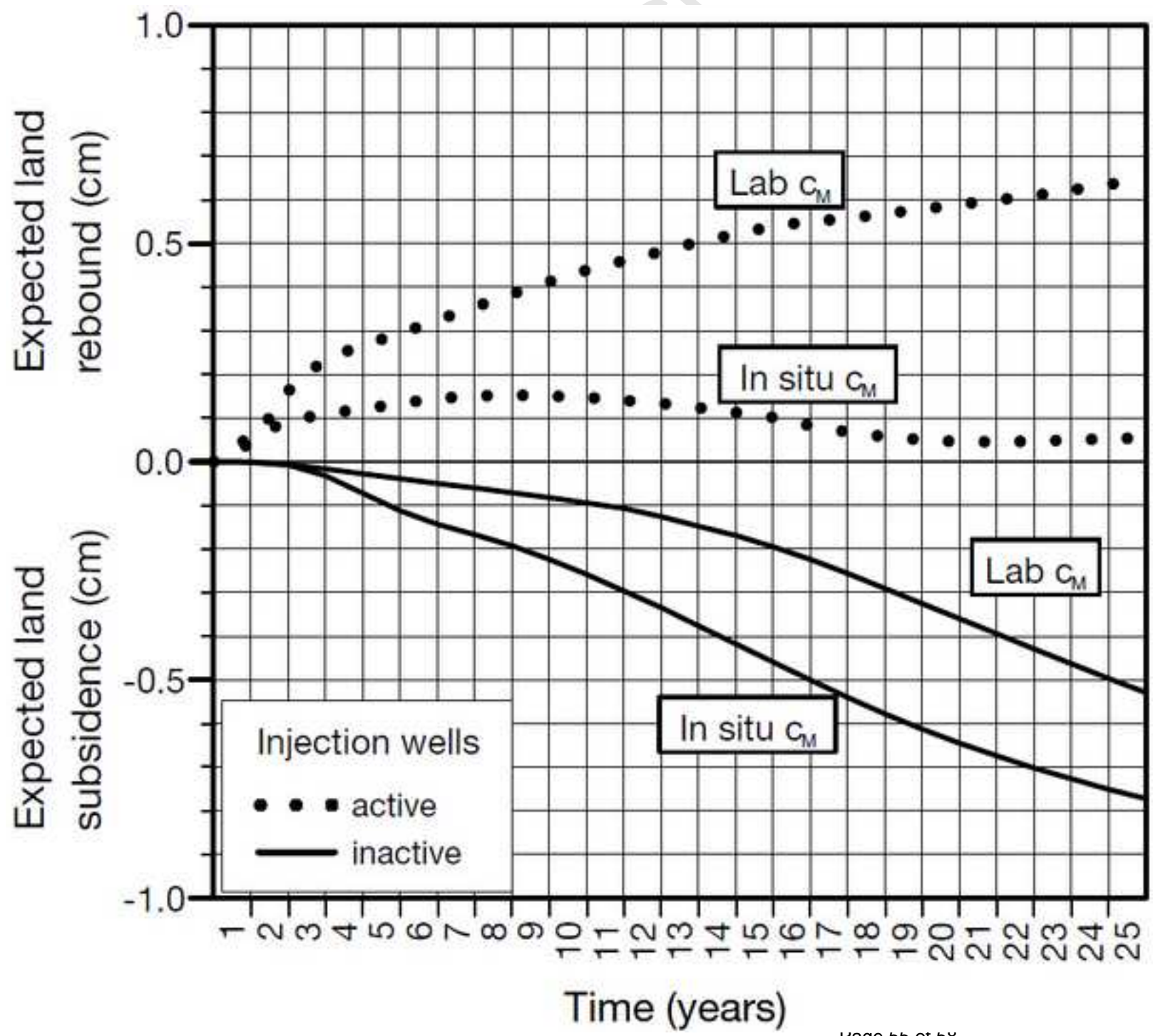


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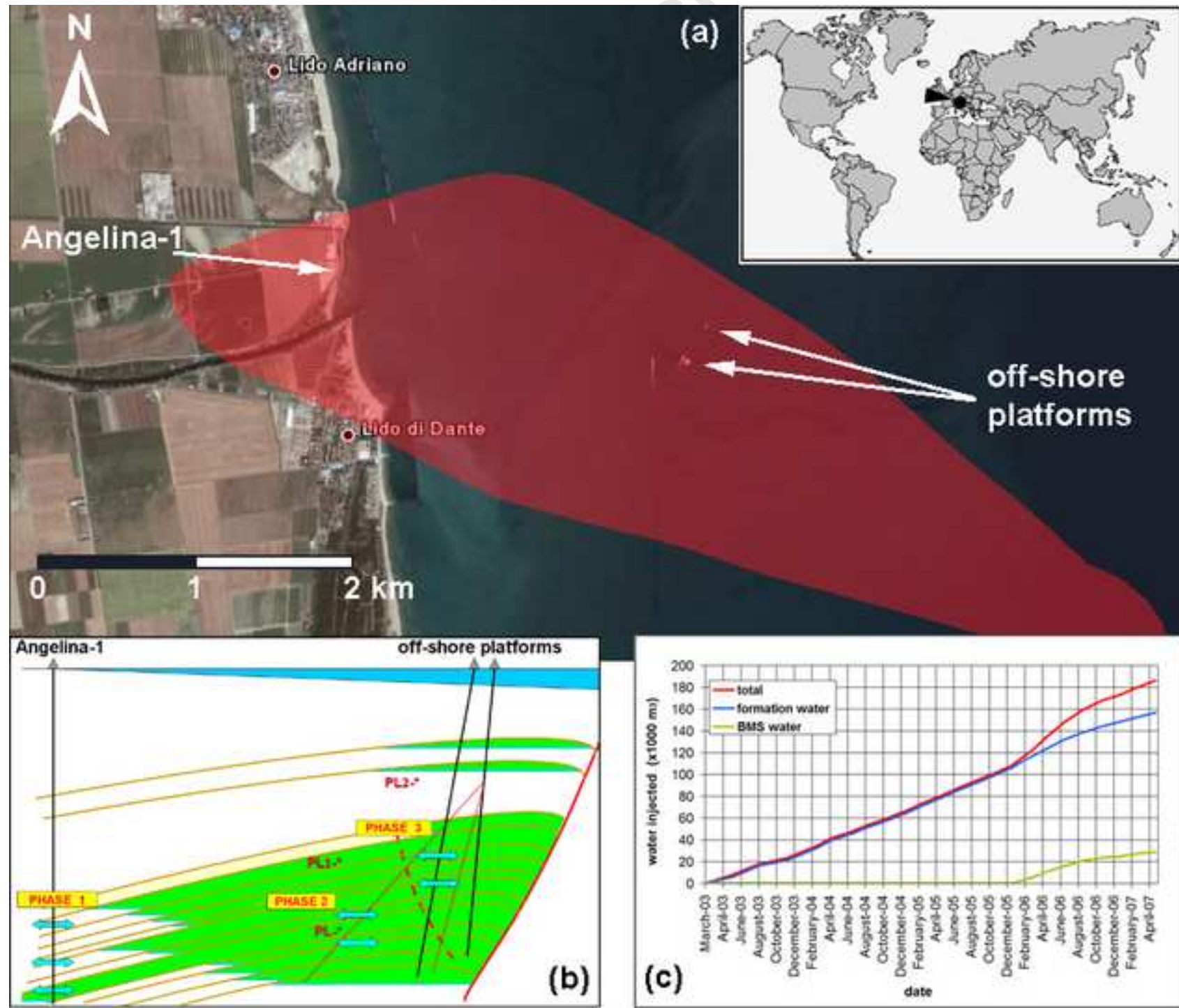


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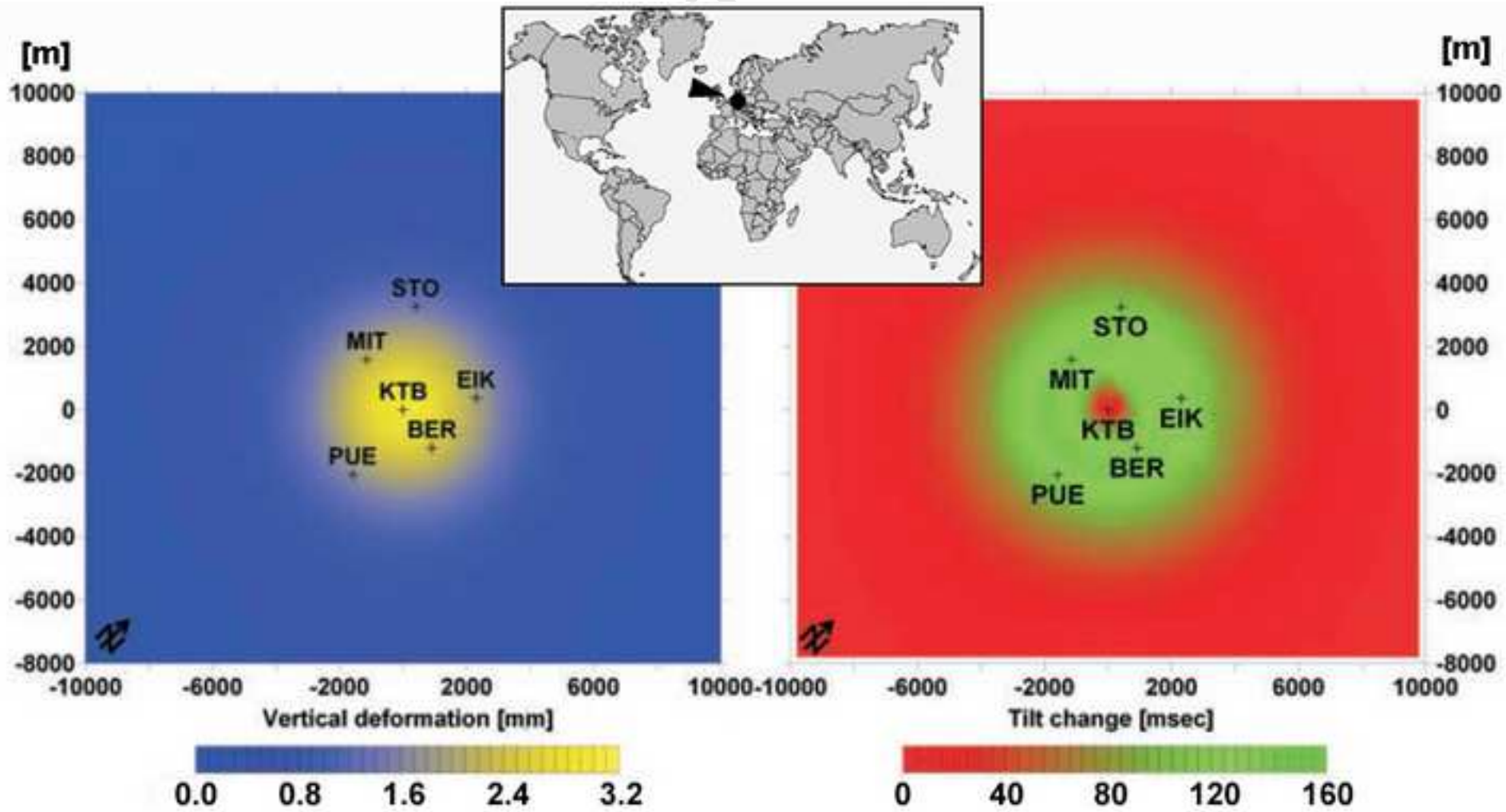


Figure 19

