



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Anomalous transient uplift observed at the Lop Nor, China nuclear test site using satellite radar interferometry time-series analysis

P. Vincent, S. M. Buckley, D. Yang, S. F. Carle

October 24, 2011

Geophysical Research Letters

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

Anomalous transient uplift observed at the Lop Nor, China nuclear test site using satellite radar interferometry time-series analysis

P. Vincent¹, S. M. Buckley^{2,3}, D. Yang², S. F. Carle⁴

¹*College of Earth Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon*

²*Center for Space Research and Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, Texas*

³*Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California*

⁴*Lawrence Livermore National Laboratory, Livermore, California*

[1] Anomalous uplift is observed at the Lop Nor, China nuclear test site using ERS satellite SAR data. Using an InSAR time-series analysis method, we show that an increase in absolute uplift with time is observed between 1997 and 1999. The signal is collocated with past underground nuclear tests. Due to the collocation in space with past underground tests we postulate a nuclear test-related hydrothermal source for the uplift signal. A possible mechanism is presented that can account for the observed transient uplift and is consistent with documented thermal regimes associated with underground nuclear tests conducted at the Nevada National Security Site (NNSS) [formerly the Nevada Test Site].

1. Introduction

[2] Residual coseismic surface effects associated with deeply buried, contained underground nuclear detonations have been well-documented [Allen, et al, 1997; Grasso, 2003]. Surface cracks are formed by the irreversible process called “spalling” where the underground detonation momentarily accelerates the shallow subsurface upward as the shockwave reaches the free surface before gravity slams it back down to a different, damaged configuration. This damage (spall) zone is on the order of 100 meters deep directly beneath surface ground zero (SGZ) tapering to zero depth at several hundred meters lateral distance. Surface craters can form if collapse of the rock mass above the test cavity, a process called “chimneying”, propagates all the way to the surface; if not, an apical void will exist between where the chimney terminates and the overburden supports the ground surface above. However, if the chimney propagates to a low-strength rock or the spall zone, the void volume within the chimney may completely fill with rubble (US Congress, 1989). Figure 1 is a schematic showing test and post-test processes relevant to our interpretation of the Lop Nor test characteristics [Houser, 1969].

[3] Subtle postseismic subsidence signals - sub-centimeter to several centimeter displacements over one-to-several kilometers horizontal distances - have been observed over past underground nuclear tests at the NNSS using InSAR [Vincent, et al., 2003; Vincent and Sweeney, 2003; Buckley, et al., 2005] and suggest the lateral extent of the spall zone can extend for up to a kilometer or more from SGZ, and the subsidence signals occur independent of whether a surface crater formed or not. All of the post-test InSAR observations at the NNSS indicate subsidence due to either gravitationally-driven closure of underground cracks formed in the damage (spall) zone above the nuclear test hypocenters with time (e.g., Pahute Mesa) or draining and relaxation of an over-pressured confining unit initially over-pressured by testing activity (e.g., Yucca Flat) [Vincent, et al., 2003]. Here we observe an anomalous transient *uplift* signal over a small cluster of three past underground tests at the Lop Nor, China nuclear test site using ERS-1/2 InSAR data—Figures 2 and 3. Although this signal was initially documented by Vincent and Sweeney [2003], and the uplift nature of the signal was documented by Buckley, et al., [2005], association with specific nuclear tests and a description of a possible source phenomena and mechanism are given here. We apply a time series analysis to the data to determine the rate and magnitude of the uplift signal with time and show its location relative to published locations of nearby underground nuclear tests.

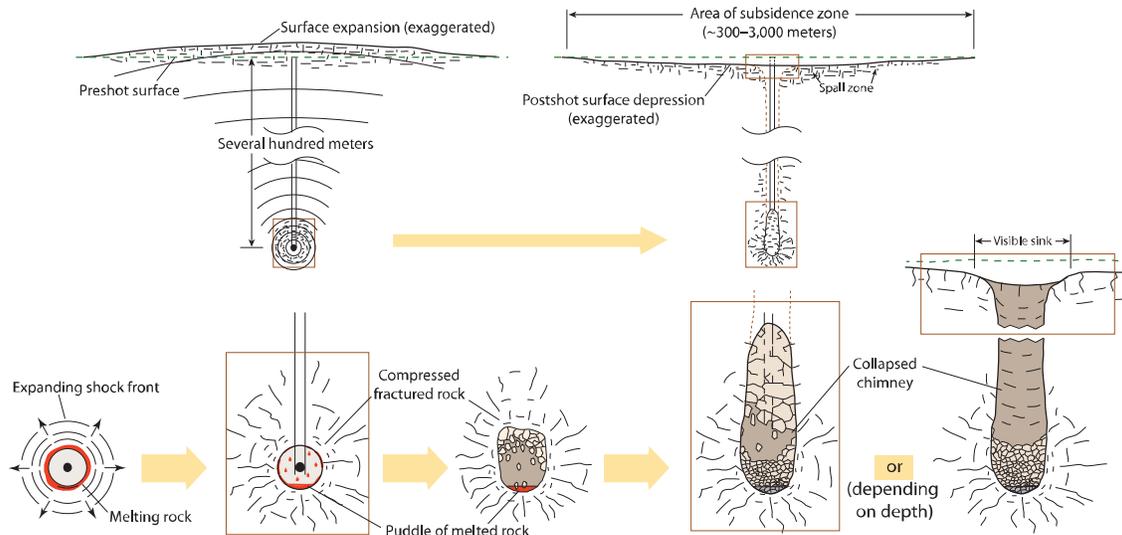


Figure 1. Schematic drawing depicting phenomenology of an underground nuclear explosion showing melt glass puddle and collapse of rock mass above the test cavity. Collapsing rock mass above the test cavity forms a “chimney” that propagates upward toward the surface forming a surface crater if it reaches the surface. [Adapted from Pawloski, et al., 2001, Allen, et al., 1997, and Houser, 1969; not to scale].

2. Data and Results

[4] Both standard and time-series InSAR processing methods were applied to the data and topographic phase was removed using a 3-arcsecond SRTM DEM. The time-series was produced from 15 ERS-1/2 Track 305, Frame 2766 SAR acquisitions spanning 1996-1999, forming 101 connected interferograms from all image-pair combinations. The maximum spatial and temporal baselines were 327 meters and 1191 days respectively. Geocoded displacement and corresponding error maps were inverted by applying a least-squares approach to a linear system of equations [Usai, 2001; Schmidt and Burgmann, 2003] to produce a time series of synthetic radar line-of-sight displacement maps, one at each of the SAR acquisition dates (Figure 2-left). Each frame represents the cumulative deformation that occurred between the time of the reference date and the date labeled in the frame. The frames for 19960102 and 19960205 do not contain deformation and are omitted. The 19960730 and 19980804 images are contaminated with atmospheric artifacts from SAR acquisitions on those dates. A time series plot of the center of the feature of interest (Figure 2-right) shows ground motion toward the radar (interpreted to be due to pure vertical uplift) beginning with the 19970401 image frame and increasing linearly up to the 19990406 (last) image frame in the series for a cumulative total of 2.7 centimeters of absolute uplift. The time series error bars are determined from the noise in the interferograms propagated through the inversion process. We determine the noise by populating the interferogram covariance matrix for each pixel using the strategy presented Hoffmann and Zebker [2003]. Their approach considers interferometric decorrelation which results in highly spatially variable phase noise and atmospheric artifacts which produce local phase biases. The interferograms covariance matrix diagonal and off-diagonal elements are filled with these noise estimates, respectively. The time series error bars are the square root of the diagonal elements of the estimated cumulative displacement covariance matrix.

[5] Standard InSAR processing of ascending orbit image pairs confirm the nearly constant uplift rate observed in the descending orbit image pairs used in the time series analysis up to the last frame in the time series (19990406). Unfortunately there is a gap in available SAR data between the last frame in the time series and the next available acquisition date (031111) and no signal is observed from this date forward from either ascending or descending ERS-2 pairs or from available Envisat data. As such, the

available InSAR data indicate that the uplift signal persists for at least $990406 - 970401 = 735$ days (2.01 years) before it begins to decay to zero sometime between 990406 (the last available frame in the time-series data set) and 031111 (the next available SAR data acquisition date) where no signal is observed from this date forward.

[6] The uplift signal is centered over 3 past underground nuclear tests conducted in the southeastern region of the Lop Nor test site in vertical shafts: event 920521 $m_b = 6.5$ event on May 21st, 1992, China's largest underground test since 1992; event 950515 $m_b = 6.1$ event on May 15th, 1995; and event 950817 $m_b = 6.0$ event on August 17, 1995 [Fisk, 2002]--see Figure 3. Using Ringdal, et al. [1992] magnitude-yield relation for hard rock emplacement environments (e.g., Semipalatinsk, Kazakhstan), $m_b = 4.45 + 0.75 \cdot \log Y$, the yields for these three tests are estimated to be 541 kt, 158 kt, and 117 kt, respectively. We show event locations determined from previous studies that match up best with the InSAR uplift signal and consider them to be the most accurate locations available for these tests (e.g., “<test_date>Wald”=Waldhauser, et al., 2002). The two tests co-located with the main elliptical shape of the signal were conducted in granite, and the adjacent test to the immediate northwest was conducted in metamorphosed sandy conglomerate [Matzko, 1994]. Both are hard rock emplacement environments separated by a mapped fault whose surface trace was digitized from Che Yongtai [1987].

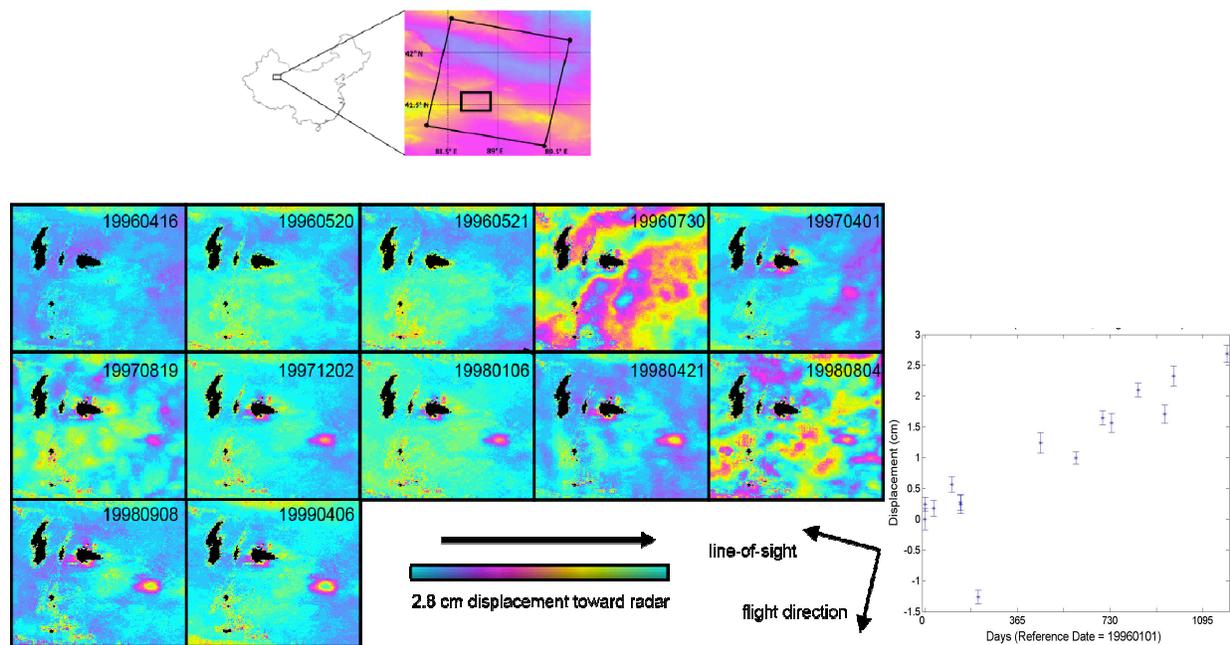


Figure 2. (Left) Location map (top) of the Lop Nor, China Test Site shown with ERS SAR data frame over a topographic base map. Cumulative deformation since January 1, 1996 from InSAR time series showing uplift feature at the Lop Nor, China Nuclear Test Site. The 19960730 and 19980804 images are affected by atmospheric artifacts. Azimuth of radar look vector is shown and inclination is 23 degrees from vertical. Once color cycle = 28 mm of line-of-site displacement. (Right) Time series plot of cumulative displacement toward the radar (uplift) with time since January 1, 1996 associated with feature shown in frames at left.

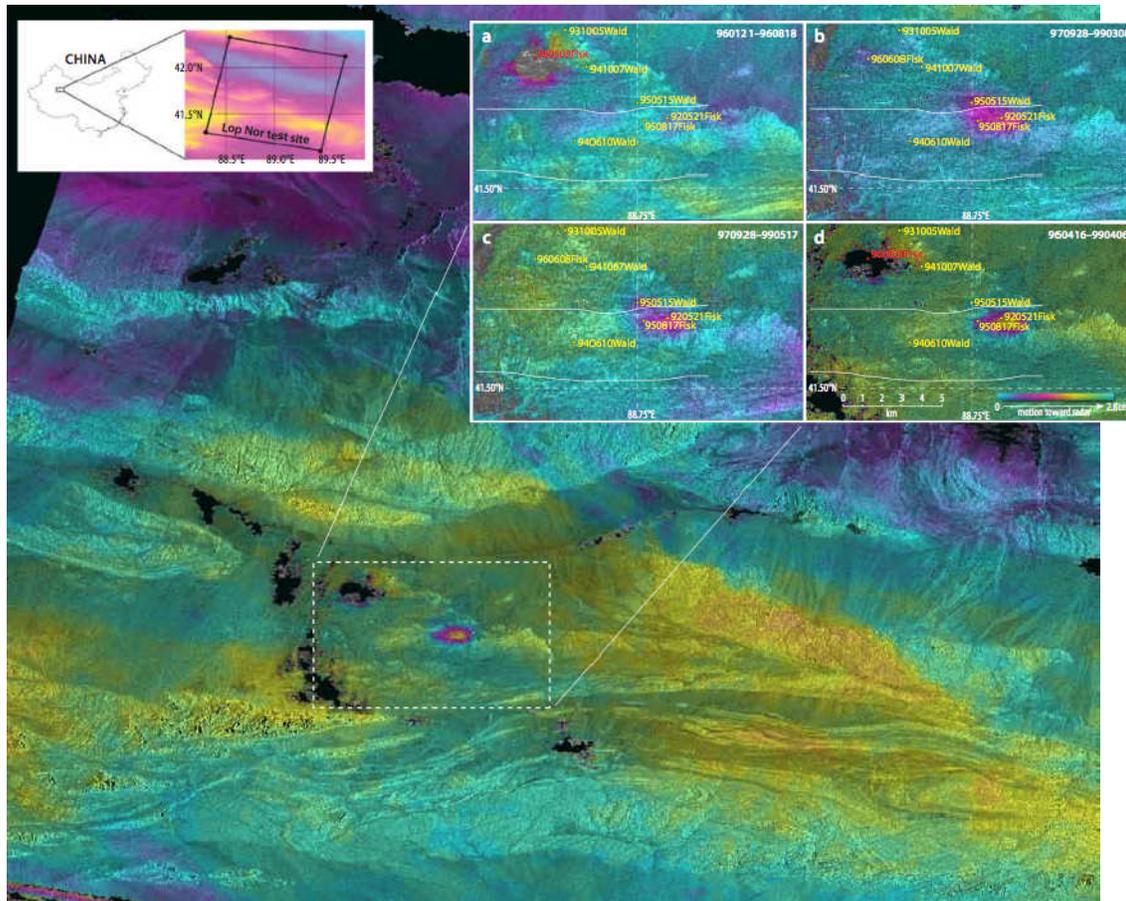


Figure 3. Uplift feature shown at different time intervals with best match to InSAR signals of past underground nuclear test locations determined from seismic location studies identified in subplots with date of test and first author (e.g., <testdate>_Fisk [Fisk, 2002]; <testdate>_Wald [Waldhouser, et al., 2004]). Red-letter labels denote interferograms that capture coseismic surface disturbance from a nuclear test conducted on 960608 (tiles a and d); the ground shaking from this test presumably disturbed the alluvium enough to cause interferometric phase decorrelation out to 1 km or more from SGZ. Dates spanned by interferograms shown. One color cycle represents 28 millimeters of motion toward radar. White horizontal fault traces were digitized from Che Yongtai [1987] (see text).

3. Analysis

[7] The cause of this anomalous uplift signal is unknown. We speculate, however, that it is caused by advection of heated ground water rising from the test cavity up through high permeability fractured granite or meta-conglomerate (depending on the test) where thermal and poroelastic expansion effects near the surface dominate gravitational (subsidence) effects to produce the observed transient uplift signal. As the heated groundwater rises toward the surface it encounters the shallow spall zones (also highly fractured and permeable) and spreads laterally from the chimney, giving rise to the larger footprint of the InSAR signal (3 km across) compared to the chimney diameter. The groundwater expands as it absorbs heat from the test cavity and rises buoyantly toward the surface. This process continues until there is insufficient heat energy remaining to drive this thermal uplift process. The high permeability of fractured granite and meta-conglomerate comprising the test chimney above each of the above-referenced tests at Lop Nor acts like an efficient conduit for advection of elevated-temperature groundwater to efficiently transport heat from the test cavity hundreds of meters below the surface.

[8] The existence of thermal groundwater plumes rising from underground test cavities is well documented for tests conducted at the NNSS [Pawloski, et al, 2001; Carle et al., 2003]. Residual heat from the CHESHIRE test conducted at the NNSS has been observed to last for several years post-test. Using a magnitude-yield relation for NNSS, $m_b = 3.92 + 0.81 \cdot \log Y$ [Murphy, 1981] and the announced yield range for the CHESHIRE test of 200 to 500 kilotons [U.S. Dept. of Energy, 2000], CHESHIRE had a body wave magnitude range of 5.8 to 6.1. Thus, the CHESHIRE test at NNSS is of comparable size to those at Lop Nor associated with the uplift signal. Figure 4 (left) shows post-test temperature profiles associated with the CHESHIRE test conducted on February 14th, 1976 on Pahute Mesa, NNSS. These temperature measurements show that 140 degrees C conditions remain near the test cavity at 201 days post test, and ~70 degrees C conditions remain at 6.5 years post test [Pawloski, et al., 2001]. The Lop Nor uplift signal is observed for approximately 735 days (2.01 years) after initiation (970401), well within the time span of significantly elevated test cavity temperatures observed for the CHESHIRE test observed at the NNSS.

[9] Figure 4 (right) shows selected 3-D profile slices of a thermal plume simulation with time as it migrates upward toward the water table for the CHESHIRE test constrained by the post-test temperature profiles shown in Figure 4 (left) [Pawloski, et al., 2001; Carle, et al., 2003]. The thermal plume took approximately 4.2 years to rise approximately 550 meters from an emplacement depth of 1,167 meters to reach the water table (approximately 500 meters below the surface) where it begins to spread laterally and dissipate. By comparison, if we assume the plume at Lop Nor begins to migrate upward soon after event 920521 and reaches the water table which is only 3 meters deep [Matzko, 1994] when the InSAR signal first appears on 970401, then the Lop Nor plume would have taken approximately $970401 - 920521 = 4.8$ years to reach the surface. Given the uncertainty of the cavity depths at Lop Nor, and the uncertainty in the relative permeability between fractured volcanic rock at the NNSS versus fractured granite at Lop Nor, this inferred thermal plume migration time for the Lop Nor is reasonable. We offer two possible thermal mechanisms where the observed surface uplift could be produced and discuss the relative strengths, weaknesses, and uncertainties associated with each mechanism in the context of differing emplacement environments between Lop Nor and NNSS. Figure 5 is a schematic depicting these thermal mechanism scenarios (it is meant to depict both scenarios).

[10] *Thermal Mechanism One:* Using the CHESHIRE test thermal plume simulation as a guide, we calculate the vertical thermal strain resulting from a plume temperature of 42 degrees Celsius arriving at the top of the groundwater surface 4.8 years post test and infiltrating the spall zone estimated to be about 100 meters thick over the test cavity. For simplicity, in order to calculate the vertical thermal strains, we assume a constant temperature change within a vertical column of rock. The vertical thermal strain can be expressed as

$$\varepsilon_{th} = \frac{z}{h_z} = \alpha(T_H - T_C)$$

where z is the observed uplift due to thermal expansion, h_z is the assumed vertical column of rock over which the thermal expansion takes place, α is the coefficient of thermal expansion of granite, T_H , and T_C are the source and reference (ambient pre-test) temperatures respectively. Using parameters for the source temperature from the CHESHIRE simulations T_H (42 degrees Celsius when the plume reaches the water table 4.2 years post test), an estimate for the ambient temperature T_C associated with the upper 100 meters of granite at Lop Nor on the reference image date 960101 (10 degrees Celsius) and a value of 8.5×10^{-6} degrees Celsius⁻¹ for the coefficient of thermal expansion of granite [Lardner and Archer, 1994] we obtain the observed total uplift of 2.7 centimeters measured by our InSAR results. If we use a more reasonable ambient temperature of 5 degrees Celsius, for January 1, 1996 at Lop Nor, we can reduce the required vertical thickness of the spall zone to 86 meters to produce the observed uplift. In any case, using reasonable numbers we arrive at the observed uplift at Lop Nor using the same temperature for the plume reaching the water table at the CHESHIRE test over a similar time period.

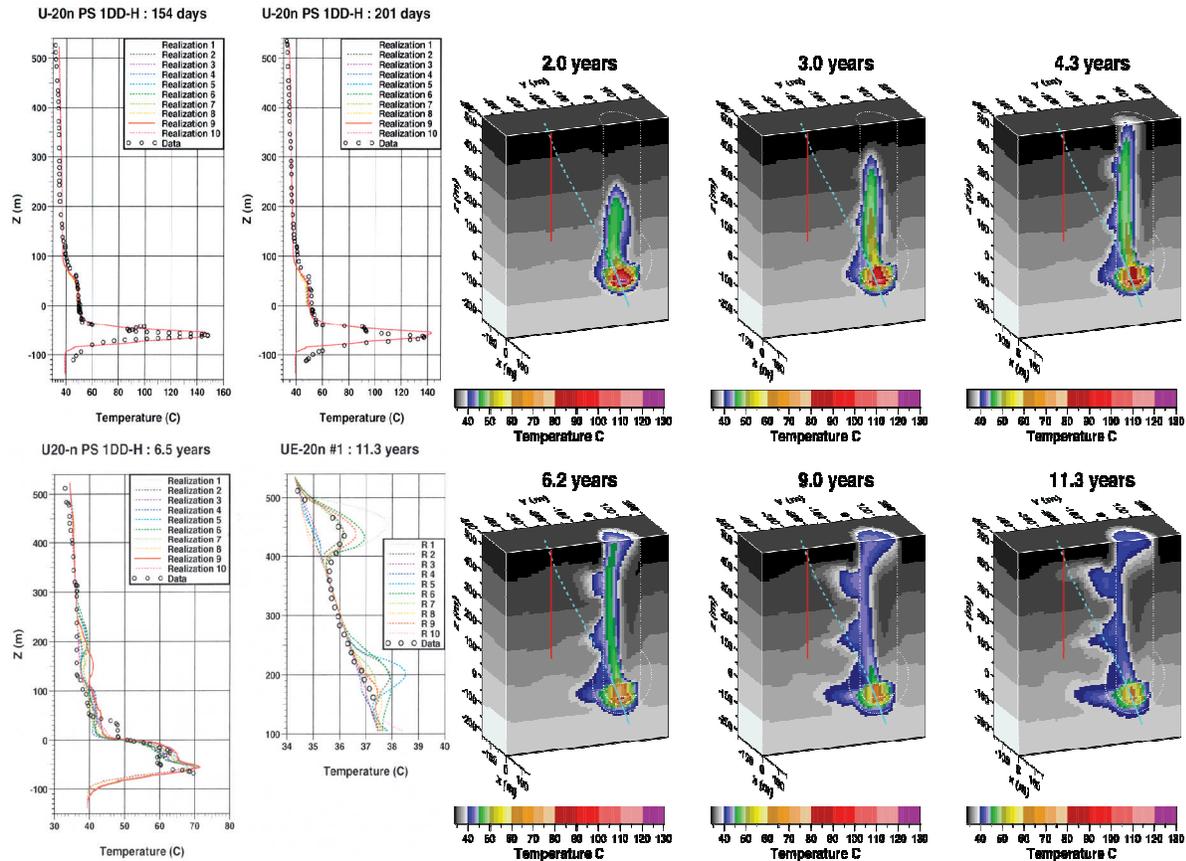


Figure 4. (Left) Measured (open circles) and simulated (curves for ten different hydrogeologic realizations labeled as R1 through R10) post-test temperature profiles associated with the CHESHIRE test conducted on February 14th, 1976 on Pahute Mesa, Nevada Test Site (see text). Temperatures taken from drill hole locations shown at right [Adapted from Pawloski, et al., 2001]. (Right) 3-D profile slices of the upward migration with time for the CHESHIRE thermal plume simulation constrained by post-test thermal profiles shown at left. The top of each slice is the water table surface (about 500 meters depth). Diagonal blue and vertical red line denotes locations (drill holes U20-n PS 1-DD-H and UE-20n #1) of the post-test well temperature profiles shown at left. Cavity radius is estimated from test yield using a formula given in Pawloski [1999] and the maximum of the announced yield range given by U.S. Dept. of Energy (2000). [Adapted from Pawloski, et al., 2001].

[11] This mechanism requires a higher temperature rise from expected pre-test ambient groundwater temperatures due to the thermal plume reaching the spill zone than that observed for the CHESHIRE test conducted at NNSS. We propose that a lower heat loss between the test cavity and the ground surface would be expected in the granite chimney at Lop Nor compared to the volcanic rock chimney at NNSS. The reason for this is that at CHESHIRE there are high-permeability zones in the rhyolitic lava layers that the chimney rises through that enable heat (and radionuclides) to spread laterally (e.g. as evident by ~1 degree C temperature anomaly 11.3 years after the test at UE-20n #1 300 meters distant from the test) [Buddemeier and Hunt, 1988; Erikson, 1991; Sawyer et al., 1999; Pawloski, et al., 2001; Carle, et al., 2003]. This is a key issue for evaluating radionuclide transport at Pahute Mesa, the main purpose for conducting the thermal plume simulations for the CHESHIRE test. This lateral dissipation of heat from the chimney would not be expected to occur, or certainly to much less of an extent, within the fractured granite chimney rising through an otherwise intact and undamaged granite pluton at Lop Nor. Without similar post-test temperature profile data available for Lop Nor there is no way to know the temperature variation with depth and time in the chimney at Lop Nor.

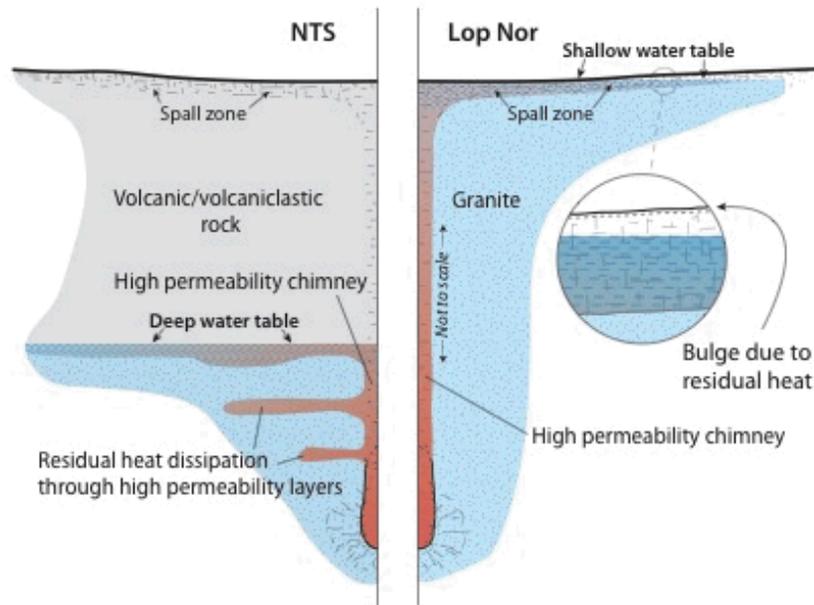


Figure 5. Schematic drawing depicting different emplacement hydrogeologic settings between (left) Nevada Test Site (NNSS) and (right) Lop Nor, China Test Site. Not to scale.

[12] *Thermal Mechanism Two*: Immediately after cavity collapse and chimney formation, which occurs within minutes to days after the test [US Congress, 1989], the chimney rubble temperature is similar to the ambient pre-test temperature of in-situ rocks prior to the test, and most of the test-related heat is contained in the melt glass zone at the base of the cavity (Figure 1). The CHESHIRE thermal groundwater simulations indicate that subsequent thermal groundwater advection heats a vertical column of rock to 10 degrees C or more above ambient temperatures throughout the entire vertical extent of the highly permeable chimney rubble in a timeframe of 4 to 6 years after the test. At Lop Nor, heating of the chimney rubble embedded within a relatively stable in-situ granitic rock vessel causes vertical expansion of the chimney rubble to the base of a deformable spall zone where the effect spreads and dissipates laterally in the much wider spall zone near the surface. Heating of a vertical column of rock within the chimney by an average of 6.4 degrees C throughout a 500 meter high chimney would produce the 2.7 cm magnitude of vertical expansion observed at Lop Nor based on a value of 8.5×10^{-6} degrees Celsius⁻¹ for the coefficient of thermal expansion of granite [Lardner and Archer, 1994]. Therefore, the magnitude and timing of the thermal groundwater advection process within chimney rubble directly beneath the spall zone provide a plausible explanation for the magnitude and timing of the Lop Nor InSAR observations.

[13] This mechanism requires a much smaller temperature change of the groundwater in the chimney (10 degrees C compared to 42 degrees C) from advection of the thermal plume, which is more consistent with the temperature profile data for the CHESHIRE test, and allows for more heat loss through the sides of the chimney (e.g., through heat conduction), and as such is perhaps more plausible than thermal mechanism one. However, this mechanism requires thermal expansion of a much longer vertical column of rubble, 500 meters, than that required for thermal mechanism one which required 100 meters (or less) of rock column to thermally expand. The net thermal expansion affect of this depth of rubble and the degree of accommodation of this expansion by readjustment (inter-fragment sliding) is uncertain and would require a coupled fluid-thermal-mechanical simulation to estimate, which is beyond the scope of this paper.

[14] Regarding which thermal mechanism is more plausible, we suspect that the actual mechanism is a compromise between the two we offer here. Namely, we do expect that the temperature change at Lop Nor would be greater than at NNSS due to less expected lateral heat dissipation through high-permeable

layers in Lop Nor granite compared to NNSS volcanic rock. We also expect that the temperature of the thermal groundwater plume would probably not be as high as the 42 degrees C called for in thermal mechanism one because this would require too little heat loss than we would expect. There is no post-test temperature profile data we are aware of to support this high a temperature rise this close to the surface this long after a test; although we are not aware of *any* post-test thermal temperature profile data for granite emplacement environments. Without similar post-test temperature profile data at Lop Nor to constrain either of these proposed mechanisms, we cannot be certain which one is more plausible.

4. Discussion

[15] The results presented here document for the first time an uplift signal associated with a thermal groundwater plume from one or more past underground nuclear explosions from any test site worldwide. This relatively slow process, taking over four years post test to be observed, is consistent with post test temperature profile data-constrained simulations of thermal plume rise from a similar magnitude underground test at the NNSS.

[16] The reason why similar uplift is not observed at NNSS is simply because the water table is several hundred meters below the surface at NNSS (well below the 100 meter-deep spall zone), compared to near the ground surface at Lop Nor. Once the thermal plume reaches the water table, it spreads and dissipates laterally preventing a thermal signal from reaching the surface where it would have most certainly been observed at NNSS from post-test temperature profile data or previous InSAR results.

[17] The absence of subsidence signals observed at Lop Nor compared to NNSS is attributed to a difference in emplacement environments. NNSS chimneys on Pahute Mesa often propagate into relatively weak volcanic sequences including non-welded ash-flow bedded tuff that are more likely to exhibit post-test subsidence compared to hard granite and meta-conglomerate rock at Lop Nor. The long-term (>10 years) post-test subsidence signals observed on Pahute Mesa at NNSS is attributed to slow gravity-driven closure of underground cracks within the spall zone facilitated by percolating groundwater above the water table acting to slowly dissolve underground crack asperities [Vincent, et al., 2003]. Since most of the spall zone for Lop Nor tests is below the water table where cracks and voids are saturated with and partially supported by pore-pressure from water, this dissolution mechanism would presumably not be available at Lop Nor and the spall zone would be more stable with time. In addition, the lack of subsidence at Lop Nor is consistent with our mechanism for explaining the thermal uplift signal, which requires a minimum amount of compaction in the post-test configuration of the damage zone.

[18] Due to the length of time needed for the thermal plume to reach the surface, and the requirement for a shallow water table, these new findings do not aid in the use of InSAR as a monitoring technique. However, these results do provide new thermal and emplacement environment constraints for characterizing past underground nuclear tests, along with location constraints of past tests to within 100 meters, similar to that for the InSAR subsidence signatures observed at NNSS. These new constraints could eventually help refine explosive yield estimates for tests conducted in evasive seismic decoupling environments that reduce the utility of seismic methods for determining yield.

[19] Acknowledgments. This work was supported by the U.S. Department of Energy Contract Numbers DE-FC52-03NA995661 and W-7405-ENG-482. The authors would like to thank helpful reviews by David Hafemeister and an anonymous reviewer. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

- Allen, B. M., S. L. Drellack Jr., M. J. Townsend, 1997. Surface Effects of Underground Nuclear Explosions, DOE/NV/11718-122, U.S. Dept. of Energy.
- Buckley, S. M., P. Vincent, D. Yang, 2005. New Ground Truth Capability from InSAR Time Series Analysis, 27th Seismic Research Review, Rancho Mirage, California, Sept. 20-22, 2005.
- Buddemeier, R.W. and J. R. Hunt, 1988, Transport of colloidal contaminants in groundwater: Radionuclide migration at the Nevada Test Site, *Applied Geochemistry*, **3**, 535–548.

- Carle, S. F., R. M. Maxwell, G. A. Pawloski, 2003. Impact of Test Heat on Groundwater Flow at Pahute Mesa, Nevada Test Site, UCRL-ID-152599.
- Che, Yongtai, 1987. Response of ground water levels in wells to underground nuclear explosions. *Shuiwendizhi Gongchengdizhe (Hydrol. and Eng. Geol.)*, 4, pp. 7-12 (in Chinese).
- Erikson, S. J., 1991, Report of Drilling and Radionuclide Migration Investigations at UE-20n #1, Pahute Mesa, Nevada Test Site, 1987, *Water Resources Center Publication #45081*, Desert Research Institute, University of Nevada.
- Fieldhouse, R.W., 1991. Chinese nuclear weapons, A current and historical overview. *Nat. Res. Def. Council*, Nuclear Weapons Databook, Working Papers, Washington, D.C., pp. 49-52.
- Fisk, M.D., 2002. Accurate locations of nuc. explosions at the Lop Nor test site using alignment of seismograms and IKONOS satellite imagery, *Bul. Seis. Soc. Amer.*, 92 (8), 2911-2925.
- Grasso, D. N., 2003. Geologic Surface Effects of Underground Nuclear Testing, Buckboard Mesa, Climax Stock, Dome Mountain, Frenchman Flat, Rainier/Aqueduct Mesa, and Shoshone Mountain, Nevada Test Site, Nevada, *USGS Open-File Report 03-125*.
- Hoffmann, J. and H.A. Zebker, 2003. Prospecting for horizontal surface displacements in Antelope Valley, California, using satellite radar interferometry. *J. Geophys. Res.*, 108, F1, 6001, doi:10.1029/2003JF000055.
- Houser, F. N., 1969. Subsidence related to underground nuclear explosions, Nevada Test Site, *Bul. Seismol. Soc. Amer.*, 59, 6, 2231-2251.
- Matzko, J. R., 1994. Geology of the Chinese nuclear test site near Lop Nor, Xinjiang Uygur Autonomous Region, China. *Engineering Geology*, 36, 173-181.
- Murphy, J., 1981. P-wave coupling of underground explosions in various geologic media, in *Identification of Seismic Sources-Earthquake or Explosion*, E. S. Husebye and S. Mykkeltveit (Editors), D. Reidel, Dordrecht, pp. 201-205.
- Pawloski, G. A., A. F. Thompson, S. F. Carle, 2001. Evaluation of the Hydrologic Source Term from Underground Nuclear Tests on Pahute Mesa at the Nevada Test Site: The CHESHIRE Test, UCRL-ID-147023.
- Ringdal, F., P. D. Marshall, R. W. Alewine, 1992. Seismic yield determination of Soviet underground nuclear explosions at the Shagan River test site, *Geophys J. Int.*, 109, 1, 65-77.
- Sawyer, D. A., J. L. Thompson, and D. K. Smith, 1999. *The CHESHIRE Migration Experiment: A summary report*, Los Alamos National Laboratory, Los Alamos, NM, LA-13555-MS.
- U.S. Congress, 1989. The Containment of Underground Nuclear Explosions, Office of Technology Assessment OTA-ISC-414 (Washington D.C.: US Government Printing Office, October 1989) 85p.
- U.S. Department of Energy, 2000. United States Nuclear Tests: July 1945 through September 1992, DOE/NV-209 (Rev. 15), Department of Energy, Las Vegas, NV.
- Vincent, P., J. Sweeney, 2003. Utility of InSAR for Test Site Monitoring, Lawrence Livermore National Laboratory, UCRL-ID-150194.
- Vincent, P., S. Larsen, D. Gallaway, R.J. Laczniak, B. Foxall, W. Walter, J. Zucca, 2003. New signatures of underground nuclear tests revealed by satellite radar interferometry, *Geophys. Res. Lett.*, 30, 22, 2141.
- Waldhouser, F., D. Schaff, P.G. Richards, W.Y. Kim (2004), Lop Nor Revisited: Underground nuclear explosion locations, 1976-1996, from double-difference analysis of regional and teleseismic data, *Bul. Seis. Soc. Amer.*, 94 (5), 1879-1889.