SAND2025-10918C

P3.5-444

Time-variable moment tensor joint inversion of traditional seismic and gradiometer data

A. Darrh and L. Preston

Sandia National Laboratories

INTRODUCTION AND MAIN RESULTS

This presentation evaluates the information gained when inverting gradiometer, traditional seismic, and both gradiometer and seismic data with varying noise levels and source mechanisms. The joint time variable moment tensor inversion can improve both source mechanism and yield estimates, even when only one array is available.

SnT 2025
8 SEPTEMBER ONLINE DAY
9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

SAND2025-10918C

Time-variable moment tensor joint inversion of traditional seismic and gradiometer data

A. Darrh and L. Preston

P3.5-444

Introduction

We apply a deterministic inversion to synthetic data from nine stations (Figure 1) consisting of traditional seismic and gradiometer data simulated for a magnitude 2.4 earthquake with a strike of 70°, dip of 80°, and rake of -20° located at a depth of 1.9 km (Smith et al., 1993) in Rock Valley, Nevada, USA. We also simulate data for a similarly scaled explosion at the same depth and location with an isotropic moment of 4.4668e+12 Nm. We invert both datasets individually and combined in a simultaneous joint inversion to obtain a time-variable moment rate function.

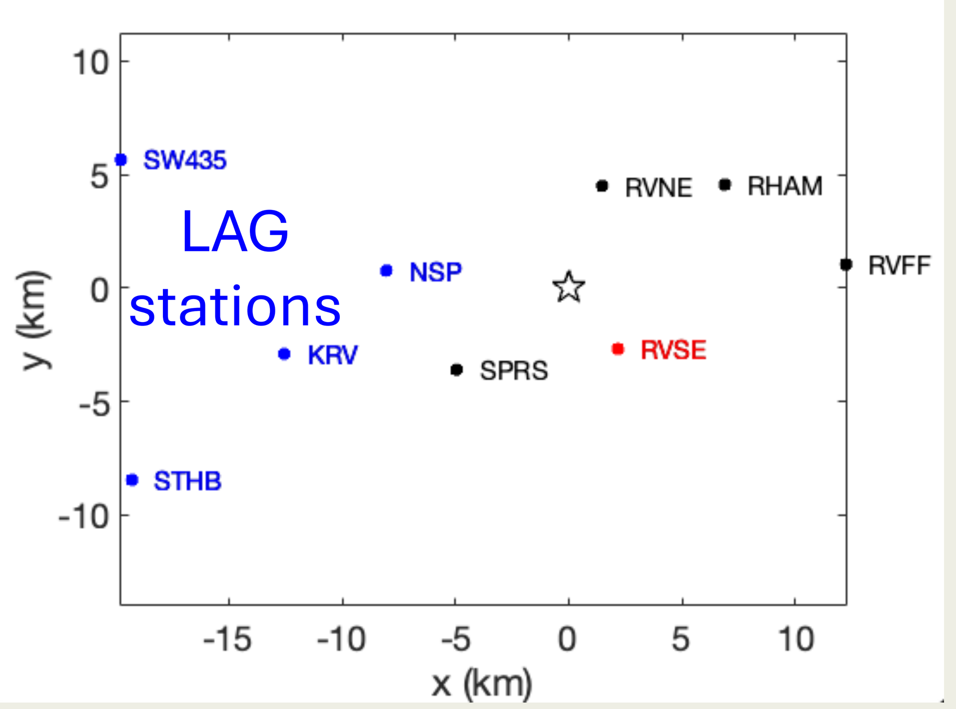


Figure 1: Locations of the stations used in our simulations for 3 cases with respect to the source (black star). Stations in blue correspond to stations that have a large azimuthal gap (labeled LAG henceforth). Red denotes the station location where data from a single station were inverted.

This approach examines the information that can be extracted from each dataset under different station geometries and noise conditions, with the aim of improving both the estimated yield and the ability to identify the source type and mechanism.

Methods/Data

- We use Parelasti (Poppeliers and Preston, 2021), a 3D waveform finite difference solution to the elastic wave equation to create the Green's function used in the inversion, consisting of 3 components for the seismic velocity data and 9 components for the gradiometer data. The Karhunen-Loève method (Poppeliers & Preston, 2022) is used to evaluate uncertainty, using 150 realizations for each case and inversion type. We use the yield equation from Ford et al. (2022) to calculate yield.
- We use an existing Geologic Framework Model (Prothro, 2018; Bodmer et al., 2023) and seismic velocities for the area (Prothro & Wagoner, 2020) as our subsurface model.
- Individual inversion objective function (ϕ):

Observed data; Model Weighting matrix; Moment rate functions

$$\min \phi = \left\| \boldsymbol{G}\boldsymbol{m} - \boldsymbol{u}^{obs} \right\|_2^2 + \lambda \left\| \boldsymbol{W}_m \boldsymbol{m} \right\|_2^2$$

Green's functions; Lagrange parameter

- Joint inversion objective function (uses the same model, $\boldsymbol{m}$):

Observed seismic data; Observed gradiometer data

$$\min \phi = \left\| \boldsymbol{G}_{seis}\boldsymbol{m} - \boldsymbol{u}_{seis}^{obs} \right\|_2^2 + \left\| \boldsymbol{G}_{grad}\boldsymbol{m} - \boldsymbol{u}_{grad}^{obs} \right\|_2^2 + \lambda \left\| \boldsymbol{W}_m \boldsymbol{m} \right\|_2^2$$

Seismic Green's functions; Gradiometer Green's functions

Inversion results

- **Case 1: Explosion data for all 9 stations contaminated with noise half the highest amplitude of the farthest offset station (Figure 2)**
- Seismic overpredicts the isotropic moment when noise is added, resulting in yields higher than the the true (black line). Gradiometer underpredicts isotropic moment/yield. For both, lower gas porosity have more certain yields.
- The joint inversion is able to recover nearly the exact isotropic moment/yield.
- **Case 2: Earthquake data for the LAG stations contaminated with noise half that of the furthest offset station amplitude (Figure 3)**
- Seismic and gradiometer individual inversions both plot closer to a negative isotropic than pure double couple (DC) when plotted on a fundamental lune (Tape & Tape, 2012).
- The joint inversion solution is able to match the true location of the source mechanism at DC, without the spread of higher probabilities displayed in the individual inversion plots.

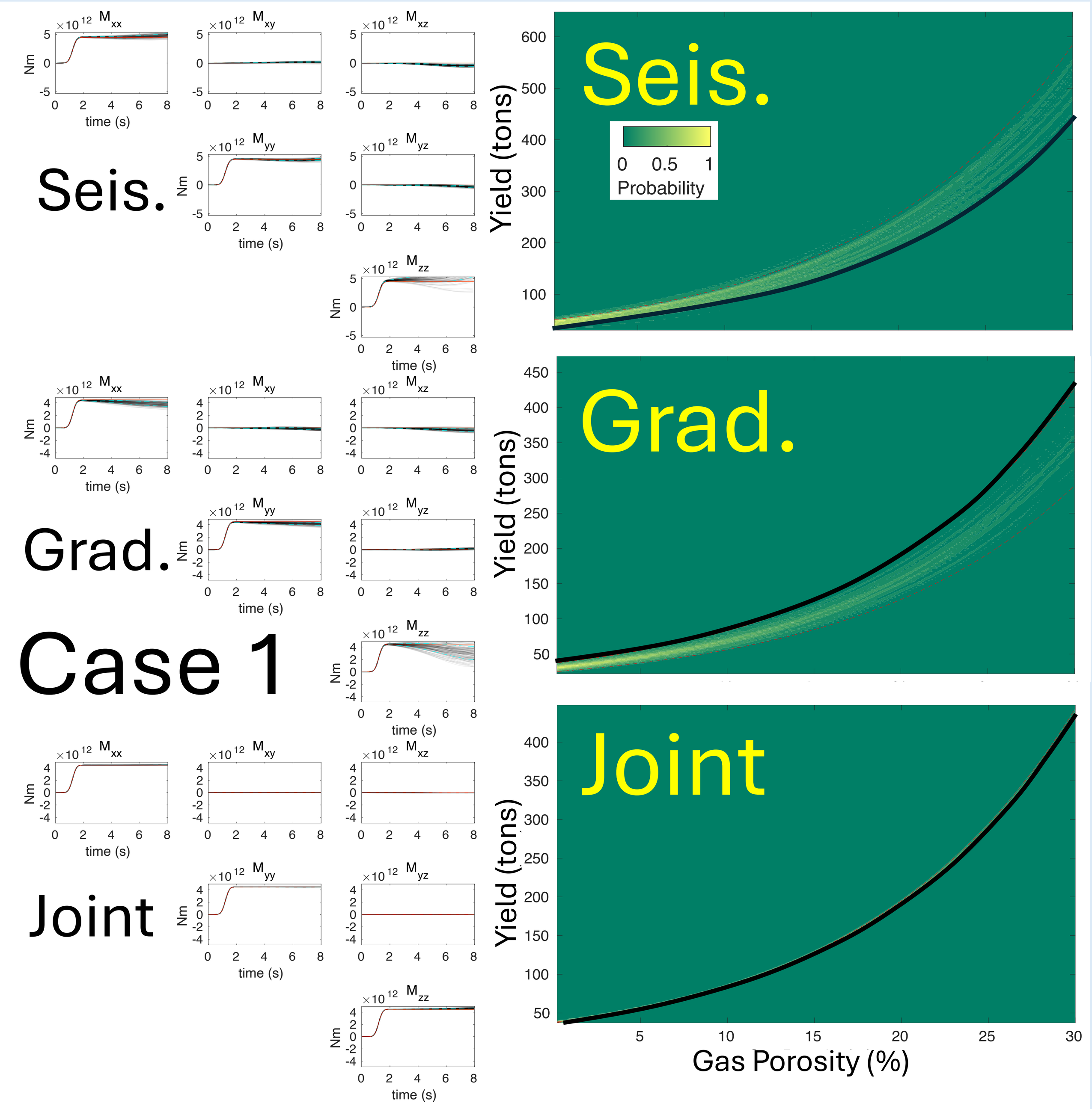


Figure 2: left column are recovered moment functions for each of the inversion runs for the seismic data, gradiometer data, and the joint inversion (grey lines). Red indicates true model, cyan dashed lines indicate 1 standard deviation. Right column indicates the probability that an inversion run returns a specific yield for a range of gas porosities, with the true yield as a black line.

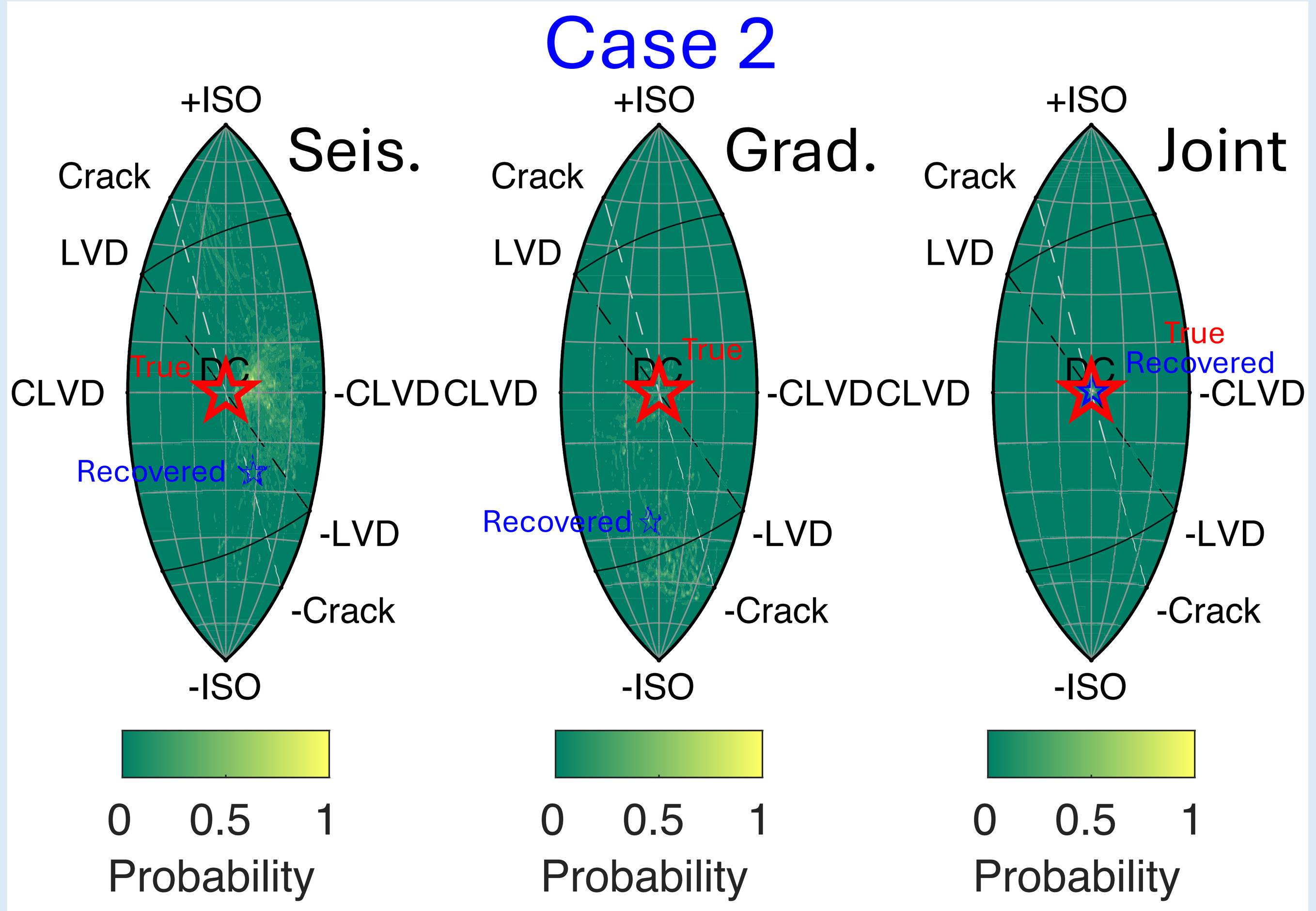
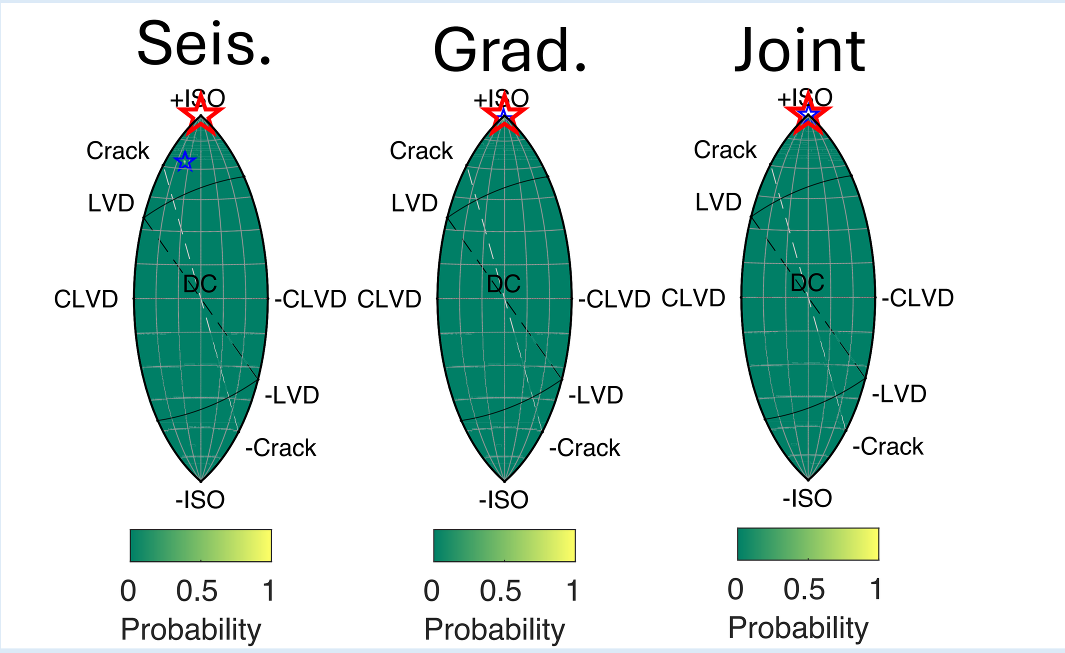


Figure 3: Probability of the source type located on a lune for 150 inversions run for each inversion type with varying noise. Red star is the true source type, blue star is the maximum probability source type.

- **Case 3: Explosion, no noise, inverting data from a single station located ~3.5 km away (Figure 4).**
- The seismic inversion does not have enough information, attempting to invert 6 unknowns with only 3 components. The source mechanism is incorrect (near + crack) and yield is greatly overpredicted
- The gradiometer inversion, attempting to invert for 6 unknowns with 9 components, is able to recover the source type at the true location of positive isotropic. Yield is slightly underpredicted.
- The joint inversion recovers both the source mechanism and the yield, with the true yield plotting in the middle of the highest probability runs and within one standard deviation of the mean of all joint inversion runs.



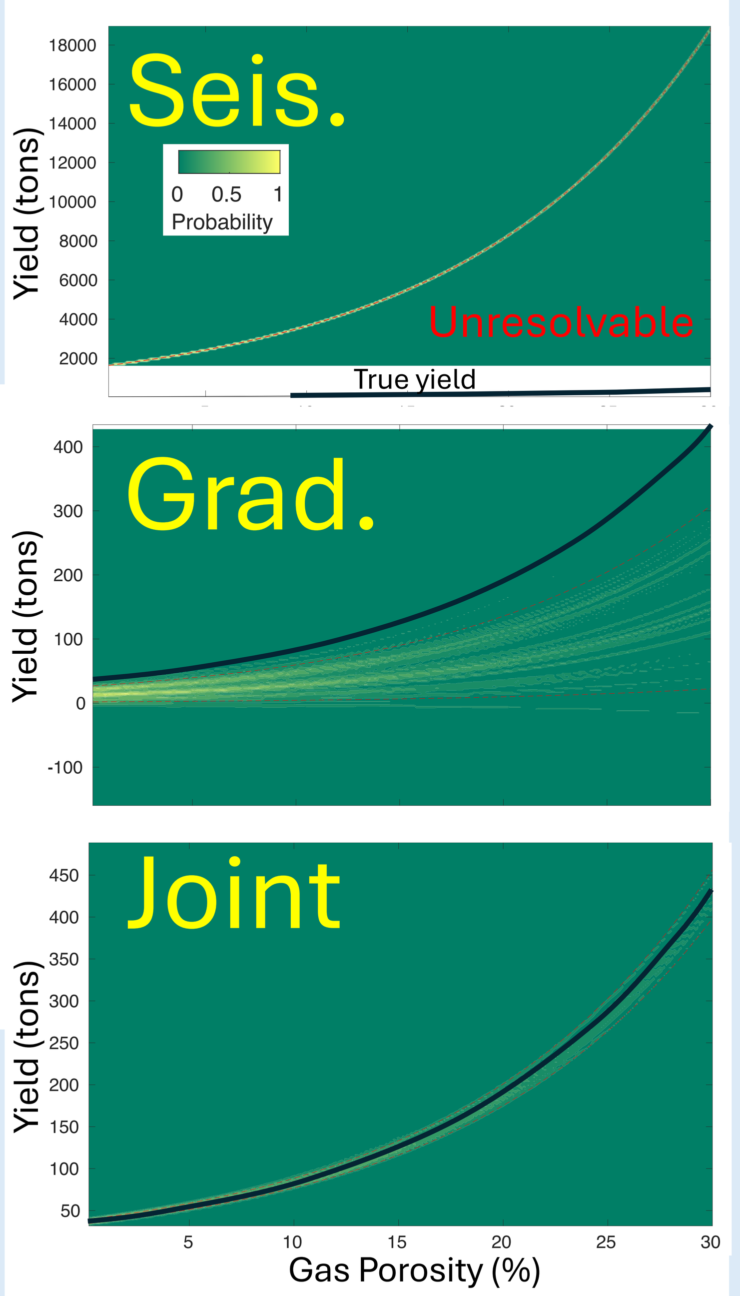


Figure 4: left - probability of the source mechanism for each inversion type, red star indicates true solution, blue star indicates maximum probability from all runs. Right: yield recovered for each inversion type as a function of gas porosity, black line indicates true yield.

Conclusions

- In all cases, the joint seismic and gradiometer inversion resulted in better recovered source mechanisms and yields. Seismic alone overpredicts yield when noise is added and the joint inversion can help correct for that.
- The joint inversion can also aid in distinguishing the correct source mechanism for stations with a large azimuthal gap.
- Preliminary simulations without noise indicate that it may be possible to extract yield and source information for an explosion with a gradiometer array where one station is also used as seismic data in a joint inversion.

Acknowledgements

The authors thank Jenny Harding for their technical review of this poster. This Source Physics Experiment (SPE) research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). The authors acknowledge important interdisciplinary collaboration with scientists and engineers from LANL, LLNL, NNSS, and SNL. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The views expressed here do not necessarily reflect the opinion of the United States Government, the United States Department of Energy, or Sandia National Laboratories.

References

Ford, S. R., Pasyanos, M. E., & Chiang, A. (2023). Explosive Yield Estimation Using Regional Seismic Moment Tensors. Bulletin of the Seismological Society of America, 113(5), 2211–2226. https://doi.org/10.1785/0120220234
Poppeliers, C., & Preston, L. (2022). An efficient method to propagate model uncertainty when inverting seismic data for time domain seismic moment tensors. Geophysical Journal International, 231(2), 1221-1232.
Prothro, L. (2018). Geologic Framework Model for the Underground Nuclear Explosions Signatures Experiment P Tunnel Testbed, Aqueduct Mesa, Nevada National Security Site (DOE/NV/03624-0312). Nevada National Security Site, Nye County, NV (United States); Mission Support and Test Services LLC, Las Vegas, NV (United States). https://doi.org/10.2172/1495705
Prothro, L. B., & Wagoner, J. (2020). Geologic framework model for the Dry Alluvium Geology (DAG) experiment testbed, Yucca Flat, Nevada National Security Site (DOE/NV/03624-0878). Nevada National Security Site/Mission Support and Test Services LLC (NNSS/MSTS), North Las Vegas, NV (United States). https://doi.org/10.2172/1670996
Smith, K. D., Brune, J. N., & Shields, G. (1993). A sequence of very shallow earthquakes in the Rock Valley fault zone, southern Nevada Test Site. EOS suppl, 74, 417.
Tape, W. and Tape, C. (2012). A geometric setting for moment tensors. Geophysical Journal International, 190(1):476–498.