ArtEmis technical report: Coincidences of groundwater radon anomalies and earthquakes in Greece (2026)

Nov 7, 2026

G. Kumar, J. Gerl, A. Atac Nyberg, T. Bäck, R. Wyss, E. Papadimitriou, V. Karakostas

Contact: g.kumar@gsi.de

Status: this report summarizes the first results of an analysis of temporal and spatial coincidences of artEmis radon sensor station, covering a limited period of data taking. The analysis method is still in development; therefore, the results are considered preliminary. Once consolidated, peer reviewed publication is foreseen.

Summary

Radon intensity peaks that appear at three or more groundwater wells within 14 days preceded five of six evaluable earthquake clusters in western Greece in the time period January to October 2026, while keeping the network on alert only 40% of the time (probability gain 2.08, P = 0.006).

Radon content in groundwater has long been reported to change before earthquakes, but a single measurements station cannot show this unambiguously. It records many anomalies with local causes, and in an active region almost any anomaly is followed by an earthquake of mostly low magnitude (M<4) within a few weeks. We test whether requiring anomalies at several distributed stations at the same time, a coincidence as used in nuclear spectroscopy, separates signals related to larger magnitude earthquakes from this “background”.

Using gamma-ray measurements from four ArtEmis groundwater stations, we identify 36 radon peaks and six coincidences of at least three stations within 14-day time intervals. Five were followed by an earthquake cluster of magnitude 4 or larger within 2 to 20 days, while one coincidence could not be associated with an earthquake within a 20-day period. Single-station peaks carry information which are a superimposition of true and false positive signals: they are followed by an earthquake as often as for a random day.

Network and data

The ArtEmis sensor measures the gamma radiation of the radon progeny Pb-214 and Bi-214 in groundwater with a CsI(Tl) scintillator (2 cm diameter, 4 cm length) read out by a silicon photomultiplier. It records the count rate every two minutes, with temperature, humidity and pressure, and sends the data in near real time.

Three stations stand in wells on Lefkada island, less than 20 km apart, in the Kefalonia Transform Fault zone, one of the most seismically active regions of Europe. A fourth station at Achilleio on the mainland, about 200 km east, is a geographically separated reference.

Station	Latitude	Longitude	Days with data (1 Jan to 26 Oct 2026)
Brunello (Lefkada)	38.8312° N	20.6723° E	194
Komilio (Lefkada)	38.7107° N	20.5955° E	283
Kalamitsi (Lefkada)	38.7559° N	20.6038° E	284
Achilleio (mainland)	39.0083° N	22.9581° E	243 (from 22 Feb)

Earthquakes of magnitude M 4 or larger were retrieved for the analysis from a regional catalogue. They are kept when the epicenter lies within the radon-sensitive strain radius of the Lefkada stations from Martinelli's relation (103 km for M 4, 269 km for M 5) [2]:

$M = 2.4 \log_{10} D - 0.83$ (M: magnitude; D: epicentral distance in km)

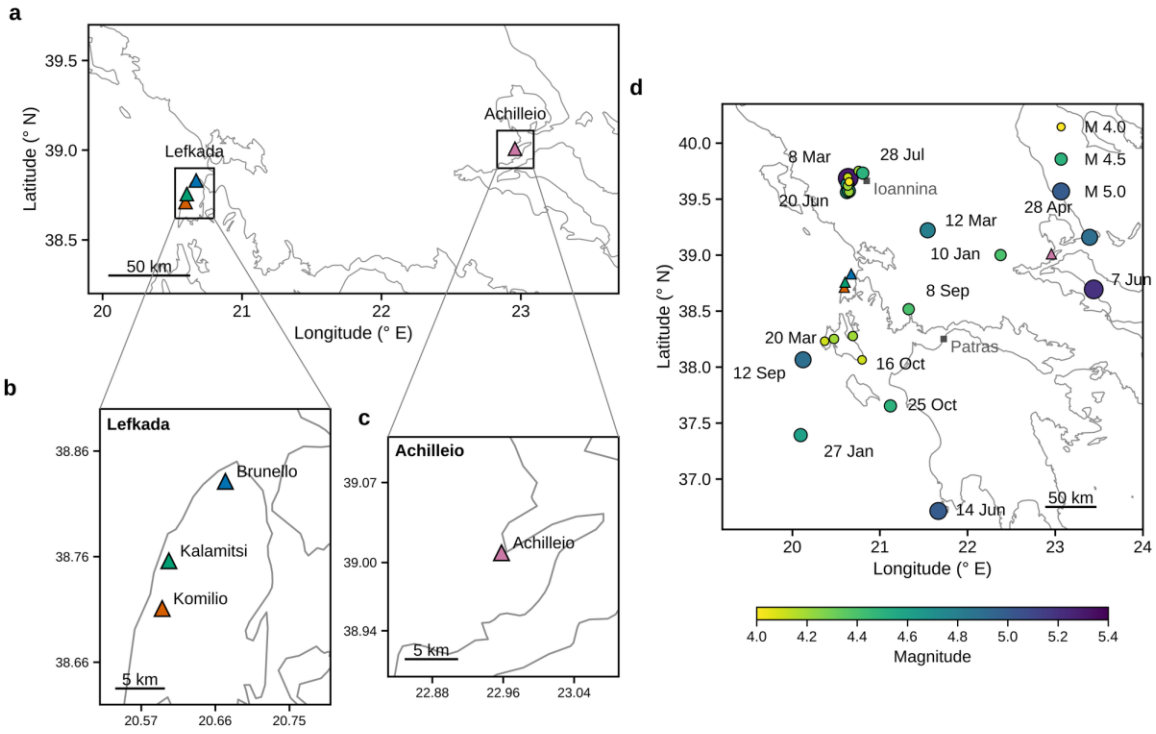


Figure 1. Radon stations and the earthquakes of magnitude M 4 or larger within the radon-sensitive strain radius in the time period January to October 2026.

Analysis method

The analysis turns each station's record into a list of dated peaks, combines them into coincidences, and tests how well the coincidences precede earthquakes against chance.

1. **Daily values and background.** The two-minute counts are averaged per day (days with at least 40% of the expected samples). Slow seasonal and hydrological changes are removed with the SNIP algorithm [1] (maximum half-width 30 days) on the logarithm of the daily counts. The excess is standardized per station; the day-to-day noise is the scatter of the 3-day mean around the 7-day mean.
2. **Peaks.** Each day, a Gaussian peak is fitted to the recent data from the last low point. A peak is declared when its top lies at least two days in the past, its amplitude exceeds three times the station's noise, and it fits clearly better than a flat line (Bayesian information criterion). It has a peak date (the fitted top) and a decision day (when it becomes recognizable, usually two days later).
3. **Coincidences.** Peaks at three or more of the four stations within 14 days, in any order. A coincidence is complete on the latest decision day of its peaks.
4. **Earthquakes.** Earthquakes within 30 days and 50 km form a sequence; sequences starting within 30 days form a cluster. A cluster is evaluated only if at least three stations recorded in the 30 days before it: 8 March, 28 April, 7 June, 28 July and 8 September, 16th October.
5. **Alarm test.** Each coincidence opens a 20-day alarm. The probability gain is the fraction of clusters caught divided by the fraction of time under alarm; random alarms score 1, so the high earthquake rate of the region is built in. P is the share of 2,000 realizations, with each station's peaks shifted randomly in time, that catch as many clusters with no more alarm time.
6. **Checks.** The test with time reversed; earthquakes shuffled instead of the radon peaks; all stations shifted together, which keeps their correlations; earthquakes outside the radius as a negative control.
7. **Real-time forecasting.** The background is replaced by a running lower envelope that uses only past data (it follows falls within about a week and rises over about two months), with the noise from the past 60 days. Its settings were chosen only to reproduce the retrospective peaks, without reference to earthquakes.

Results: single stations and coincidences

A radon peak at one station is no better than a random day, but every coincidence of three or more stations was followed by an earthquake cluster within 1 to 20 days.

Single stations carry mixed information. Of the 30 peaks with a full 30 days of data after them, 24 (80%) were followed by an earthquake of magnitude 4 or larger within 30 days. That is exactly the share of all days followed by such an earthquake (85%).

Coincidences precede earthquake clusters.

Coincidence (peak dates)	Complete	Next cluster	Days after latest peak
Brunello 13 Feb, Kalamitsi 19 Feb, Komilio 25 Feb	27 Feb	8 Mar, M 5.3 (102 km)	11
Brunello 10 Apr, Komilio 14 Apr, Achilleio 22 Apr, Kalamitsi 24 Apr	26 Apr	28 Apr, M 4.9 (41 km from Achilleio)	4

Coincidence (peak dates)	Complete	Next cluster	Days after latest peak
Achilleio 24 Jun, Komilio 26 Jun, Kalamitsi 8 Jul	10 Jul	28 Jul, M 4.5 (108 km)	20
Komilio 22 Aug, Achilleio 31 Aug, Brunello 4 Sep	6 Sep	8 Sep, M 4.4 (67 km)	4
Kalamitsi 6 Sep, Achilleio 13 Sep, Komilio 14 Sep, Brunello 15 Sep	17 Sep	none within 20 days	false positive
Kalamitsi 8 Oct, Achilleio 11 Oct, Komilio 12 Oct, Brunello 15 Oct	17 Oct	16 Oct, M 4.2 (55 km); 25 Oct, M 4.5 (131 km)	8

The only evaluable earthquake cluster without a proper coincidence is the threefold cluster with earthquakes on June 7, 14 and 20. Unfortunately, in the relevant time period Brunello station was offline. Therefore, for triple coincidences besides the two remaining Lefkada stations also the distant Achilleio station would have been required to show a signal. Indeed, Achilleio peaked, Kalamitsi rose and Komilio showed a shoulder, which, however, was just not detected by our algorithm. We note that the M 5.2 earthquake on June 7 occurred east of Achilleio, just at the edge of visibility for the Lefkada stations, the M 5.0 earthquake was far in the south at the edge for all stations and the M 4.0 earthquake north of Lefkada was outside the strain radius of Achilleio.

The mid-September coincidence signal is not followed by any detected earthquake within the 20-day period. Checking the timeseries structure, this is apparently a false positive event which could be avoided with a further improved algorithm, more emphasizing on slopes.

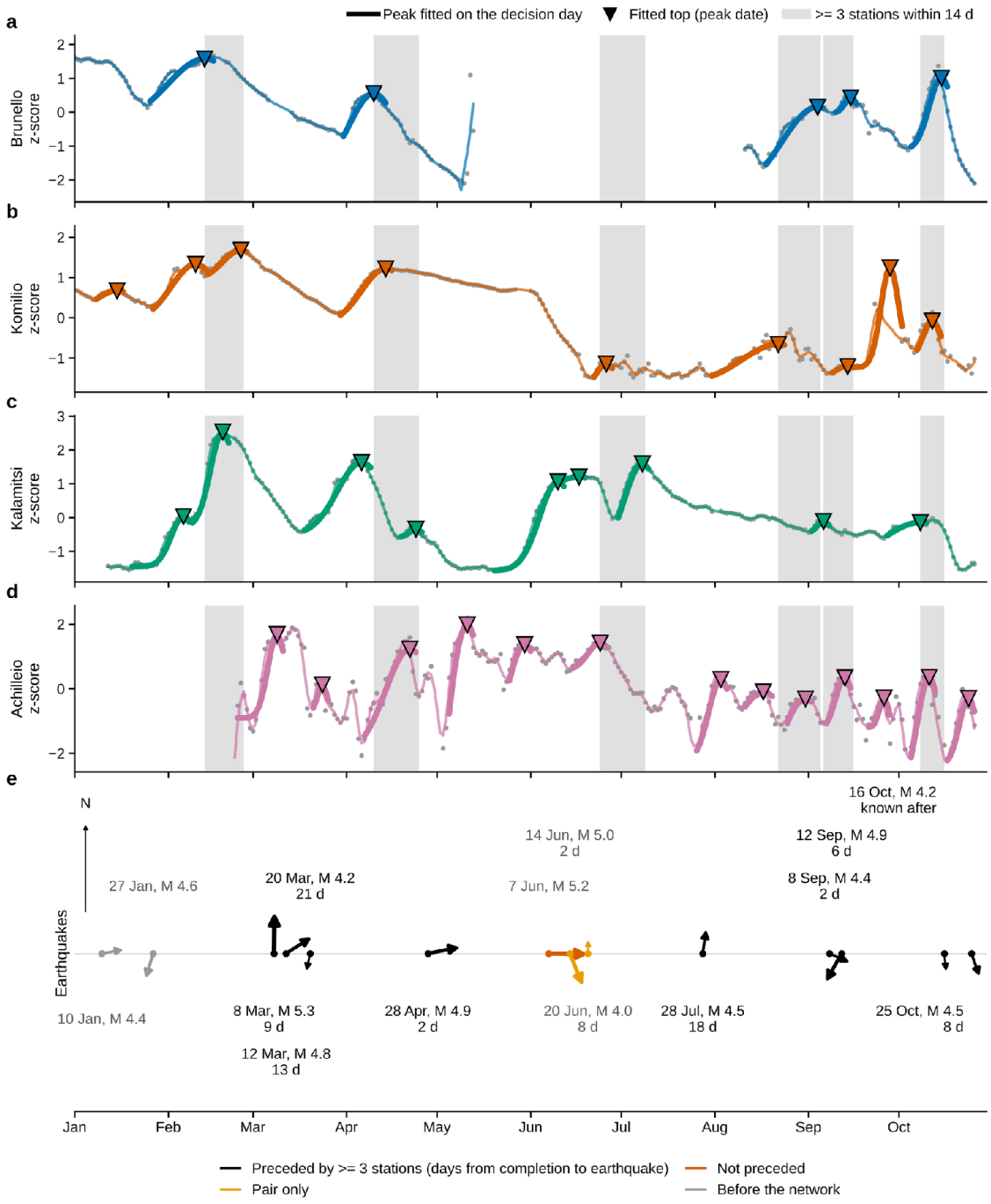


Figure 2. Radon peaks at the four stations, the six coincidences (grey bands) and the earthquake sequences that followed.

Results: alarm test

Requiring three or more stations cuts the time under alarm to a third while keeping five of the six hits, which random timing almost never achieves (P = 0.006).

Stations required	Time under alarm	Clusters caught	Probability gain	P
1	98%	6 of 6	1.02	0.39
at least 2	63%	5 of 6	1.31	0.025
at least 3	40%	5 of 6	2.08	0.006
4	20%	2 of 6	1.66	0.067

Single stations and pairs cannot be told apart from chance. With time reversed, the three- and four-station coincidences follow only one of the six clusters so they precede the earthquakes rather than respond to them.

Further checks [4].

- Earthquakes shuffled, radon fixed: five of six clusters preceded, against 2.4 on average for randomly placed clusters (P = 0.015, 10,000 realizations).
- All stations shifted together, which keeps any correlation between them: P = 0.004.
- Earthquakes outside the radon-sensitive radius are preceded only at chance level, so the association is specific to nearby earthquakes.
- With the 14-day coincidence window, alarms of 10 and 30 days give gains of 2.12 (P = 0.08) and 1.49 (P = 0.02). Other coincidence windows (10, 18 or 21 days) give 1.40; the peak threshold (two or three times the noise) makes no difference.
- The earthquake effectiveness [5], a proxy for the strain at a station, explains which stations took part: the April and June earthquakes were strong at Achilleio and weak at Lefkada, while the March, July, September and October earthquakes were strong at Lefkada..

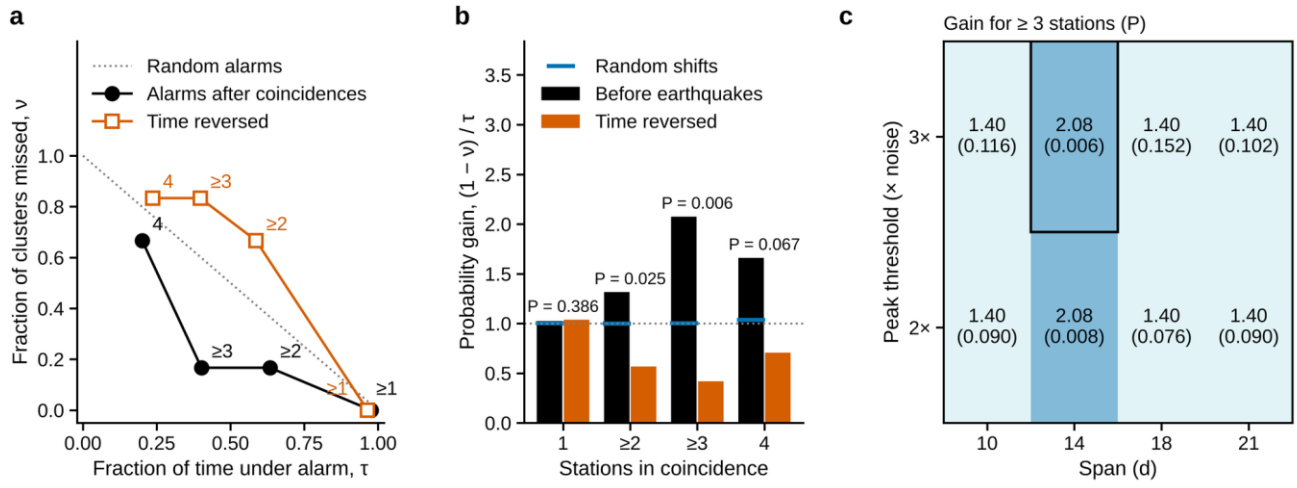


Figure 3. Molchan [3] error diagram and probability gain by number of stations, with the sensitivity to the coincidence window and the peak threshold.

Results: real-time forecasting

Using only the data available on each day, the network would have completed a coincidence 10, 14, 7, 9 and 14 days before the March, April, July, September and October earthquake clusters.

The real-time detector recovered 32 of the 36 retrospective peaks (89%) within five days. It formed seven coincidences of three or more stations. With 20-day alarms started when a coincidence was complete, they covered 46% of the time and caught five of six clusters (gain 1.81, P = 0.003). The coincidence completed on 17 September was not followed by a cluster within 20 days and must be considered false positive with the present algorithm.

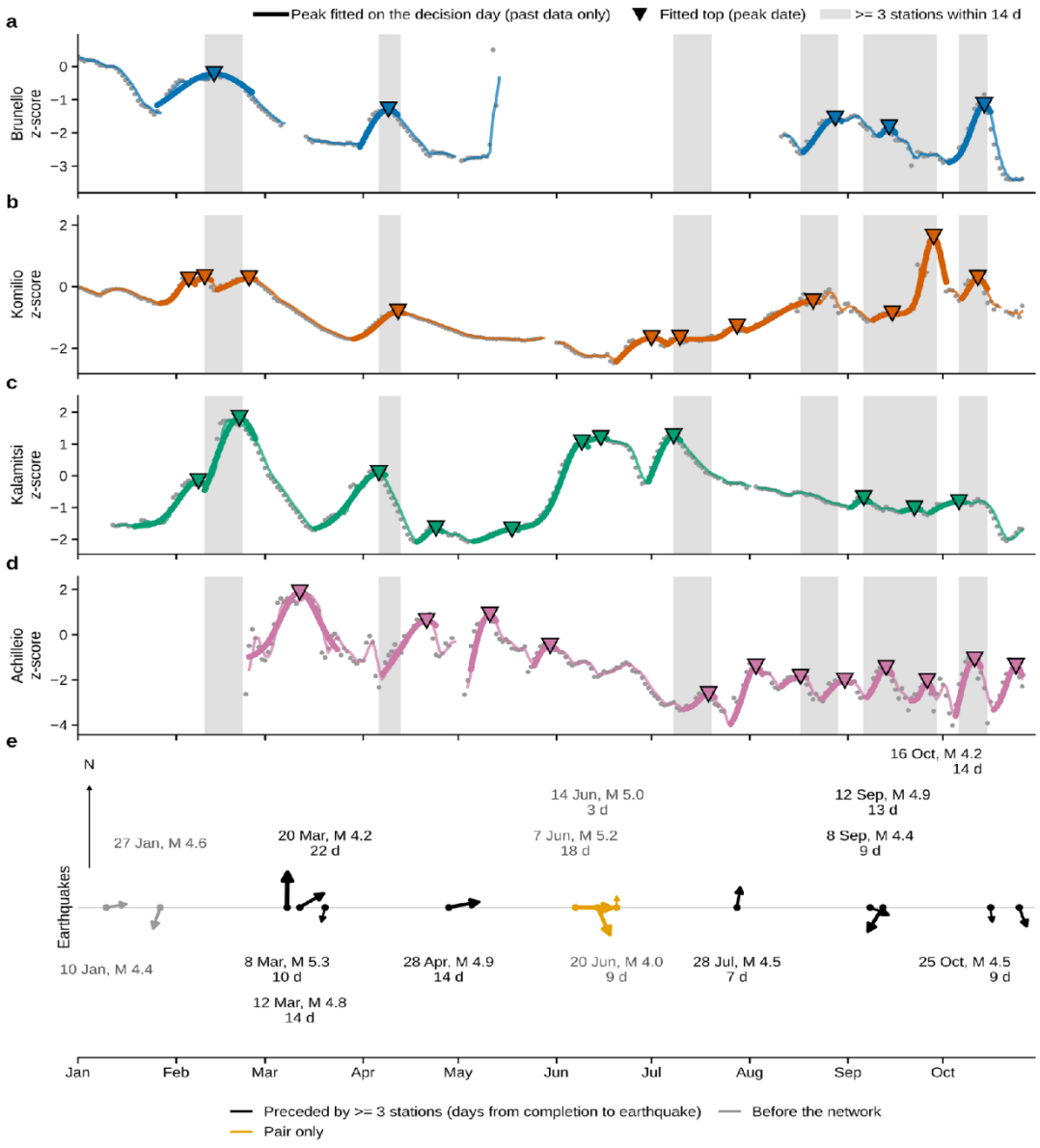


Figure 4. Coincidences found by the real-time detector, using only the data available on each day.

Limitations and next steps

The results rest on about eight and a half months of data, six coincidences and six evaluable earthquake clusters, so each event still influences the numbers considerably. The method was developed and evaluated on the same period. All rules, including the real-time detector, are now fixed, and the network will be evaluated prospectively on new data, which is the decisive test. A larger network will allow higher coincidence orders, better resilience to sensor failures and a geographical weighting of the stations.

Acknowledgements

This work is funded by the European Commission under the Euratom Research and Training Programme (Project 101061712, ArtEmis, HORIZON-EURATOM-2021-NRT-01).

How to cite

Kumar, G. et al. Coincidences of groundwater radon anomalies at several stations and earthquakes in western Greece. ArtEmis technical report (2026). A peer-reviewed article is in preparation.

Key references

1. Ryan, C. G. et al. SNIP, a statistics-sensitive background treatment for the quantitative analysis of PIXE spectra in geoscience applications. Nucl. Instrum. Methods B 34, 396–402 (1988).
2. Martinelli, G. in Isotopic and Geochemical Precursors of Earthquakes and Volcanic Eruptions, IAEA-TECDOC-726, 48–62 (IAEA, 1993).
3. Molchan, G. M. Strategies in strong earthquake prediction. Phys. Earth Planet. Inter. 61, 84–98 (1990).
4. Zechar, J. D. & Jordan, T. H. Testing alarm-based earthquake predictions. Geophys. J. Int. 172, 715–724 (2008).
5. Dobrovolsky, I. P., Zubkov, S. I. & Miachkin, V. I. Estimation of the size of earthquake preparation zones. Pure Appl. Geophys. 117, 1025–1044 (1979).