Article Title - La Palma Earthquakes

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Abstract

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>
> The abstract should begin with a short description of the problem addressed, briefly describe the new data or analyses, then briefly state the main conclusion(s) and how they are supported, and address any uncertainty.

In September 2021, a significant jump in seismic activity on the island of La Palma (Canary Islands, Spain) signaled the start of a volcanic crisis that still continues at the time of writing. Earthquake data is continually collected and published by the Instituto Geográphico Nacional (IGN). We have created an accessible dataset from this and completed preliminary data analysis which shows seismicity originating at two distinct depths, consistent with the model of a two reservoir system feeding the currently very active volcano.

1 Introduction

> The content of your notebook may be broken into any number of markdown or code cells. Markdown cells use MyST markdown and support standard markdown typography and many directives and roles for figures, tables, equations, etc.

La Palma is one of the west most islands in the Volcanic Archipelago of the Canary Islands, a Spanish territory situated is the Atlantic Ocean where at their closest point are 100km from the African coast Figure 1 The island is one of the youngest, remains active and is still in the island forming stage.

> Figures may be added to your notebook using the figure directive. They may refer to images saved in your `images/` folder, images from the web, or notebook cell outputs referenced by label. The `:name:` is used to reference the figure in your text; a reference to the following figure is found in the paragraph above. The figure caption is given as the body of this directive.

La Palma has been constructed by various phases of volcanism, the most recent and currently active being the *Cumbre Vieja* volcano, a north-south volcanic ridge that constitutes the southern half of the island.

1.1 Eruption History

A number of eruptions were recorded since the colonization of the islands by Europeans in the late 1400s, these are summarized in Table 1.

> Simple tables may be created using the list-table directive. Similar to figures, tables may be referenced in the text by their `name`. The caption for this table is the first line of the directive.

This equates to an eruption on average every 79 years up until the 1971 event. The probability of a future eruption can be modeled by a Poisson distribution (1).

> Numbered equations may be defined using the math directive or in line. Equations defined with the math directive may be reference in the text by label.

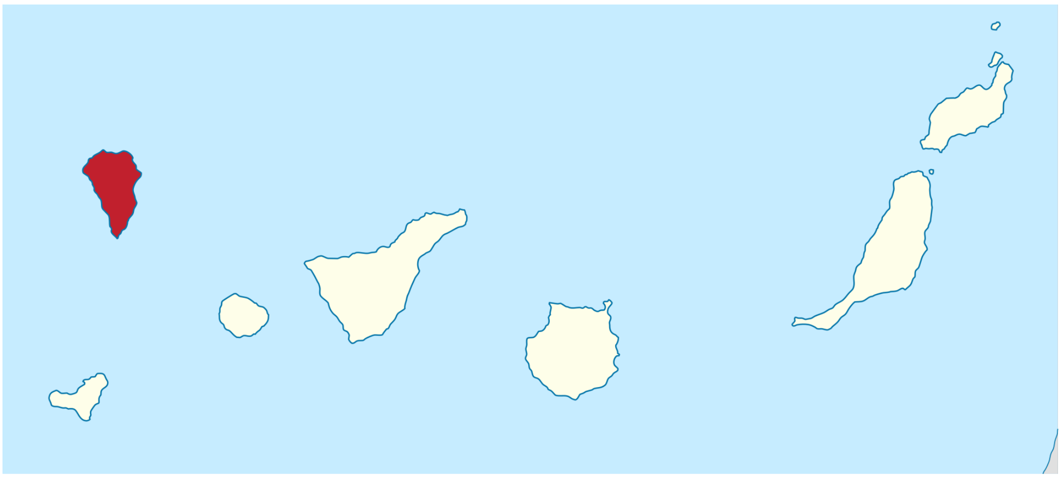


Figure 1. Map of La Palma in the Canary Islands. Image credit NordNordWest

Table 1. Recent historic eruptions on La Palma

Name	Year
Current	2021
Teneguía	1971
Nambroque	1949
El Charco	1712
Volcán San Antonio	1677
Volcán San Martin	1646
Tajuya near El Paso	1585
Montaña Quemada	1492

$$p(x) = \frac{e^{-\lambda}\lambda^x}{x!} \tag{1}$$

Where λ is the number of eruptions per year, $\lambda = \frac{1}{79}$ in this case. The probability of a future eruption in the next t years can be calculated by:

$$p_e = 1 - \mathrm{e}^{-t\lambda} \tag{2}$$

So following the 1971 eruption the probability of an eruption in the following 50 years — the period ending this year — was 0.469. After the event, the number of eruptions per year moves to $\lambda = \frac{1}{75}$ and the probability of a further eruption within the next 50 years (2022-2071) rises to 0.487 and in the next 100 years, this rises again to 0.736.

1.2 Magma Reservoirs

> You may add citations two ways. First, you may simply insert a markdown link to a DOI like so: Thompson et al. (1994). No additional bibliographic information is required for this approach; the reference will be looked up by DOI and added implicitly to the references. Alternatively, you may provide the bibliography directly as `references.bib` bibtex file, then embed the citation by bibtex key in your text using the `cite:p` or `cite:t` for parenthetical or textual citations, respectively. The following paragraph provides an example of this. A single paper may combine both DOI and bibtex citations.

Studies of the magma systems feeding the volcano, such as Marrero et al. (2019) has proposed that there are two main magma reservoirs feeding the Cumbre Vieja volcano; one in the mantle (30-40km depth) which charges and in turn feeds a shallower crustal reservoir (10-20km depth).

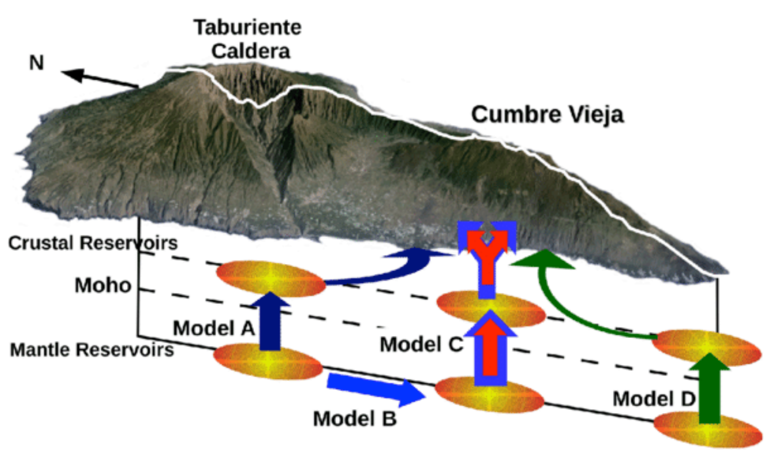


Figure 2. Proposed model from Marrero et al

In this paper, we look at recent seismicity data to see if we can see evidence of such a system action, see Figure 2.

2 Dataset

> All data used in the notebook should be present in the `data/` folder so notebooks may be executed in place with no additional input.

The earthquake dataset used in our analysis was generated from the IGN web portal this is public data released under a permissive license. Data recorded using the network of Seismic Monitoring Stations on the island. A web scraping script was developed to pull data into a machine-readable form for analysis. That code tool is available on GitHub along with a copy of recently updated data.

2.1 Main Timeline Figure

> Code cells may be seamlessly interleaved with markdown cells. Currently, with a single-article submission, code cannot be hidden in the output document.

```
import pandas as pd
import matplotlib
import matplotlib.pyplot as plt
%matplotlib inline
import seaborn as sns
import numpy as np
sns.set_theme(style="whitegrid")

def make_category_columns(df):
    df['Depth'] = 'Shallow (<18km)'
    df.loc[(df['Depth(km)'] >= 18) & (df['Depth(km)'] <= 28), 'Depth'] = 'Interchange (18km>x>28km
    df.loc[df['Depth(km)'] >= 28, 'Depth'] = 'Deep (>28km)'

    df['Mag'] = 0
    df.loc[(df['Magnitude'] >= 1) & (df['Magnitude'] <= 2), 'Mag'] = 1
    df.loc[(df['Magnitude'] >= 2) & (df['Magnitude'] <= 3), 'Mag'] = 2
    df.loc[(df['Magnitude'] >= 3) & (df['Magnitude'] <= 4), 'Mag'] = 3
    df.loc[(df['Magnitude'] >= 4) & (df['Magnitude'] <= 5), 'Mag'] = 4

    return df
```

2.2 Visualising Long term earthquake data

Data taken directly from the IGN Catalog

> Supported cell outputs below include `pandas` dataframe, raw text output, `matplotlib` plot, and `seaborn` plot.

```
df_ign = pd.read_csv('./data/lapalma_ign.csv')
df_ign = make_category_columns(df_ign)
df_ign.head()
```

```
Event        Date      Time  Latitude  Longitude  Depth(km)  \
0   es2017eugju  2017 -03 -09  23:44:06   28.5346   -17.8349       26.0
1   es2017euhlh  2017 -03 -10  00:16:10   28.5491   -17.8459       27.0
2   es2017cpaoh  2017 -03 -10  00:16:11   28.5008   -17.8863       20.0
3   es2017eunnk  2017 -03 -10  03:20:26   28.5204   -17.8657       30.0
4   es2017kajei  2017 -08 -21  02:06:55   28.5985   -17.7156        0.0
```

```
      Intensity  Magnitude  Type Mag                        Location  \
0                      1.6         4  NE FUENCALIENTE DE LA PALMA.IL
1                      2.0         4  N FUENCALIENTE DE LA PALMA.ILP
2                      2.1         4               W LOS CANARIOS.ILP
3                      1.6         4  NW FUENCALIENTE DE LA PALMA.IL
4                      1.6         4                 E EL PUEBLO.ILP

              DateTime           Timestamp  Swarm  Phase  \
0  2017 -03 -09 23:44:06  1489103046000000000    0.0      0
1  2017 -03 -10 00:16:10  1489104970000000000    0.0      0
2  2017 -03 -10 00:16:11  1489104971000000000    0.0      0
3  2017 -03 -10 03:20:26  1489116026000000000    0.0      0
4  2017 -08 -21 02:06:55  1503281215000000000    0.0      0

                      Depth  Mag
0  Interchange (18km>x>28km)    1
1  Interchange (18km>x>28km)    2
2  Interchange (18km>x>28km)    2
3               Deep (>28km)    1
4            Shallow (<18km)    1
```

```
df_ign['DateTime'] = pd.to_datetime(df_ign['Date'] + ' ' + df_ign['Time'])
df_ign['DateTime'];
```

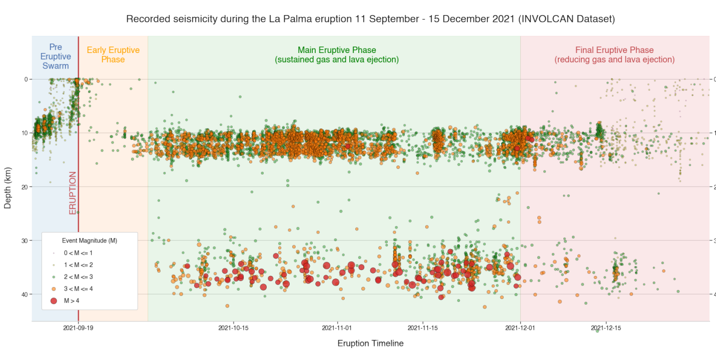
```
df_ign_early = df_ign[df_ign['DateTime'] < '2021 -09 -11']
df_ign_pre = df_ign[(df_ign['DateTime'] >= '2021 -09 -11')&(df_ign['DateTime'] < '2021 -09 -19 14:1
df_ign_phase1 = df_ign[(df_ign['DateTime'] >= '2021 -09 -19 14:13:00')&(df_ign['DateTime'] < '2021
df_ign_phase2 = df_ign[(df_ign['DateTime'] >= '2021 -10 -01')&(df_ign['DateTime'] < '2021 -12 -01')
df_ign_phase3 = df_ign[(df_ign['DateTime'] >= '2021 -12 -01')&(df_ign['DateTime'] <= '2021 -12 -31'

df_erupt = df_ign[(df_ign['Date'] < '2022 -01 -01') & (df_ign['Date'] > '2021 -09 -11')]

df_erupt_1 = df_erupt[df_erupt['Magnitude'] < 1.0]
df_erupt_2 = df_erupt[(df_erupt['Magnitude'] >= 1.0)&(df_erupt['Magnitude'] < 2.0)]
df_erupt_3 = df_erupt[(df_erupt['Magnitude'] >= 2.0)&(df_erupt['Magnitude'] < 3.0)]
df_erupt_4 = df_erupt[(df_erupt['Magnitude'] >= 3.0)&(df_erupt['Magnitude'] < 4.0)]
df_erupt_5 = df_erupt[df_erupt['Magnitude'] > 4.0]
```

```
tab20_colors = (
    (0.12156862745098039, 0.4666666666666667,  0.7058823529411765  ),  # 1f77b4
    (0.6823529411764706,  0.7803921568627451,  0.9098039215686274  ),  # aec7e8
    (1.0,                 0.4980392156862745,  0.054901960784313725),  # ff7f0e
    (1.0,                 0.7333333333333333,  0.47058823529411764 ),  # ffbb78
    (0.17254901960784313, 0.6274509803921569,  0.17254901960784313 ),  # 2ca02c
    (0.596078431372549,   0.8745098039215686,  0.5411764705882353  ),  # 98df8a
    (0.8392156862745098,  0.15294117647058825, 0.1568627450980392  ),  # d62728
    (1.0,                 0.596078431372549,   0.5882352941176471  ),  # ff9896
    (0.5803921568627451,  0.403921568627451,   0.7411764705882353  ),  # 9467bd
    (0.7725490196078432,  0.6901960784313725,  0.8352941176470589  ),  # c5b0d5
    (0.5490196078431373,  0.33725490196078434, 0.29411764705882354 ),  # 8c564b
    (0.7686274509803922,  0.611764705882353,   0.5803921568627451  ),  # c49c94
    (0.8901960784313725,  0.4666666666666667,  0.7607843137254902  ),  # e377c2
    (0.9686274509803922,  0.7137254901960784,  0.8235294117647058  ),  # f7b6d2
    (0.4980392156862745,  0.4980392156862745,  0.4980392156862745  ),  # 7f7f7f
```

```
    (0.7803921568627451,  0.7803921568627451,  0.7803921568627451  ),  # c7c7c7
    (0.7372549019607844,  0.7411764705882353,  0.13333333333333333 ),  # bcbd22
    (0.8588235294117647,  0.8588235294117647,  0.5529411764705883  ),  # dbdb8d
    (0.09019607843137255, 0.7450980392156863,  0.8117647058823529  ),  # 17becf
    (0.6196078431372549,  0.8549019607843137,  0.8980392156862745),    # 9edae5
)
```

```
from matplotlib.patches import Rectangle

import datetime as dt
from matplotlib.dates import date2num, num2date

matplotlib.rcParams['font.sans -serif'] = "Helvetica"
matplotlib.rcParams['font.family'] = "sans -serif"
matplotlib.rcParams['xtick.labelsize'] = 14
matplotlib.rcParams['ytick.labelsize'] = 14
matplotlib.rcParams['ytick.labelleft'] = True
matplotlib.rcParams['ytick.labelright'] = True

%matplotlib inline
fig = matplotlib.pyplot.figure(figsize=(24,12))
fig.tight_layout()
# Creating axis
# add_axes([xmin,ymin,dx,dy])
ax_min = fig.add_axes([0.01, 0.01, 0.01, 0.01])
ax_min.axis('off')
ax_max = fig.add_axes([0.99, 0.99, 0.01, 0.01])
ax_max.axis('off')

ax_timeline = fig.add_axes([0.04, 0.1, 0.92, 0.85])
ax_timeline.spines["top"].set_visible(False)
ax_timeline.spines["right"].set_visible(False)
ax_timeline.spines["left"].set_visible(False)
ax_timeline.grid(axis='x')


ax_timeline.axvline(x=dt.datetime(2021, 9, 19, 14, 13), ymin=0.075, ymax=0.98, color='r', linewidt


def make_scatter(df, c, alpha=0.8):
    M = 3*np.exp2(1.3*df['Magnitude'])
    return ax_timeline.scatter(df['DateTime'], df['Depth(km)'], s=M, c=c, alpha=alpha, edgecolor='

# make_scatter(df_erupt, c=tab20c_colors[ -1])
points_1 = make_scatter(df_erupt_1, c=[tab20_colors[12]], alpha=0.3)
points_2 = make_scatter(df_erupt_2, c=[tab20_colors[16]], alpha=0.4)
points_3 = make_scatter(df_erupt_3, c=[tab20_colors[4]], alpha=0.5)
points_4 = make_scatter(df_erupt_4, c=[tab20_colors[2]], alpha=0.6)
points_5 = make_scatter(df_erupt_5, c=[tab20_colors[6]], alpha=0.8)

ax_timeline.tick_params(axis='x', labelrotation=0, bottom=True)
ax_timeline.set_ylabel('')
ax_timeline.yaxis.set_ticks_position('both')
ax_timeline.yaxis.set_ticks_position('both')
```

```
xticks = ax_timeline.get_xticks()
new_xticks = [date2num(pd.to_datetime('2021 -09 -11')),
    date2num(pd.to_datetime('2021 -09 -19 14:13:00'))]
new_xticks = np.append(new_xticks, xticks[2: -1])
ax_timeline.set_xticks(new_xticks)

ax_timeline.invert_yaxis()
ax_timeline.spines['bottom'].set_position(('data', 45))
ax_timeline.margins(tight=True, x=0)
ax_timeline.legend(
    [points_1, points_2, points_3, points_4, points_5],
    ['0 < M <= 1','1 < M <= 2','2 < M <= 3','3 < M <= 4','M > 4'],
    loc='lower left', bbox_to_anchor=(0.01, 0.1, 0.15, 0.1), fancybox=True,
    borderpad=1.0, labelspacing=1, mode="expand", title="Event Magnitude (M)",
    fontsize=14, title_fontsize=14, framealpha=1)

ax_timeline.set_ylim(ax_timeline.get_ylim()[0], -9)

plt.annotate('ERUPTION', (0.055, 0.42), rotation=90, xycoords='axes fraction', fontweight='bold', f
plt.annotate('Pre\nEruptive\nSwarm', (0.035, 0.88), rotation=0, xycoords='axes fraction', fontweigh
plt.annotate('Early Eruptive\nPhase', (0.12, 0.9), rotation=0, xycoords='axes fraction', fontweight
plt.annotate('Main Eruptive Phase\n(sustained gas and lava ejection)', (0.45, 0.9), rotation=0, xyc
plt.annotate('Final Eruptive Phase\n(reducing gas and lava ejection)', (0.86, 0.9), rotation=0, xyc

ax_timeline.add_patch(Rectangle((date2num(pd.to_datetime('2021 -09 -11')), -8), date2num(pd.to_date
ax_timeline.add_patch(Rectangle((date2num(pd.to_datetime('2021 -09 -19 14:13:00')), -8), date2num(p
ax_timeline.add_patch(Rectangle((date2num(pd.to_datetime('2021 -10 -01')), -8), date2num(pd.to_date
ax_timeline.add_patch(Rectangle((date2num(pd.to_datetime('2021 -12 -01')), -8), date2num(pd.to_date

ax_timeline.set_title("Recorded seismicity during the La Palma eruption 11 September - 15 December 
ax_timeline.set_ylabel("Depth (km)", dict(fontsize=20), labelpad=20)
ax_timeline.set_xlabel("Eruption Timeline", dict(fontsize=20), labelpad=20);
```

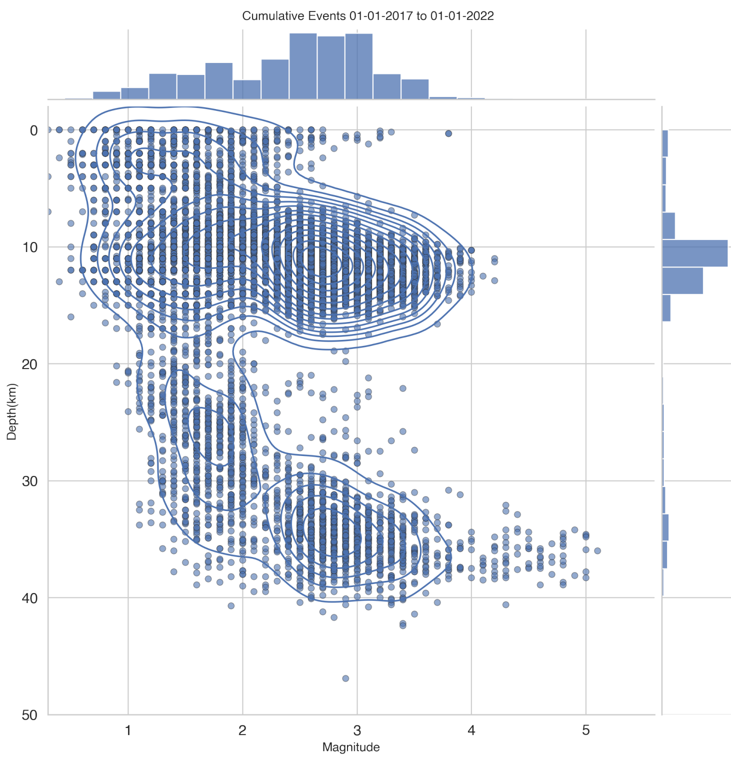


2.3 Cumulative Distrubtion Plots

```
def cumulative_events_mag_depth(df, hue='Depth', kind='scatter', ax=None, dpi=100, palette=None, kc
    matplotlib.rcParams['ytick.labelright'] = False
    g = sns.jointplot(x="Magnitude", y="Depth(km)", data=df,
                      kind=kind, hue=hue, height=10, space=0.1, marginal_ticks=False, ratio=8, alph
                      hue_order=['Shallow (<18km)', 'Interchange (18km>x>28km)', 'Deep (>28km)'],
                      ax=ax, palette=palette, ylim=( -2,50), xlim=(0.3,5.6), edgecolor=".2", margin
    if kde:
        g.plot_joint(sns.kdeplot, color="b", zorder=1, levels=15, ax=ax)
```

```
    g.fig.axes[0].invert_yaxis();
    g.fig.set_dpi(dpi)
```

```
import warnings

with warnings.catch_warnings():
    warnings.simplefilter("ignore")
    cumulative_events_mag_depth(df_ign, hue=None, dpi=200)
    plt.suptitle('Cumulative Events 01 -01 -2017 to 01 -01 -2022', y=1.01);
```



3 Results

The dataset was loaded into this Jupyter notebook and filtered down to La Palma events only. This results in 5465 data points which we then visualized to understand their distributions spatially, by depth, by magnitude and in time.

From our analysis above, we can see 3 different systems in play.

Firstly, the shallow earthquake swarm leading up to the eruption on 19th September, related to significant surface deformation and shallow magma intrusion.

After the eruption, continuous shallow seismicity started at 10-15km corresponding to magma movement in the crustal reservoir.

Subsequently, high magnitude events begin occurring at 30-40km depths corresponding to changes in the mantle reservoir. These are also continuous but occur with a lower frequency than in the crustal reservoir.

4 Conclusions

From the analysis of the earthquake data collected and published by IGN for the period of 11 September through to 9 November 2021. Visualization of the earthquake events at different depths appears to confirm the presence of both mantle and crustal reservoirs as proposed by Marrero et al. (2019).

Open Research

> Data availability statement should be specified in a separate cell with metadata `"part": "availability"`, similar to the abstract.
>
> AGU requires an Availability Statement for the underlying data needed to understand, evaluate, and build upon the reported research at the time of peer review and publication.

A web scraping script was developed to pull data into a machine-readable form for analysis. That code tool is available on GitHub along with a copy of recently updated data.

References

Marrero, J., García, A., Berrocoso, M., Llinares, Á., Rodríguez-Losada, A., & Ortiz, R. (2019, 7). Strategies for the development of volcanic hazard maps in monogenetic volcanic fields: the example of La Palma (Canary Islands). *Journal of Applied Volcanology*, *8*. doi: 10.1186/s13617-019-0085-5

Thompson, J. D., Higgins, D. G., & Gibson, T. J. (1994). CLUSTAL w: improving the sensitivity of progressive multiple sequence alignment through sequence weighting, position-specific gap penalties and weight matrix choice. *Nucleic Acids Research*, *22*(22), 4673–4680. Retrieved from `https://doi.org/10.1093%2Fnar%2F22.22.4673` doi: 10.1093/nar/22.22.4673