

**Современные методы оценки сейсмической
опасности и прогноза землетрясений
22 - 23 октября 2025 г. Москва**

**Систематический прогноз
землетрясений Камчатки**

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1. Основные понятия

- Систематический прогноз землетрясений даётся регулярно и на постоянный временной интервал.
- Объекты прогноза:
 - ✓ время землетрясения (интервал тревоги).
 - ✓ место эпицентра (зона тревоги).
 - ✓ магнитуа землетрясения (магнитудный интервал).
 - ✓ вероятность успешности очередного прогноза.
- Успешность прогноза:
 - ✓ время предсказано успешно, если на интервале тревоги происходят землетрясения с эпицентрами в зоне анализа.
 - ✓ место предсказано успешно, если на данном интервале все эпицентры землетрясений попадают в зону тревоги.

Метрики прогноза

1. Вероятность обнаружения $U = M^* / M$,
 M^* - число интервалов с успешным прогнозом.
 M - число всех интервалов с эпицентрами в зоне анализа.
2. Вероятность успешности прогноза на очередном интервале $P = M^* / N$,
 N – число всех интервалов прогноза.

2. Технология

Машинное обучение

- Метод обучения
 - ✓ метод ортантов (обобщение метода минимальной области тревоги).
- Режимы обучения:
 - ✓ Первичное обучение для выбора полей и оценивания их параметров.
 - ✓ Доучивание перед каждым интервалом прогноза по всем имеющимся временным срезам полей и выборке возможных предвестников землетрясений.

Схема систематического прогноза

- Компьютер регулярно обрабатывает разнотипные данные мониторинга и преобразует их в сеточные поля.
- Машинное обучение выявляет эмпирические закономерности и осуществляет прогноз землетрясений.
- Аналитические программные средства поддерживают принятие экспертных решений по объявлению тревоги.

Двухэтапный прогноз

Пусть успешный прогноз получен на всех интервалах:

$M^*=M$, вероятность успешного обнаружения $U=M^*/M=1$.

Тогда успешный прогноз на очередном интервале $P=M/N$.

В ряде сейсмоактивных регионов число целевых землетрясений невелико по сравнению с числом интервалов прогноза.

Чтобы увеличить P , надо уменьшить число прогнозов N .

Поэтому мы перешли к **схеме двухэтапного прогноза**.

- **Этап 1:** Прогноз интервалов тревоги, на которых целевые землетрясения ожидаются в зоне анализа.
- **Этап 2:** Прогноз зон тревоги только на интервалах тревоги.

3 Моделирование

Опыт двухэтапного прогноза в регионах Камчатки, островной части Японии и Калифорнии показал:

- Вероятности обнаружения всех эпицентров землетрясений на интервале тревоги в зонах тревоги: $U=M^*/M=0.7-0.8$.
- Вероятности того, что на очередном интервале тревоги произойдут землетрясения со всеми эпицентрами в зоне тревоги $P=M^*/N^*=0.2-0.25$.

Возможные причины малых значений P

1. Для выбора интервалов тревоги алгоритм должен отличать процессы подготовки землетрясений с магнитудами $m \geq 6.0$ и $m < 6.0$. Разделение землетрясений на классы по порогу $m=6.0$ не связано с физикой сейсмического процесса.
2. Магнитуды землетрясений измеряются с ошибкой $0.1-0.3$.
3. Описание анализируемых процессов недостаточно полное.

Вывод: искать новые исходные данные и новые поля.

Данные

- Каталог: КФ ФИЦ ЕГС РАН с 1986 г., $m \geq 3.5$, $H \leq 160$ км.
- Сетка полей прогноза: $\Delta x \times \Delta y \times \Delta t = 0.1^\circ \times 0.075^\circ \times 30$ суток.
- Целевые землетрясения: $m \geq 6.0$ и $H \leq 60$ км.
- Обучение с 2001 г.: 134 интервала прогноза, из них с эпицентрами 12 .
- Тестирование от 13.01.2012 до 01.09.2025: 166 интервалов прогноза, из них с эпицентрами 20 .



Зона анализа и
целевые землетрясения
на интервале тестирования.

Мы рассмотрим результаты анализа прогностических возможностей полей произведения плотности эпицентров землетрясений на их среднюю магнитуду.

Поля отличаются по параметрам локально-ядерного сглаживания и по методам их дополнительной обработки.

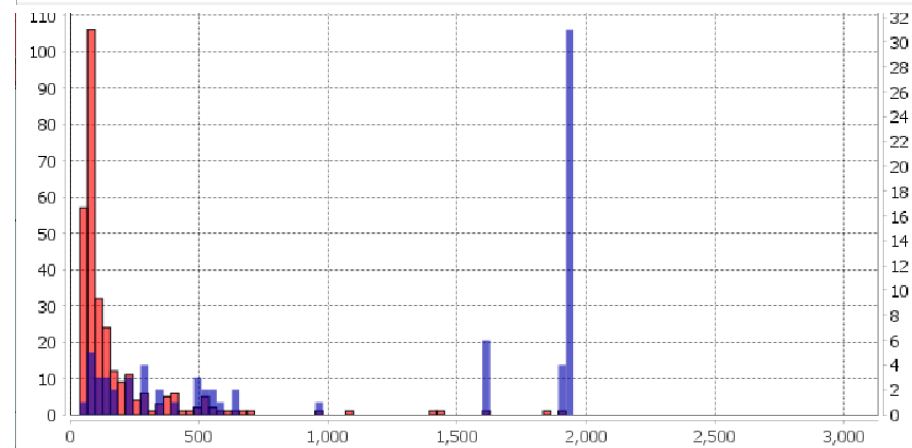
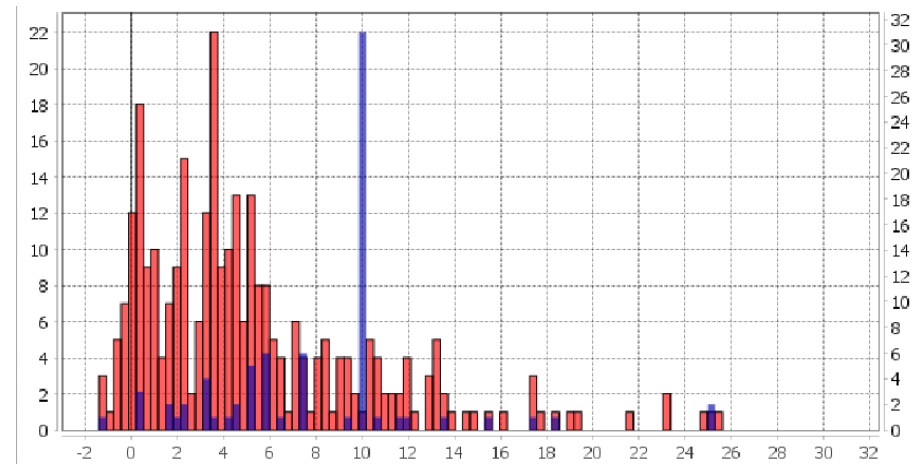
Анализировались также **4d** поля произведений плотности гипоцентров землетрясений на их среднюю магнитуду. Эти поля позволяют в некоторой степени отфильтровать по глубине шумовую компоненту сейсмичности, относящуюся к землетрясениям вне очаговой области.

Этап 1: поля прогноза интервалов тревоги

Значения полей на всех интервалах прогноза. Значения полей на наиболее информативных предвестниках интервалов тревоги.

➤ Поле t-статистики Стьюдента от адаптивно сглаженного (метод AWS) поля максимальных по глубине значений произведений плотности гипоцентров землетрясений на их среднюю магнитуду, $R=130$ км, $H=30$ км, $T=365$ суток.

➤ Поле произведений плотности эпицентров землетрясений на их среднюю магнитуду, $R=60$ км, $T=100$ суток.

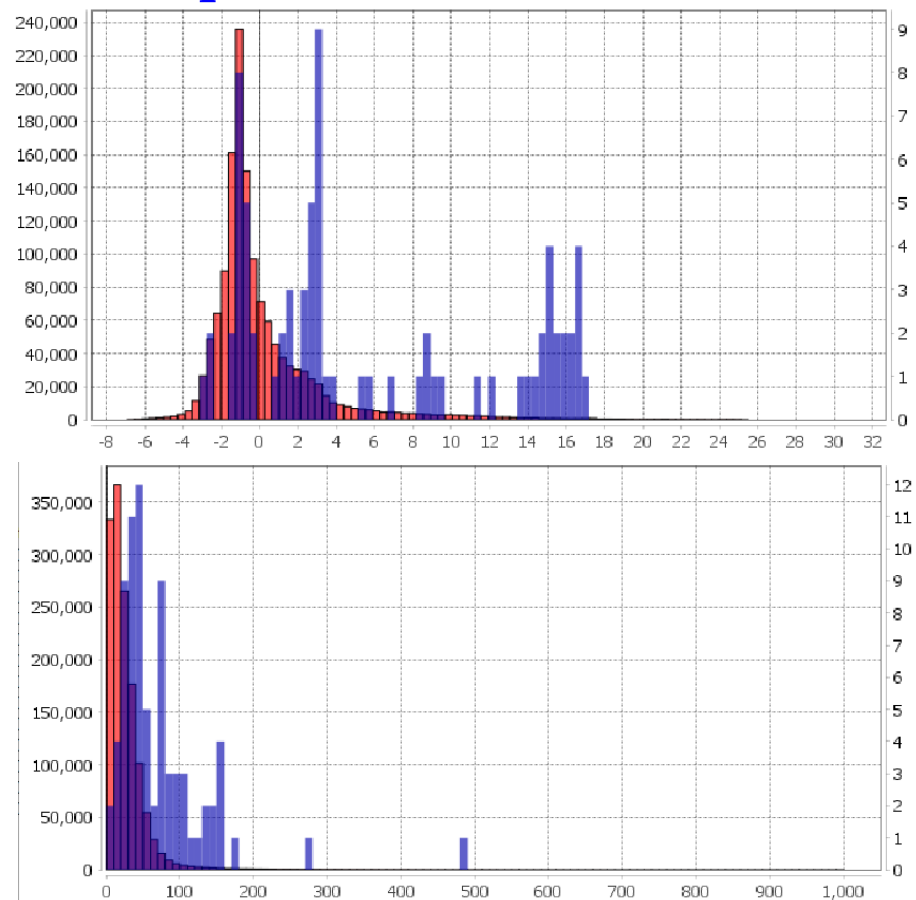


Этап 2: поля прогноза зон тревоги на интервалах тревоги

Значения полей на всех узлах сетки зоны анализа. Значения полей на узлах наиболее информативных предвестников землетрясений.

➤ Поле t-статистики Стьюдента от адаптивно сглаженного (метод AWS) поля максимальных по глубине значений произведений плотности гипоцентров землетрясений на их среднюю магнитуду, $R=130$ км, $H=30$ км, $T=365$ суток.

➤ Поле произведений плотности эпицентров землетрясений на их среднюю магнитуду, $R=60$ км, $T=100$ суток.



Прогноз по статистике от 13.01.2012 до 01.09.2025

Всего: **166** интервалов прогноза, из них **20** с эпицентрами. По всей статистике выделено: **56** интервалов тревоги, из них **16** с эпицентрами в зоне анализа и **14** со всеми эпицентрами в зонах тревоги. При этом доля средней площади зон тревоги составляет **40%**. Вероятность обнаружения:

$$U_{\text{интерв. тревоги}} = 16/20 = 0.8,$$

$$U_{\text{зон тревоги}} = 14/20 = 0.7.$$

Прогноз на очередной интервал $t_0 = 01.09.2025$:

По прогнозному значению объёма тревоги выделено: **42** интервала тревоги, из них **12** с эпицентрами в зоне анализа и **11** со всеми эпицентрами в зонах тревоги. При этом доля средней площади зон тревоги от площади зоны анализа составляет **40%**. Вероятности успешности прогноза:

$$P_{\text{инт. тревоги}}(t_0) = 12/42 = 0.29,$$

$$P_{\text{зон тревоги}}(t_0) = 11/42 = 0.26.$$

Камчатка

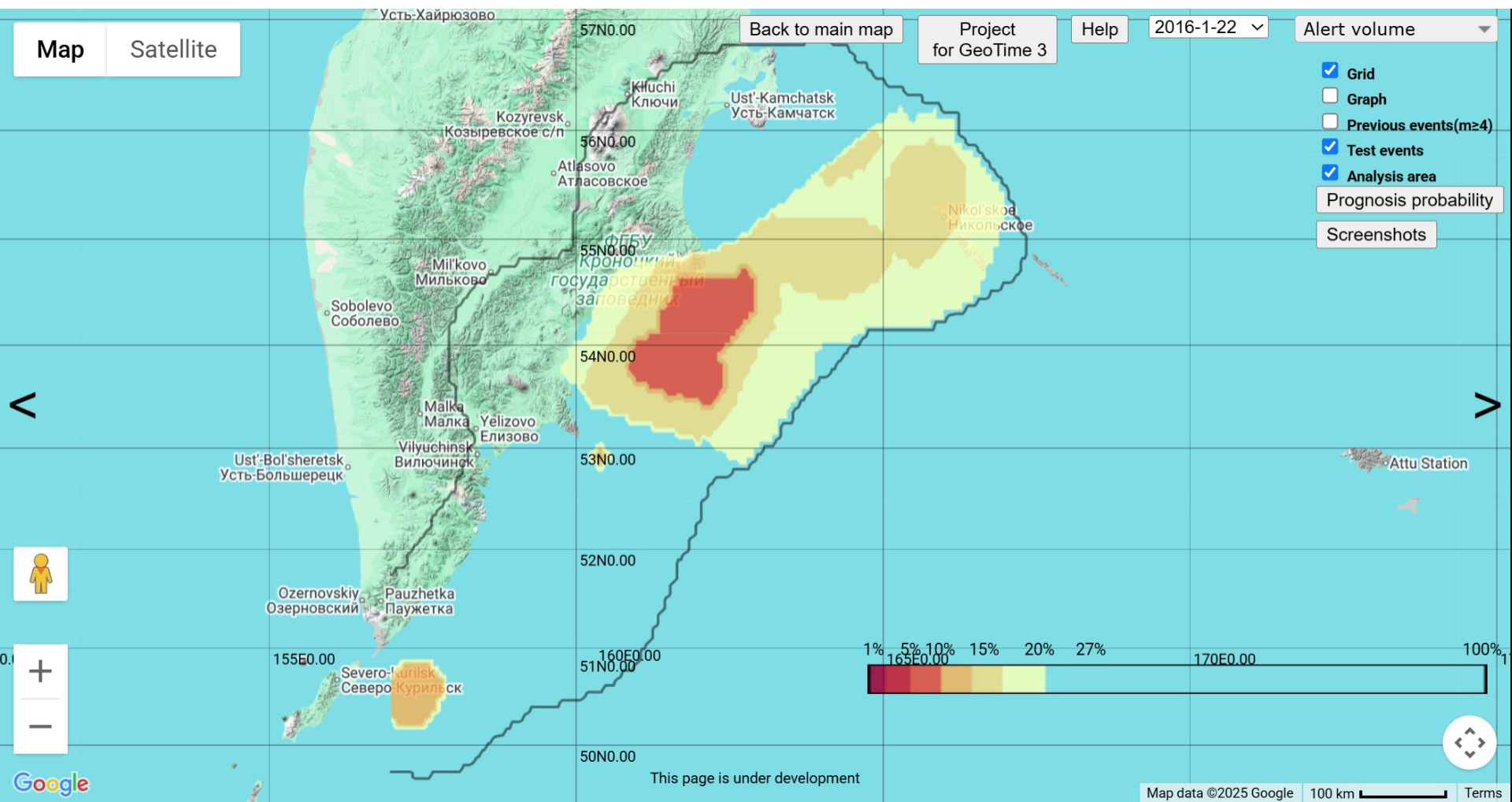
Обучение от **01.01.2001.**

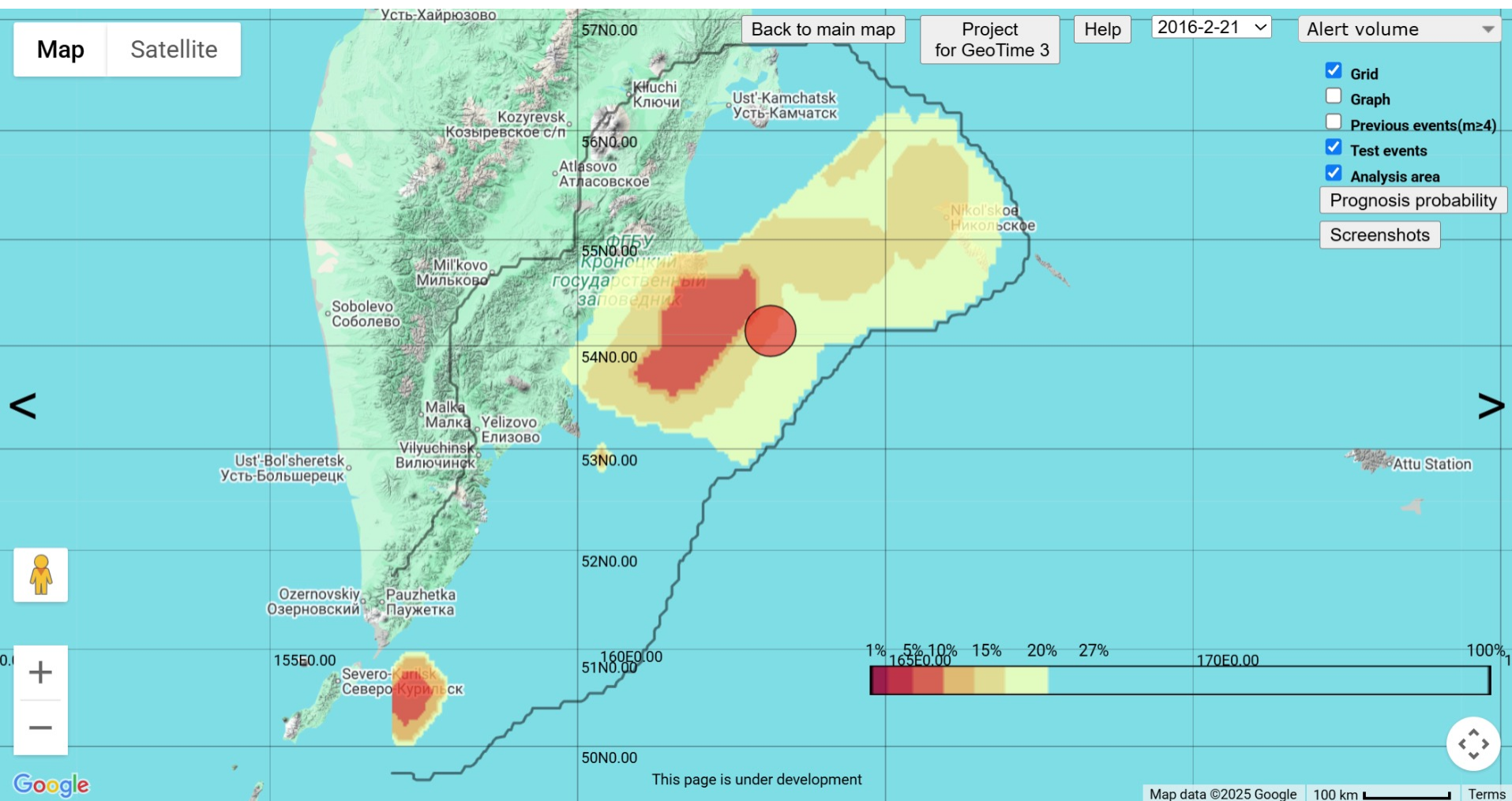
Тестирование **13.01.2012.**

Volume of alarm (expected)	Volume of alarm (observed)	Number of predicted events	Probability of detection U
1.0%	2,10%	7	8,54%
5.0%	8,23%	34	41,46%
10.0%	17,27%	40	48,78%
15.0%	23,91%	51	62,20%
20.0%	31,48%	58	70,73%
27.0%	39,99%	62	75,61%



Прогноз 22.01.2016-01.10.2025. Интервалы в 30 суток.





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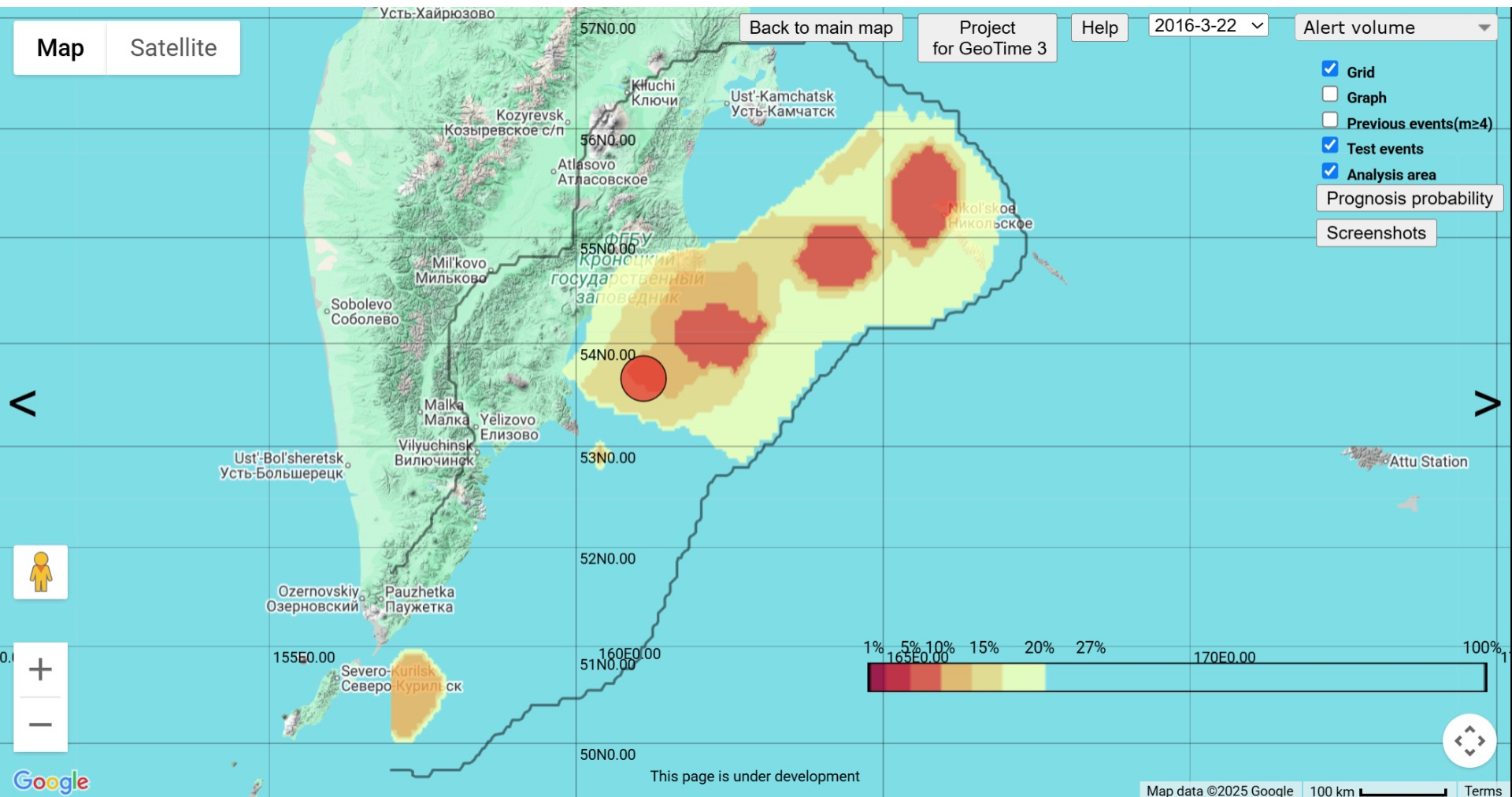
2016-3-22 ▾

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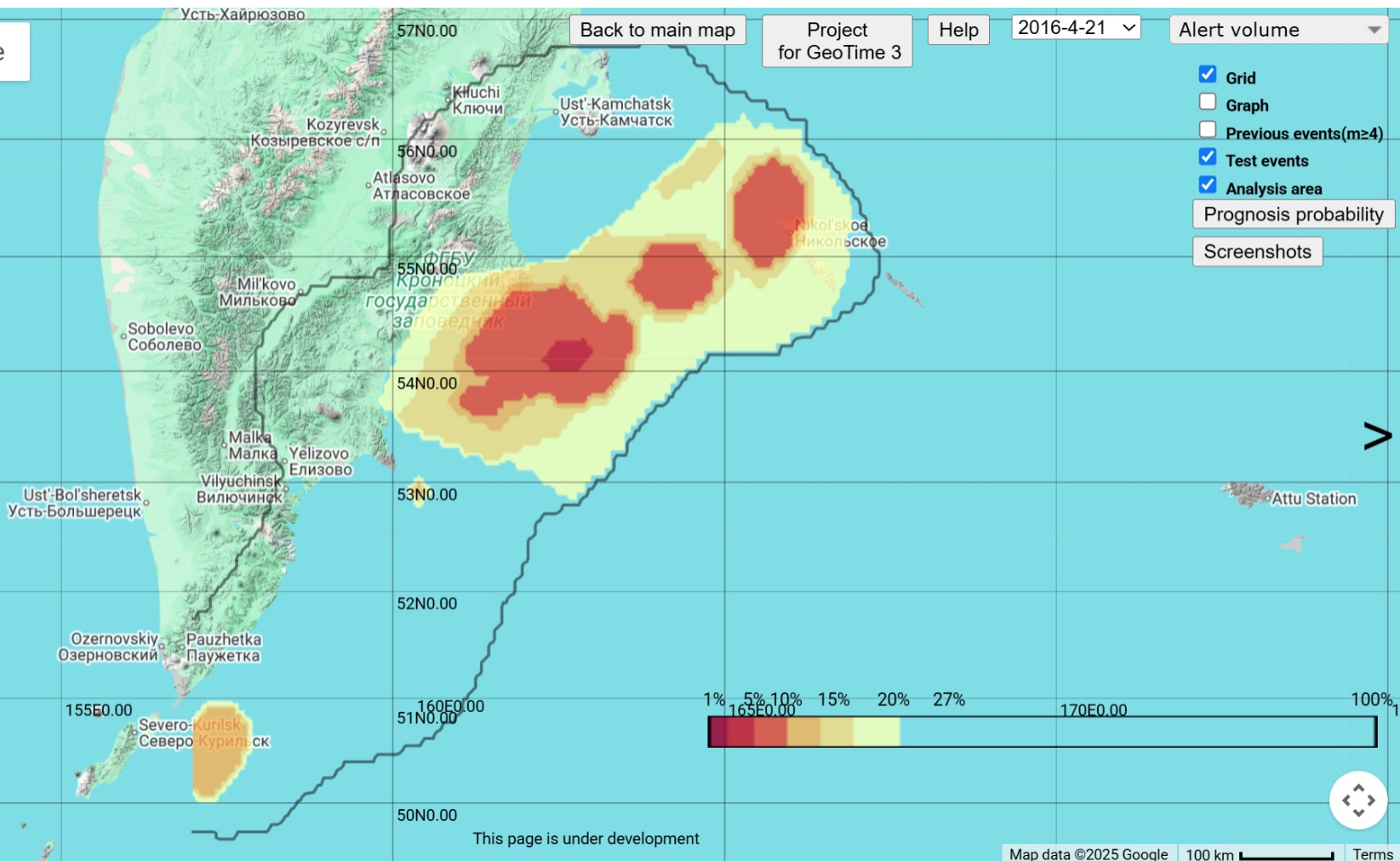
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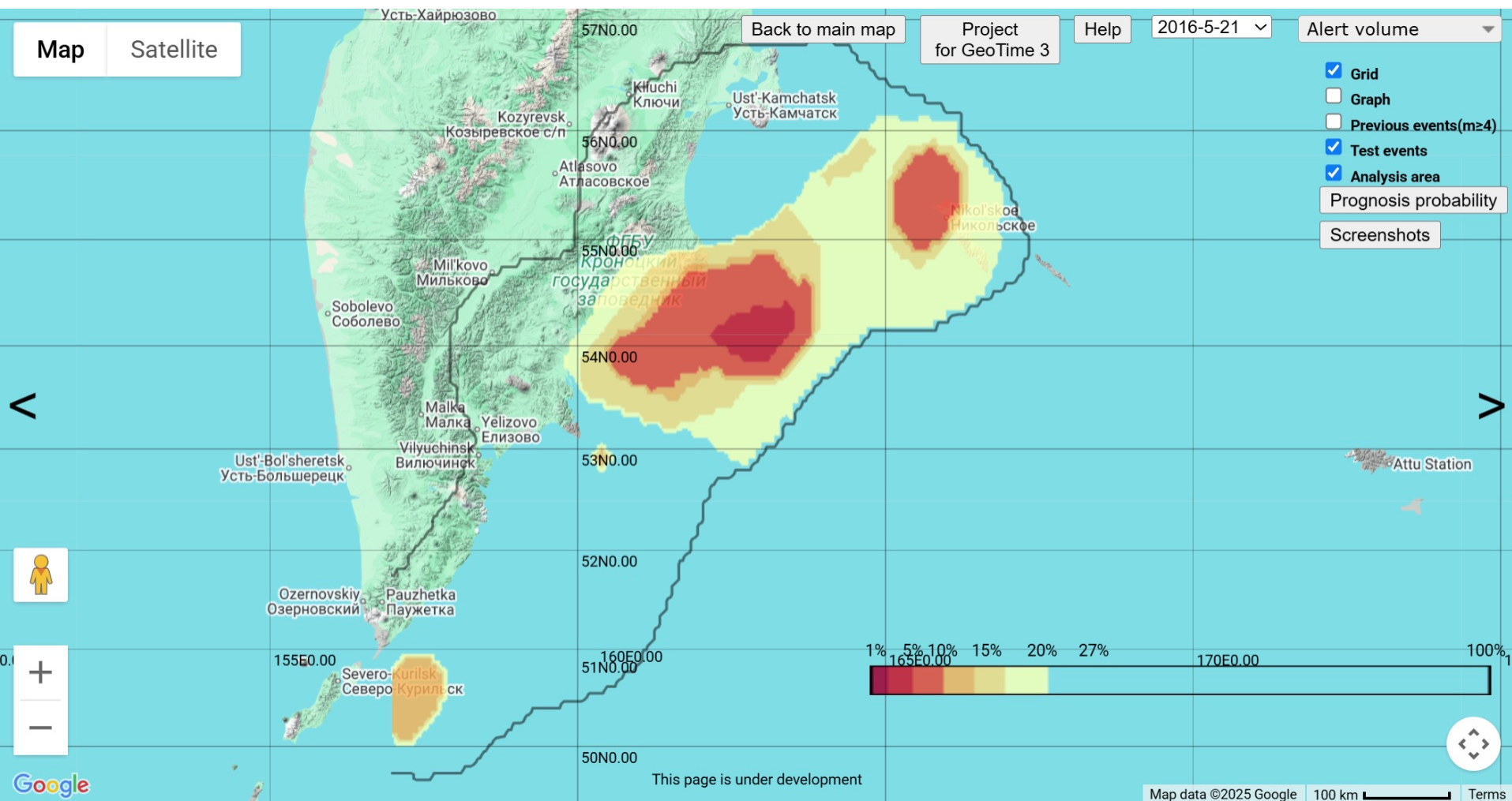
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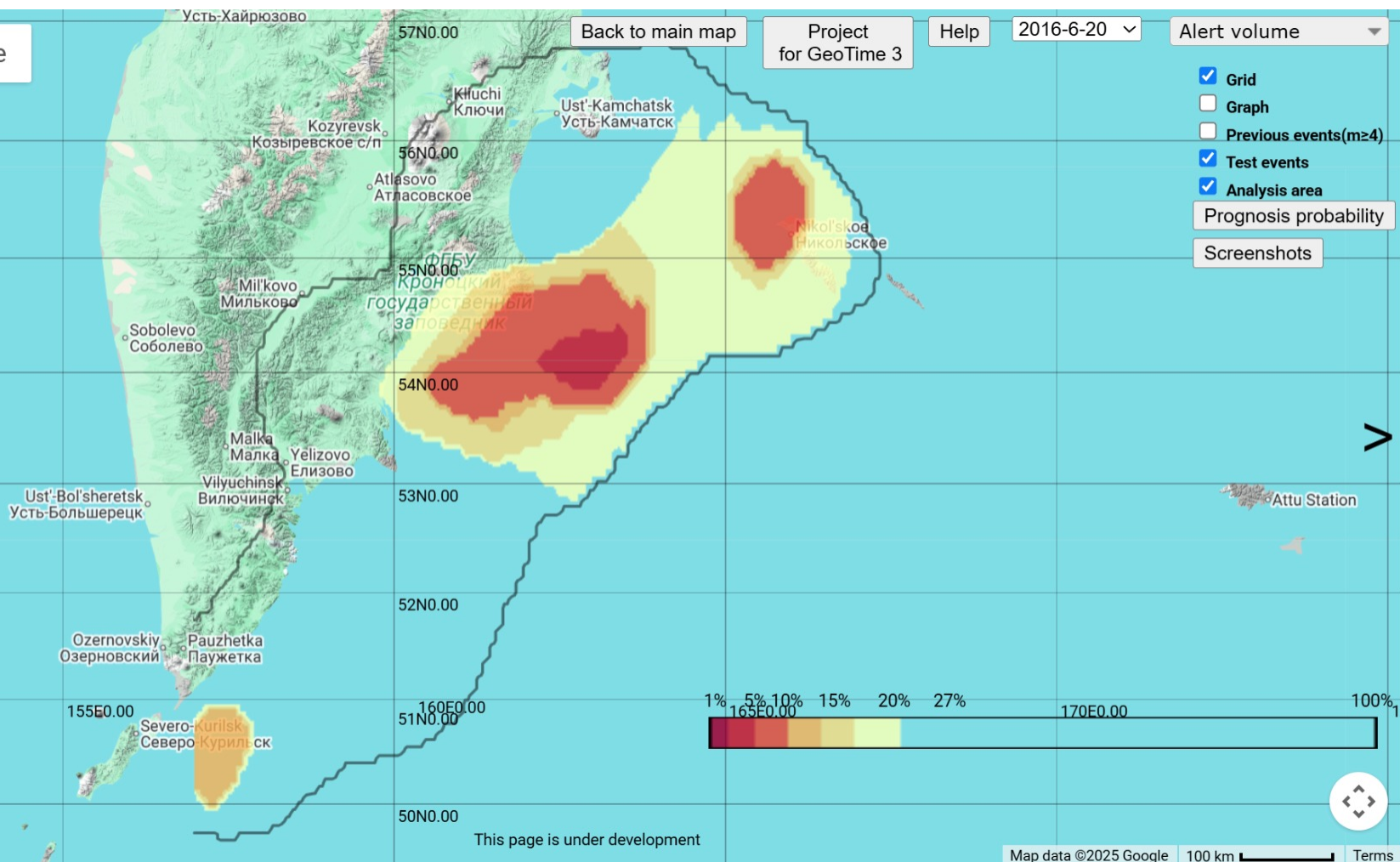
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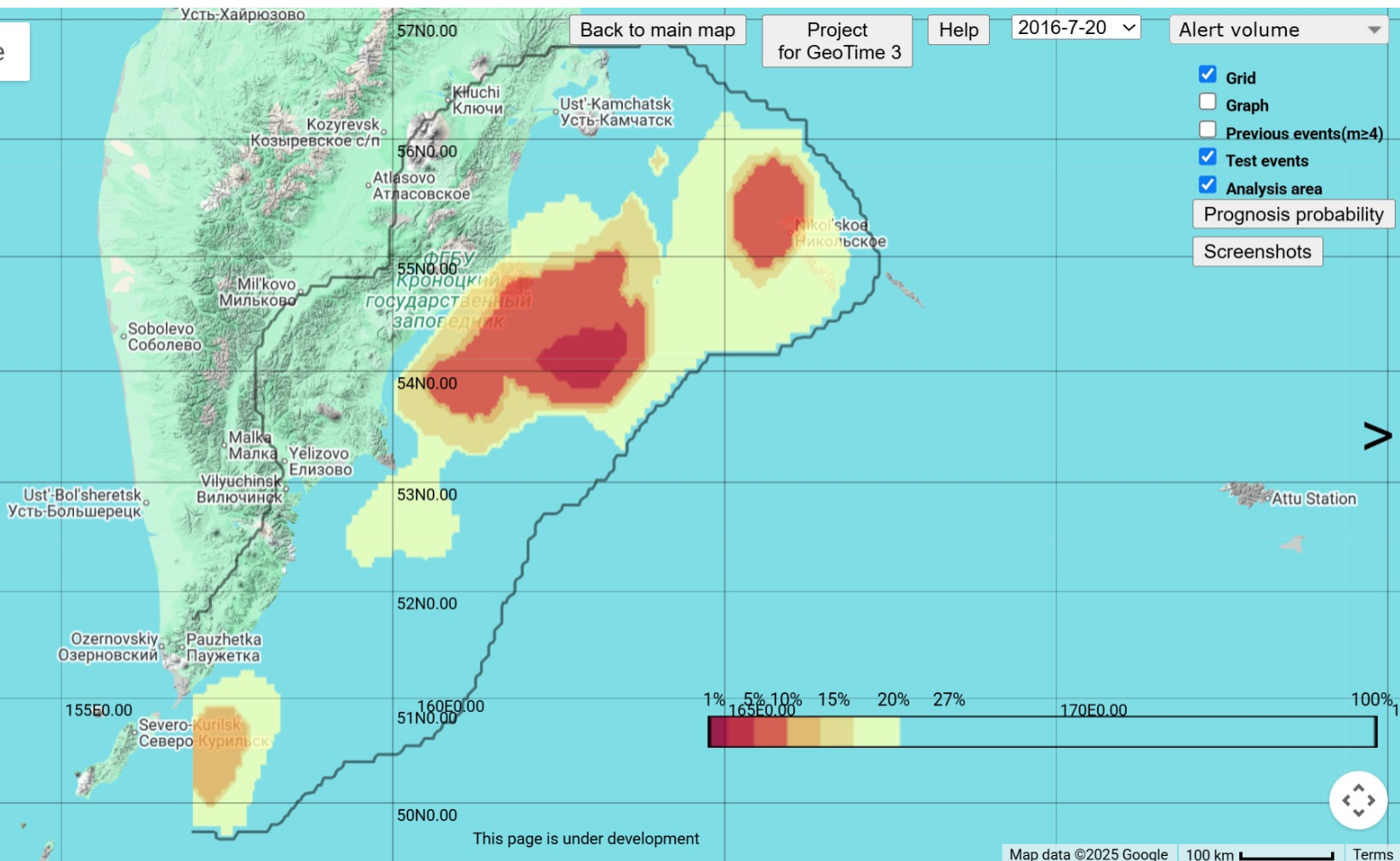
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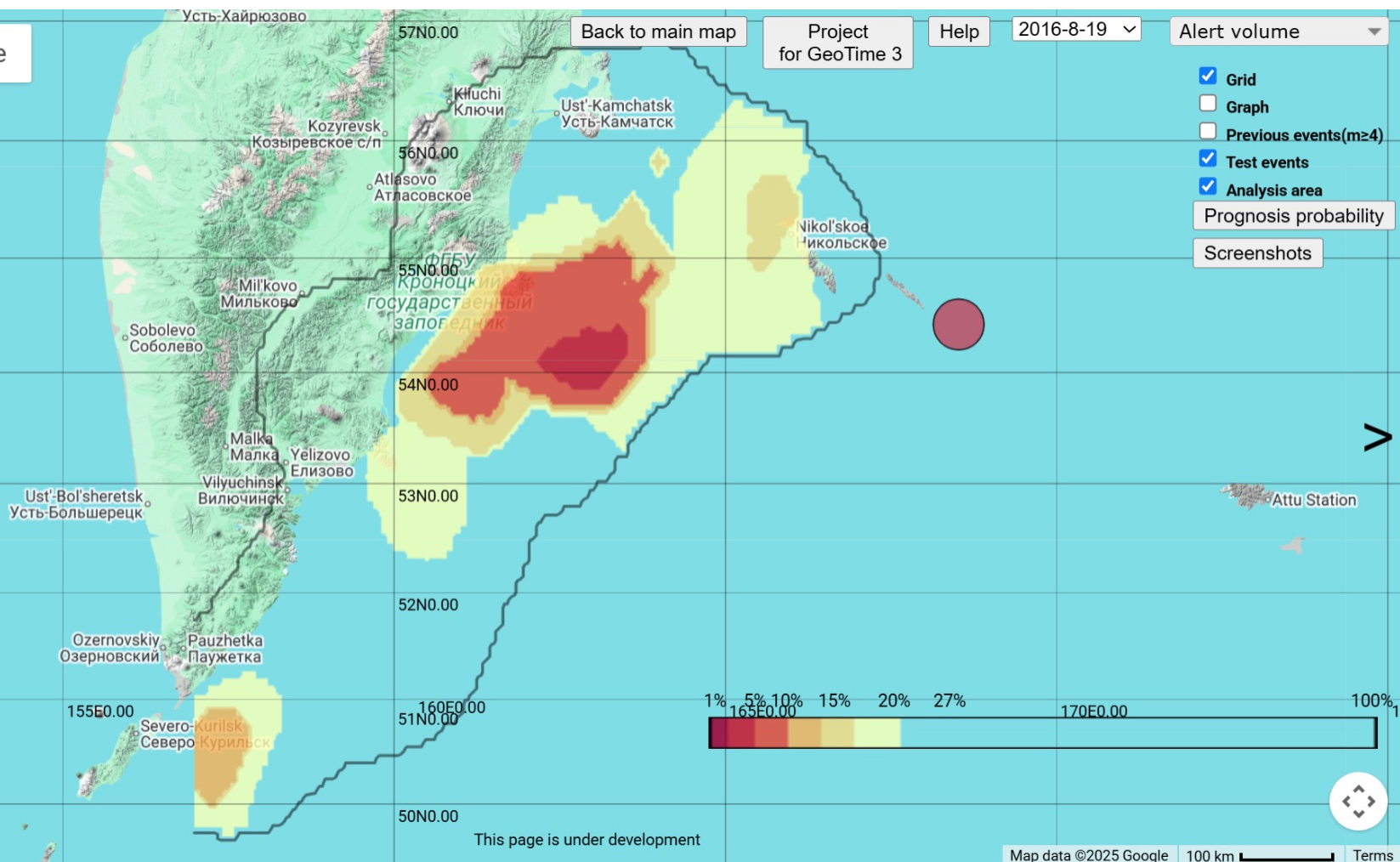
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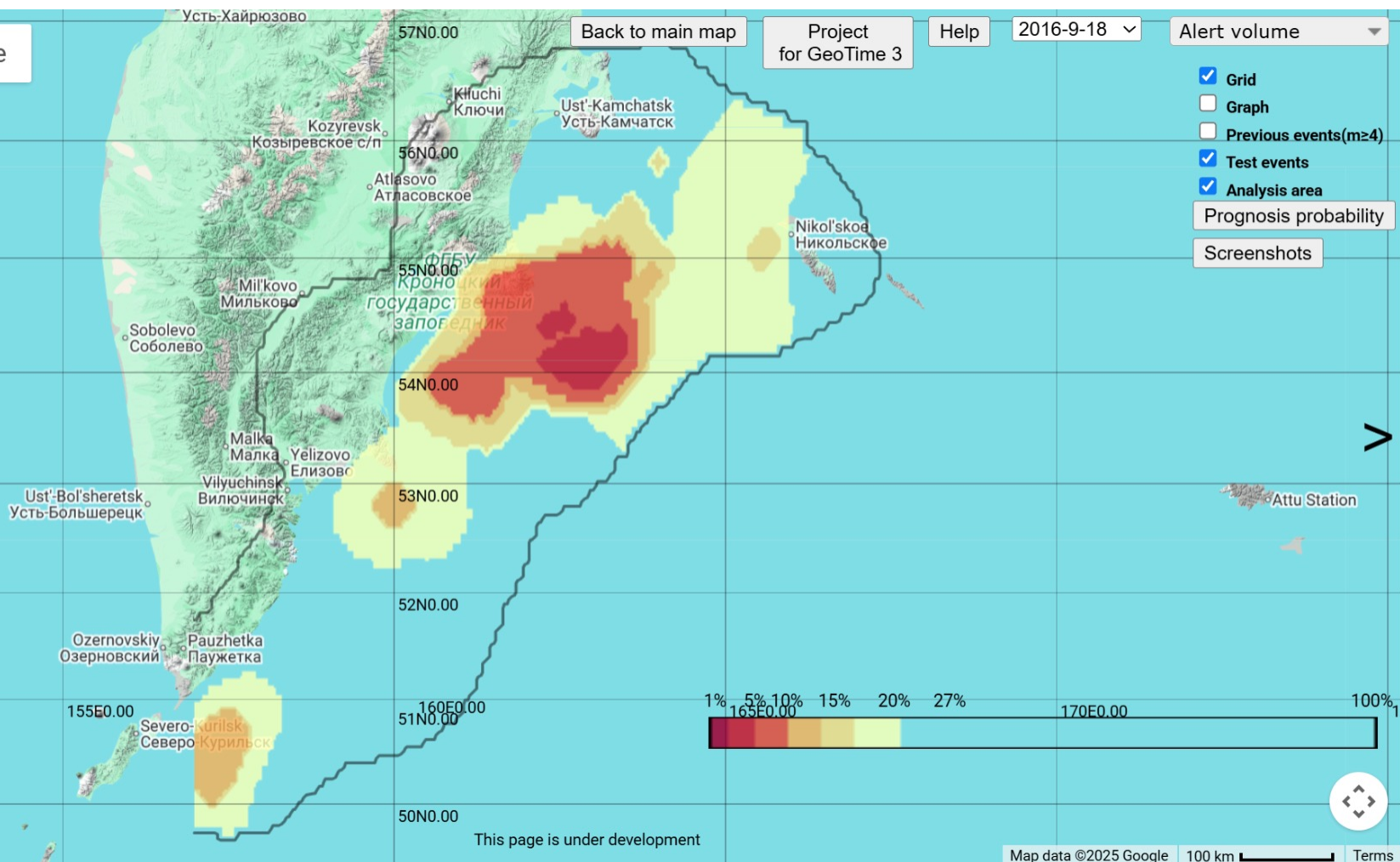
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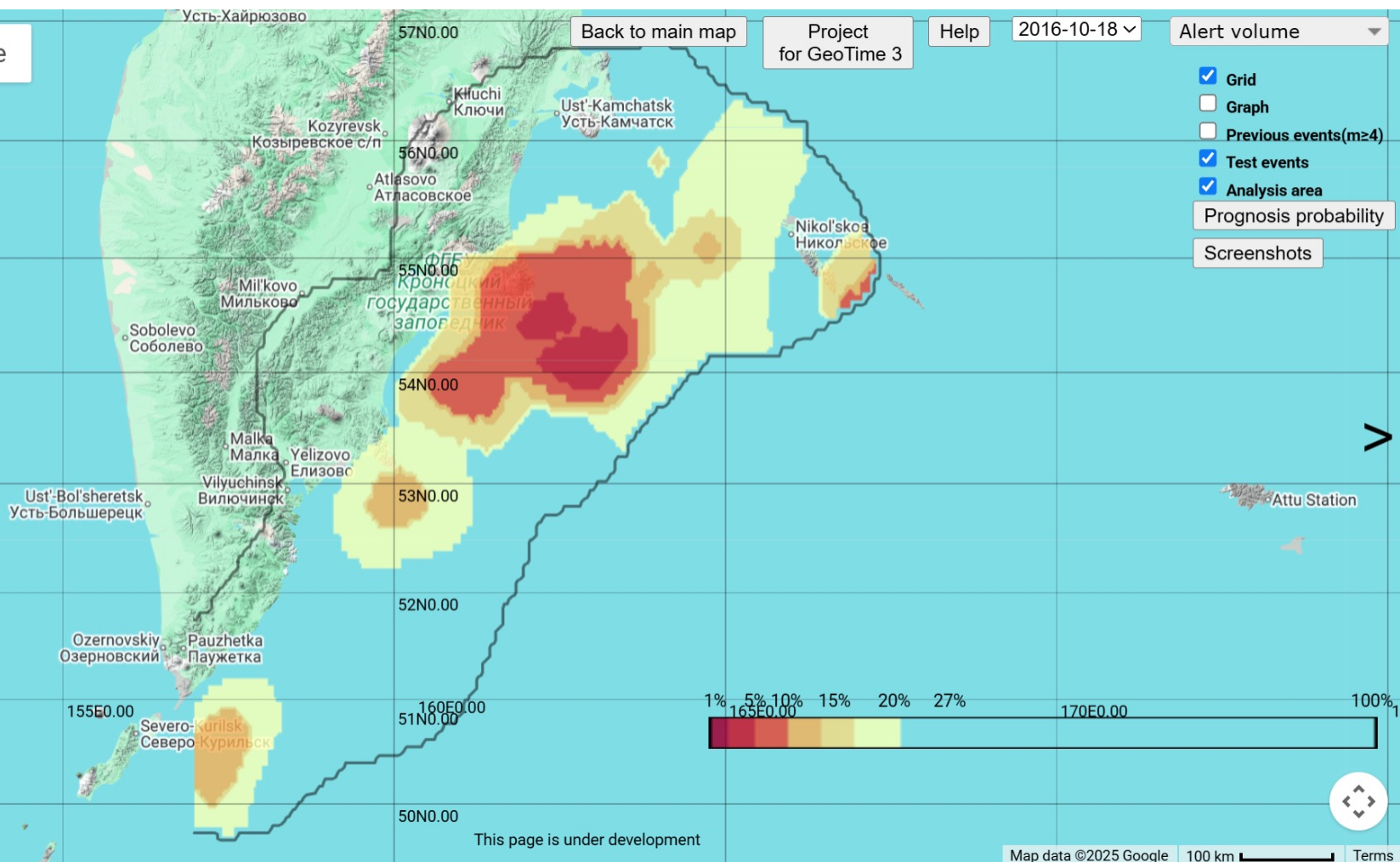
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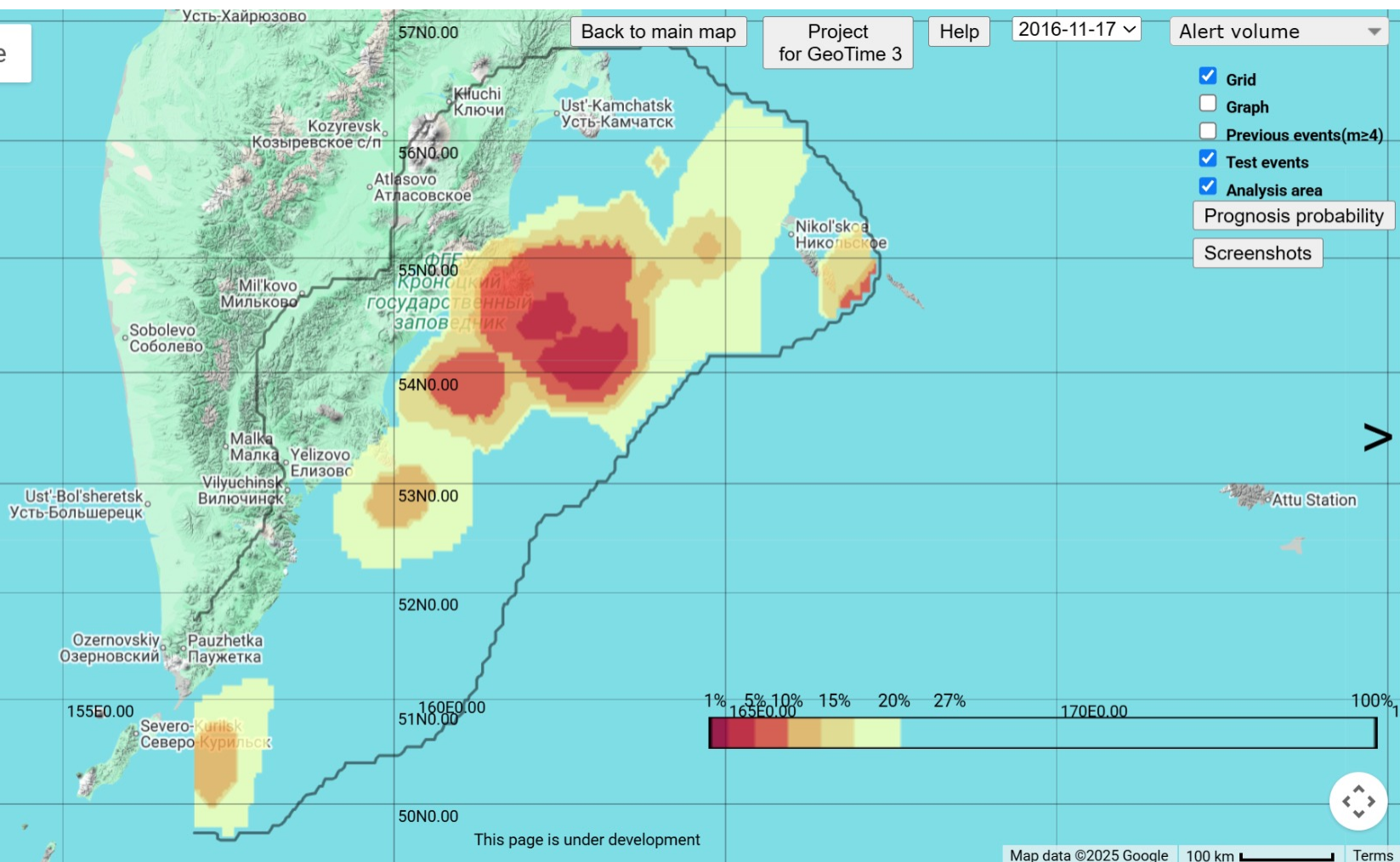
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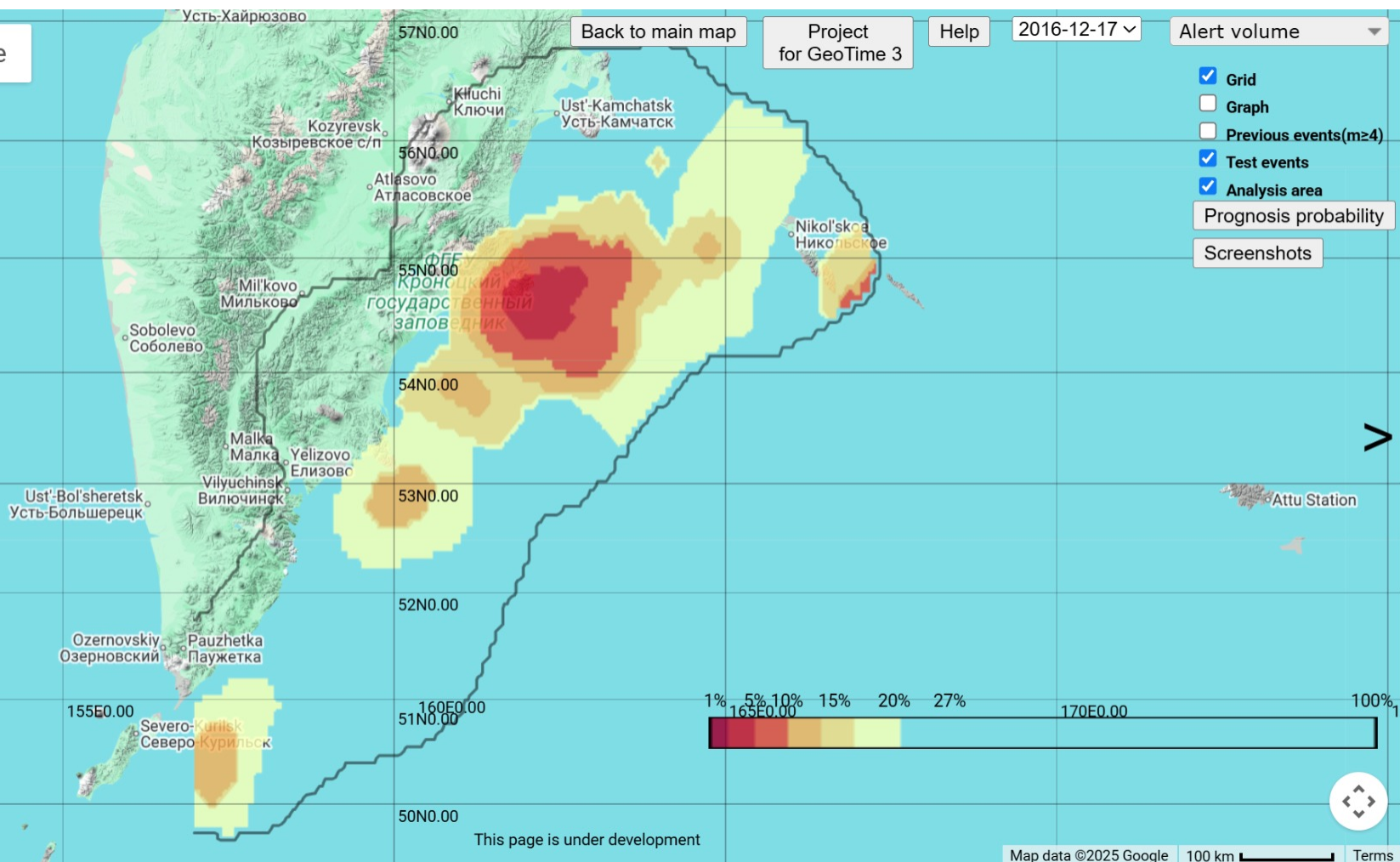
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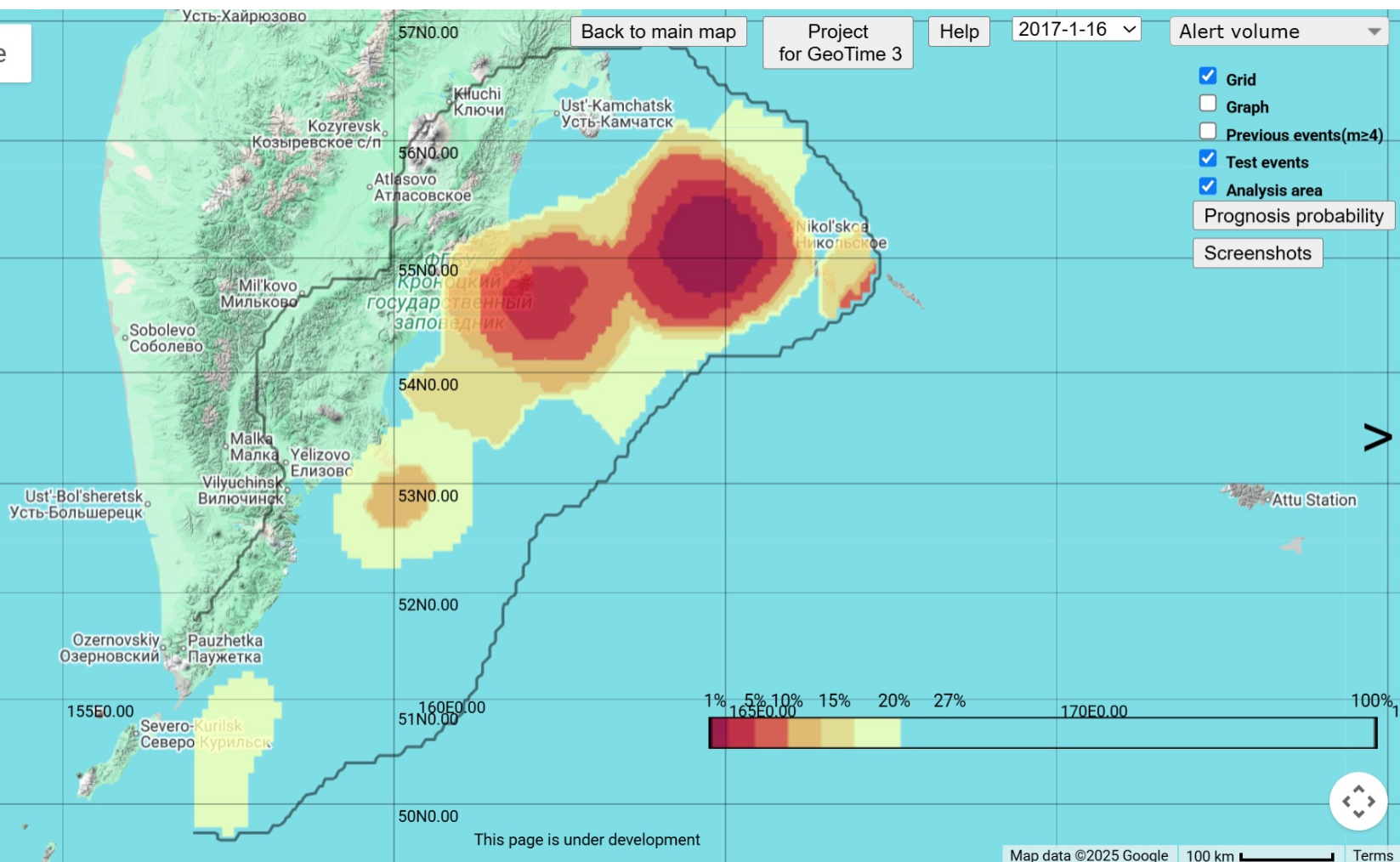
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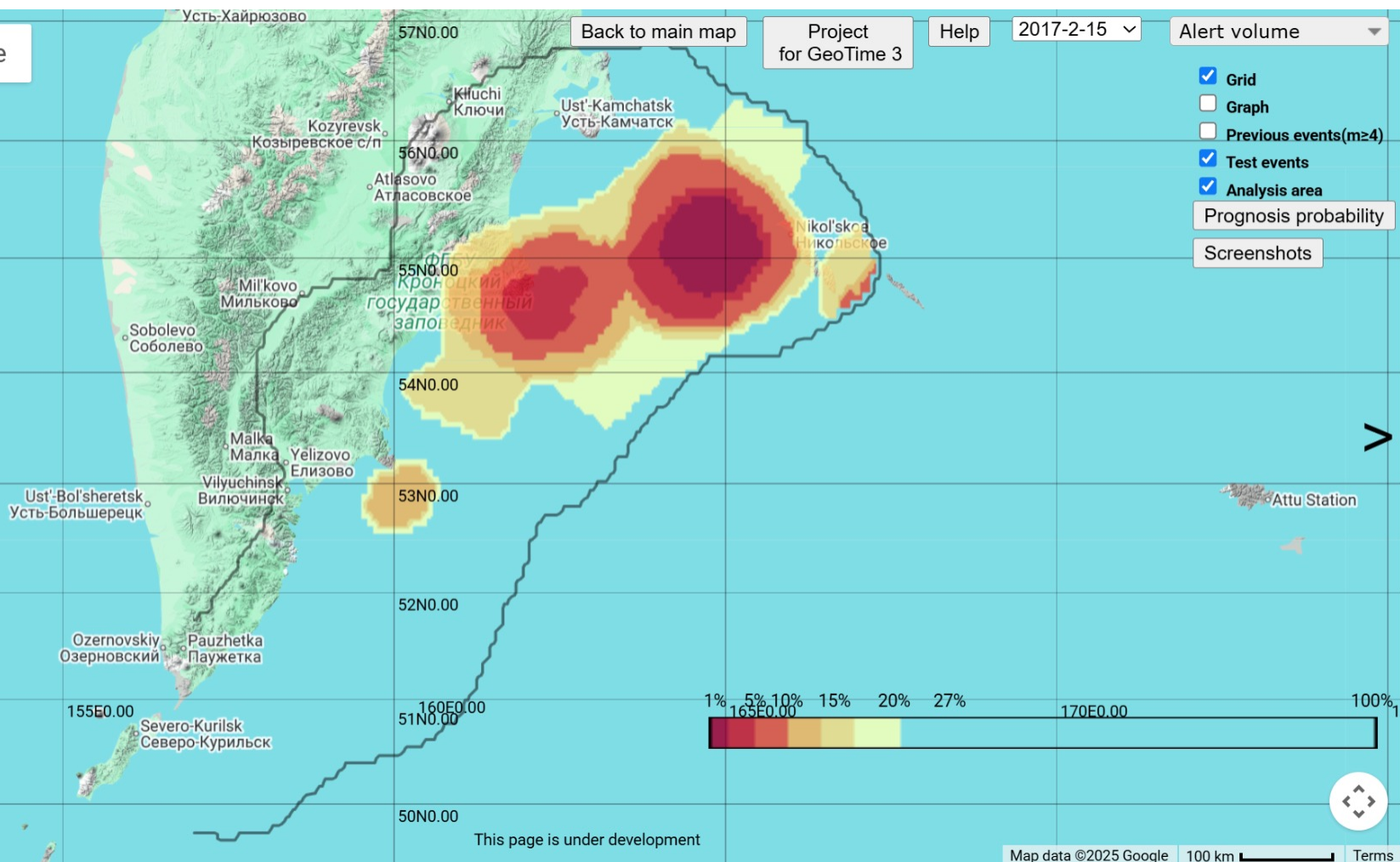
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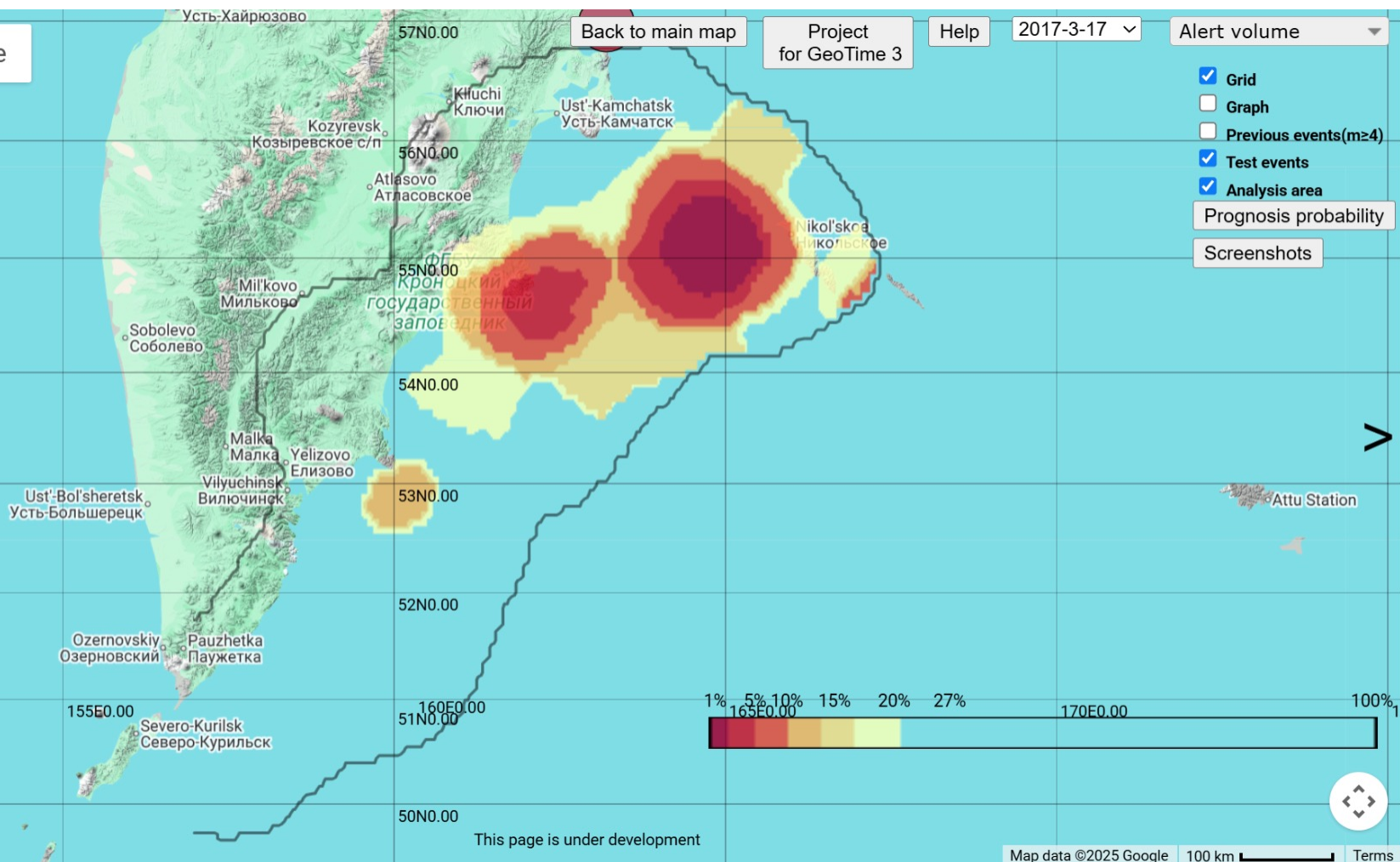
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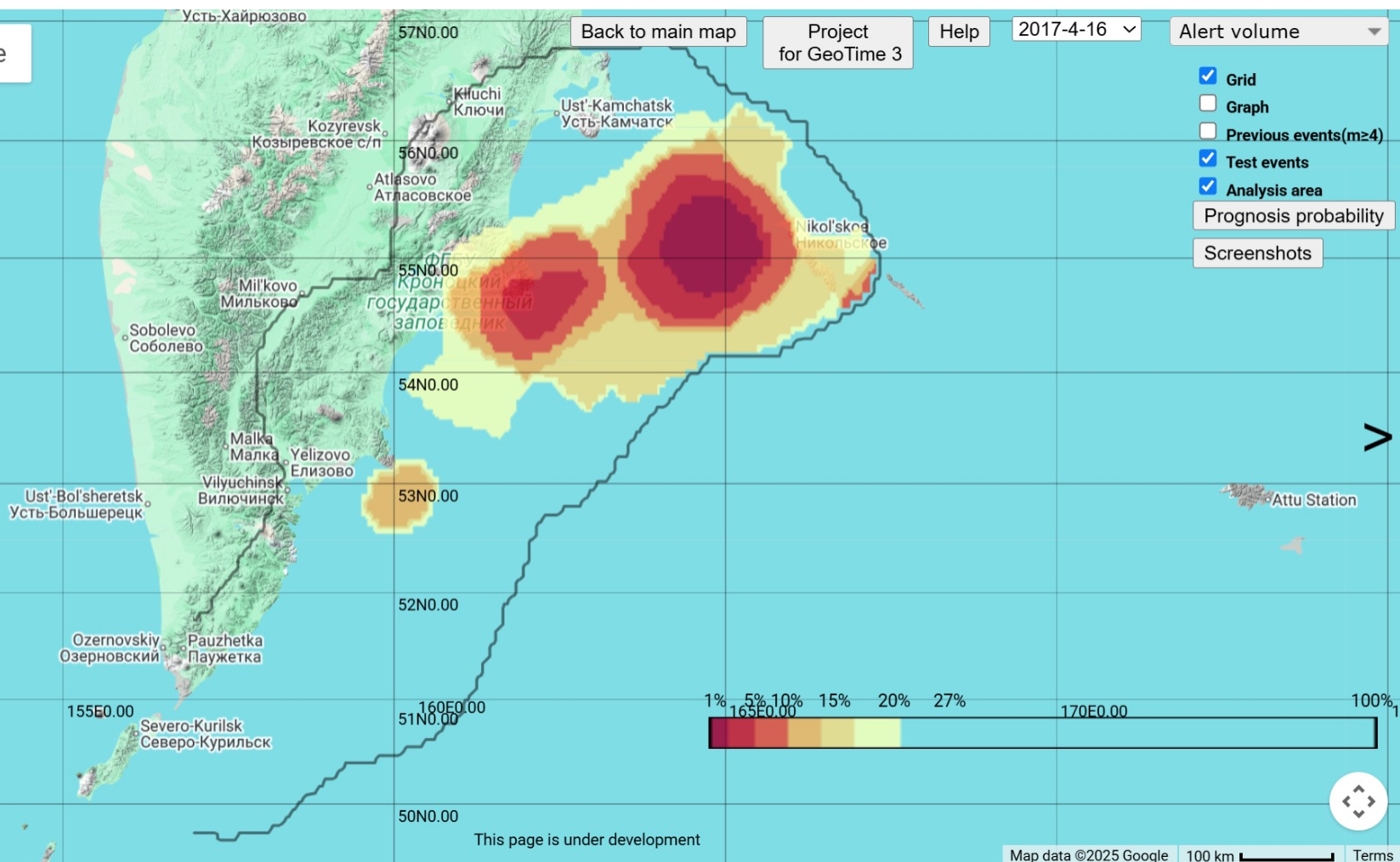
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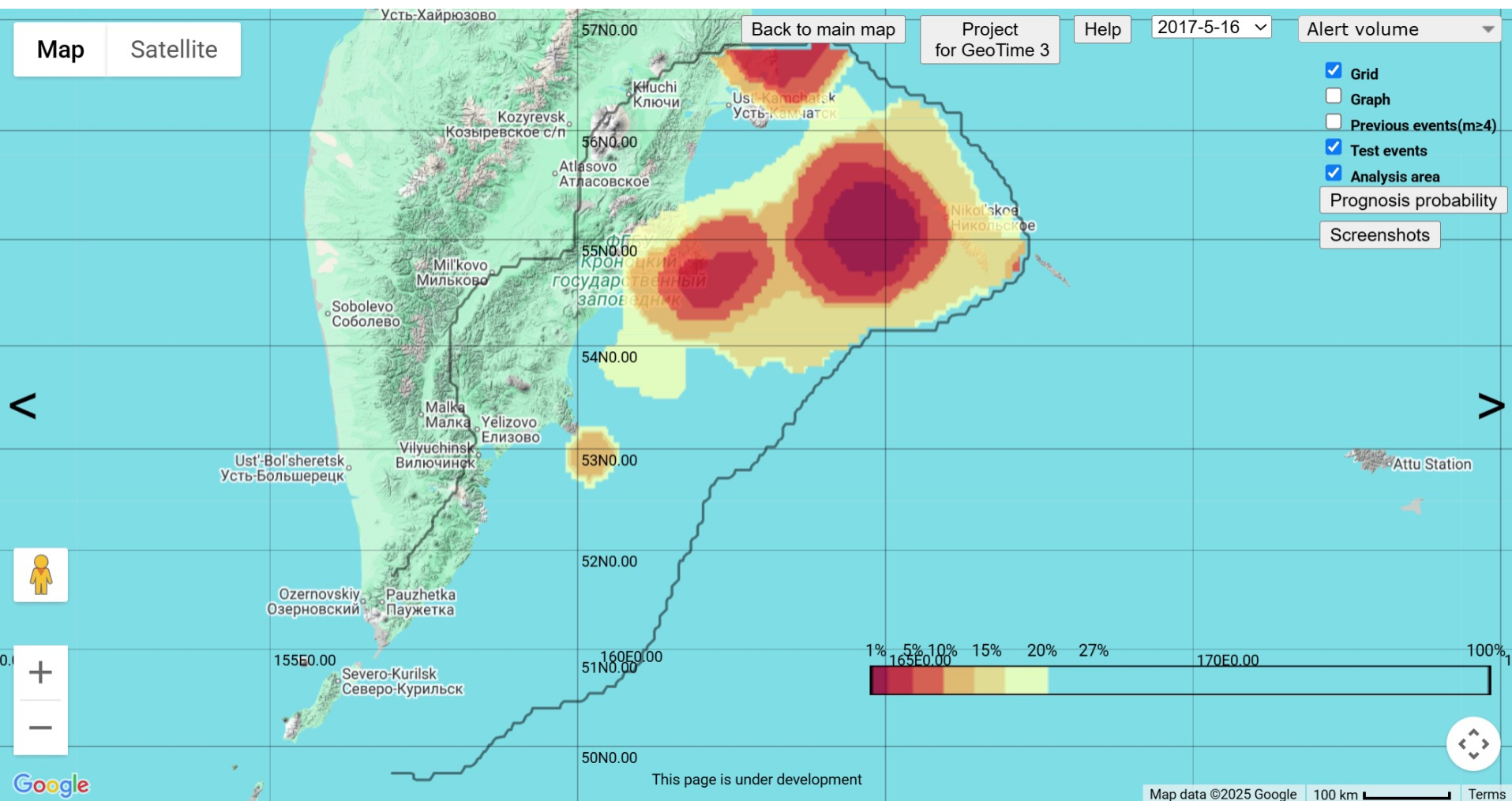
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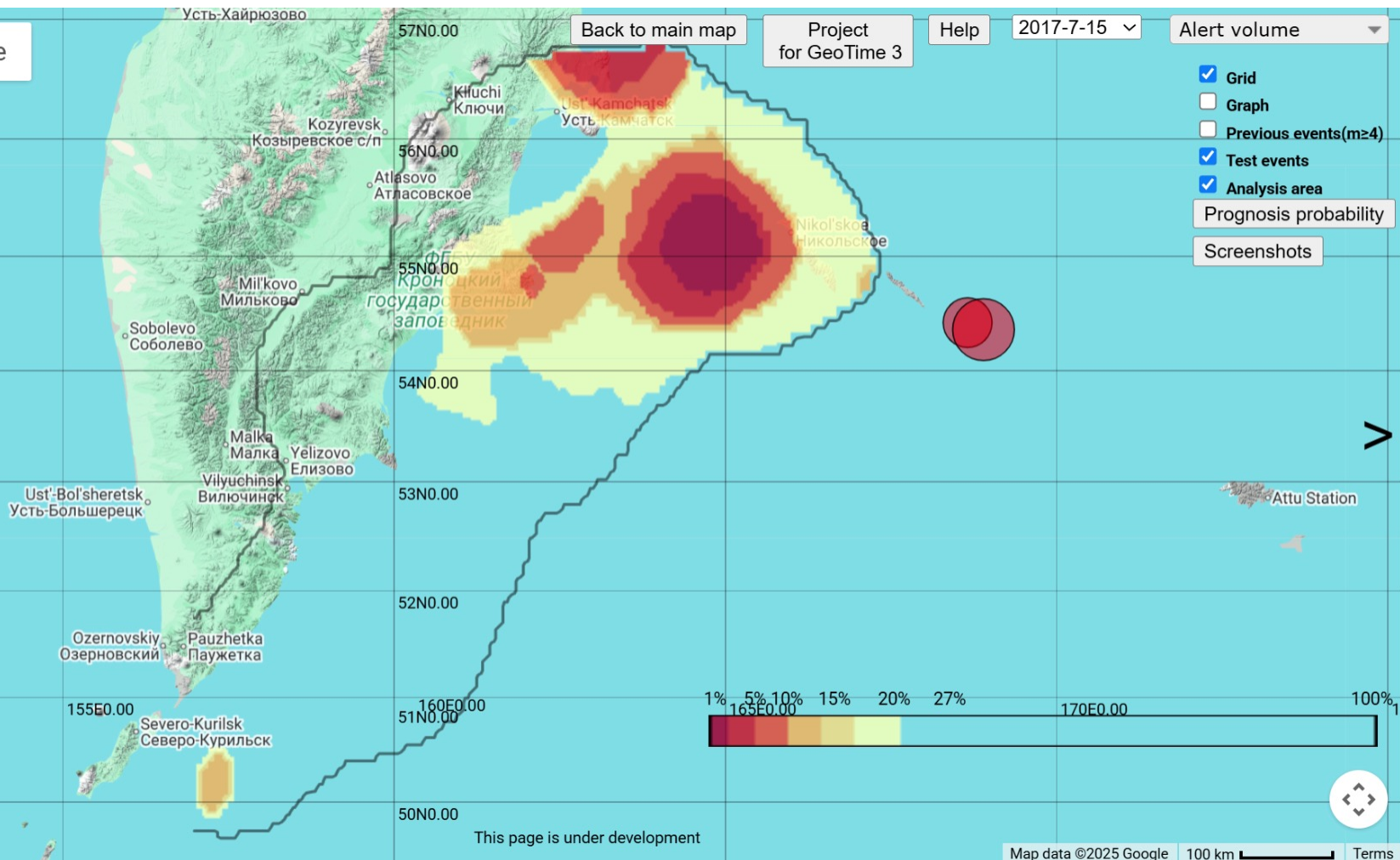
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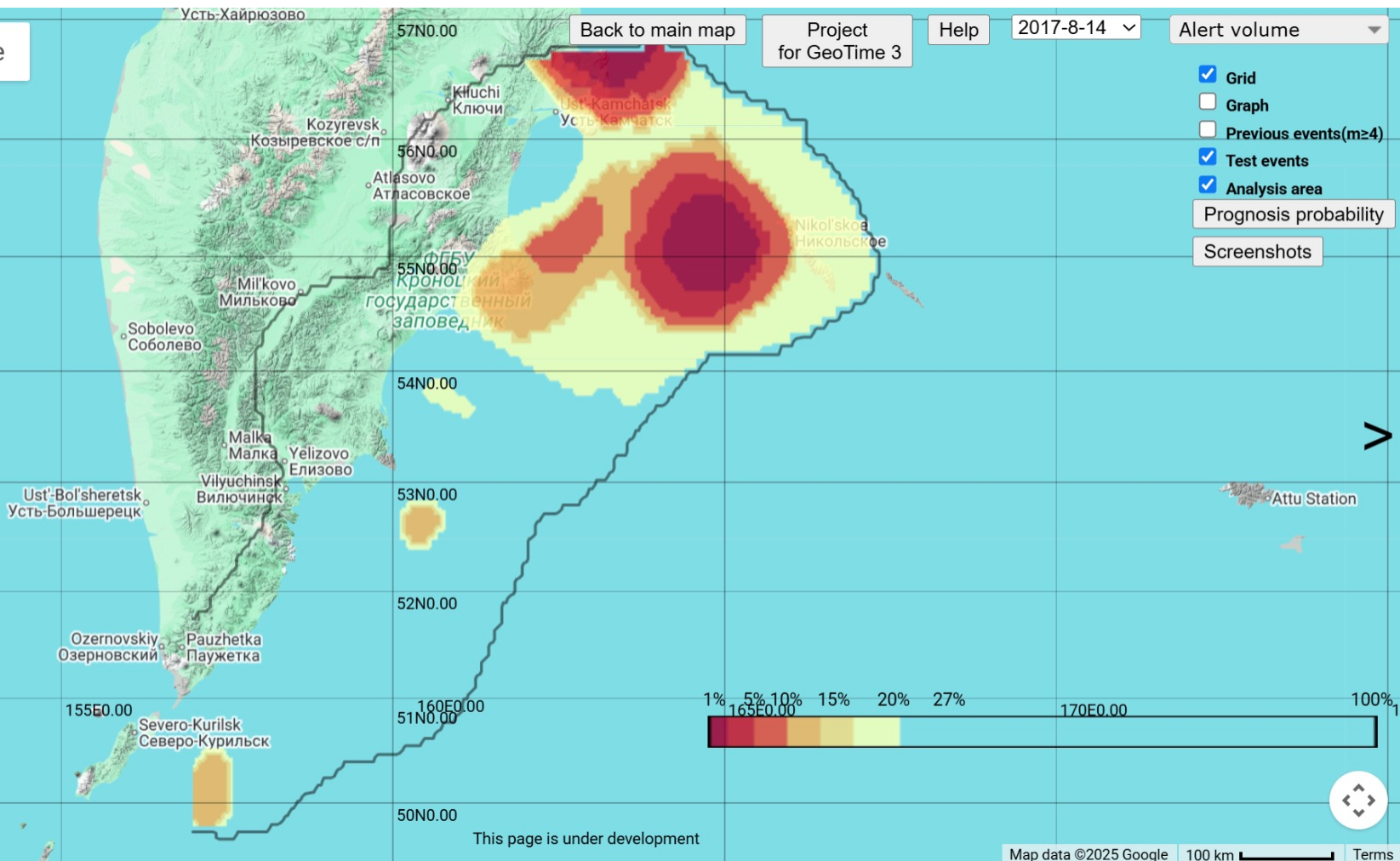
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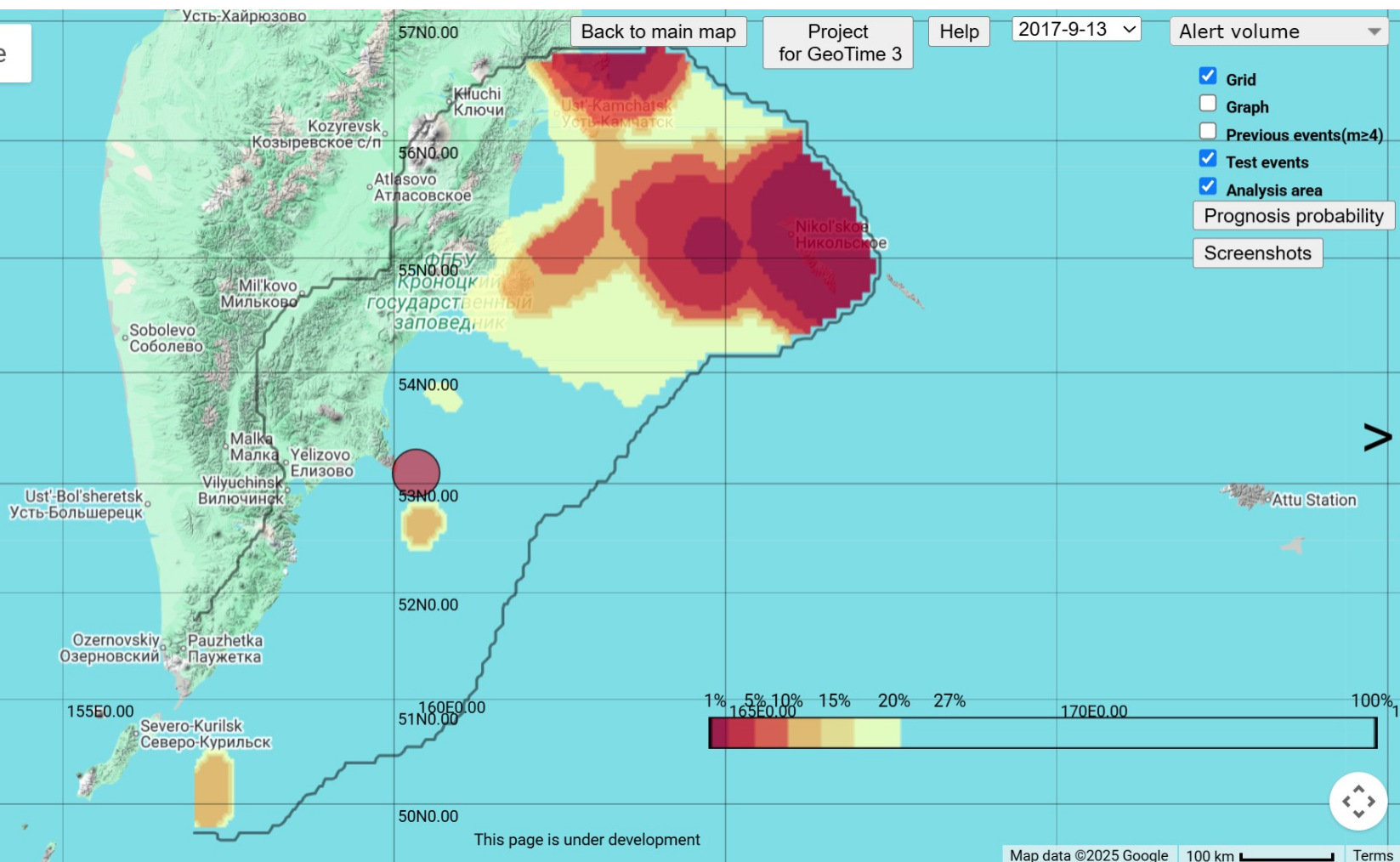
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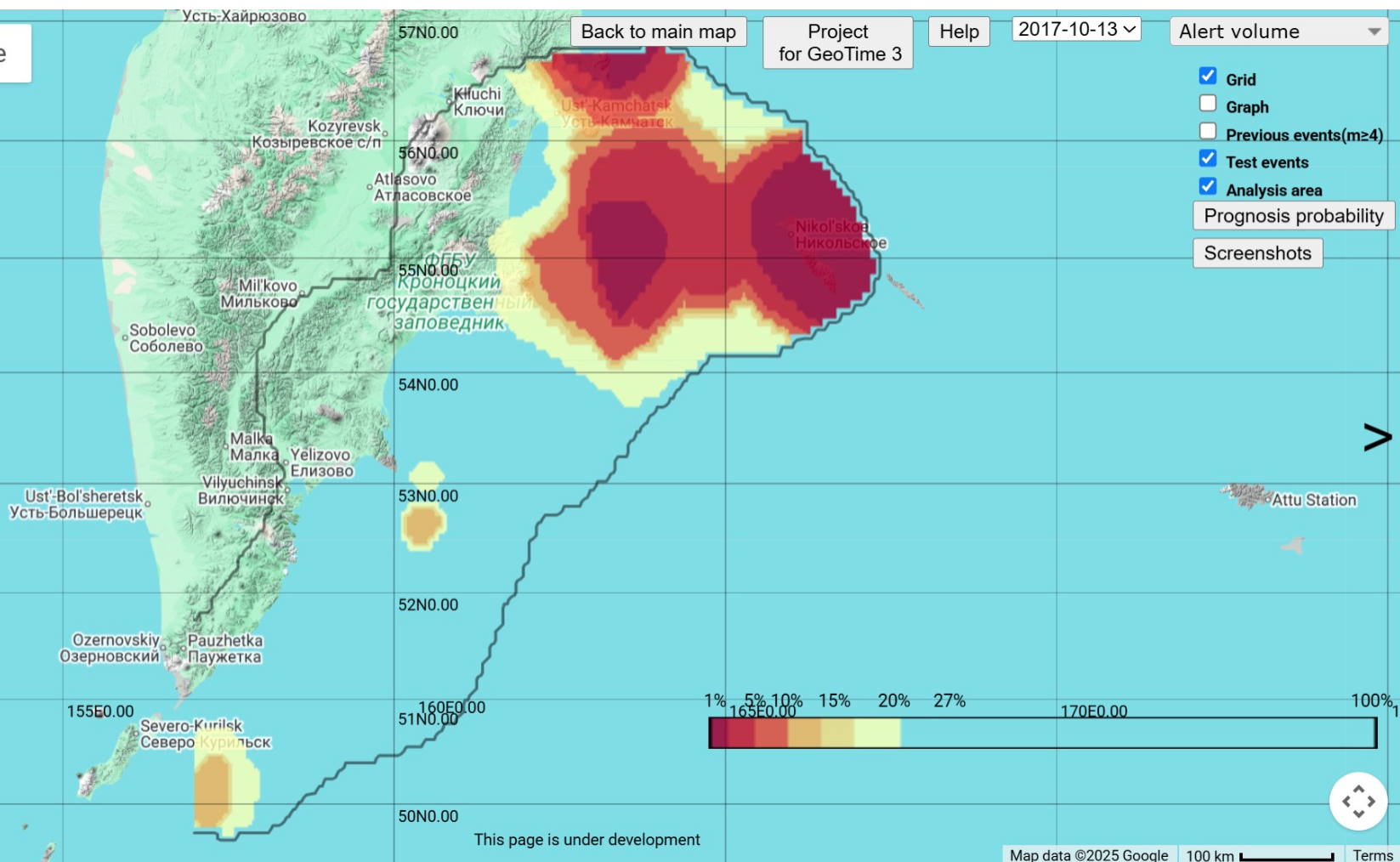
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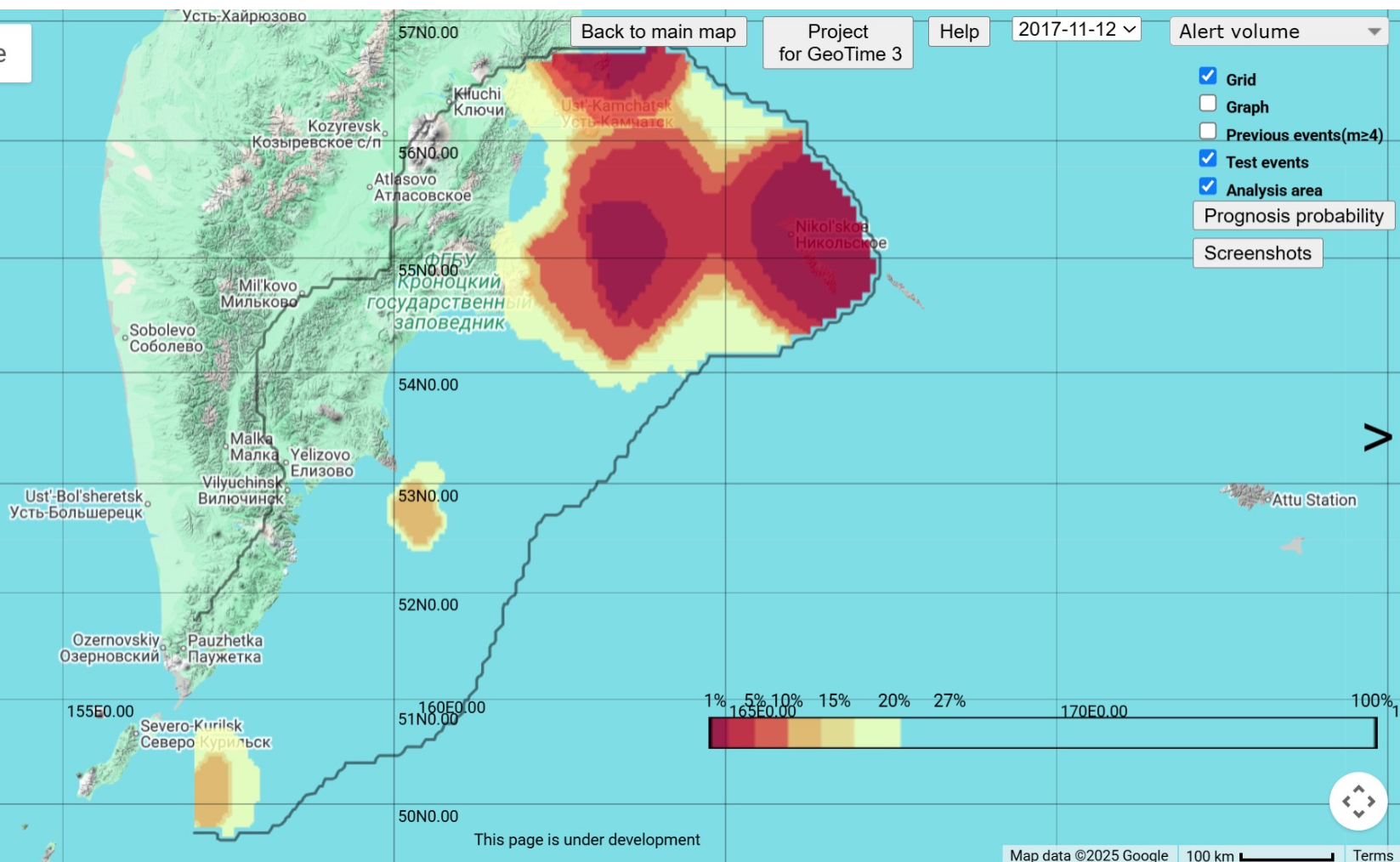
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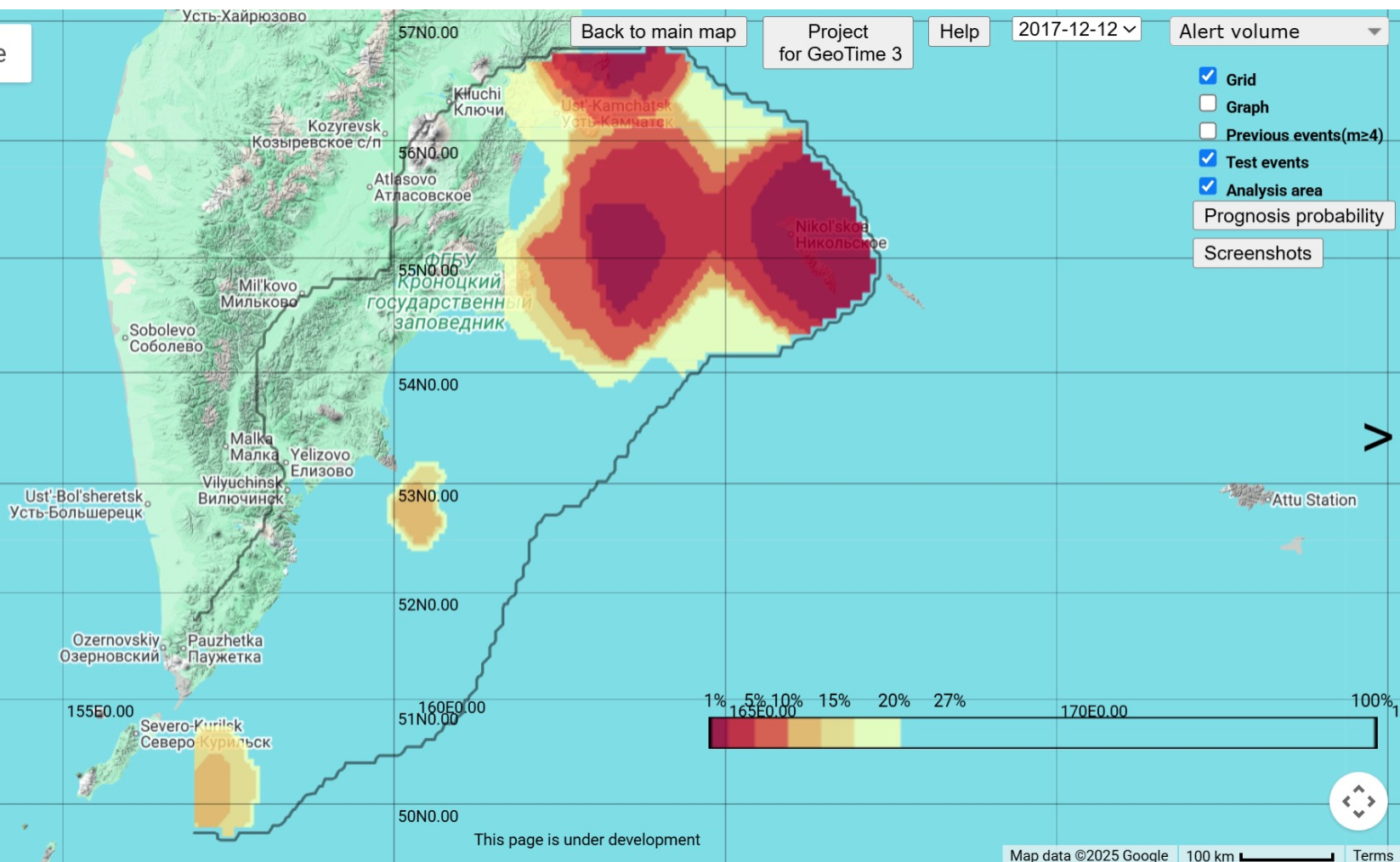
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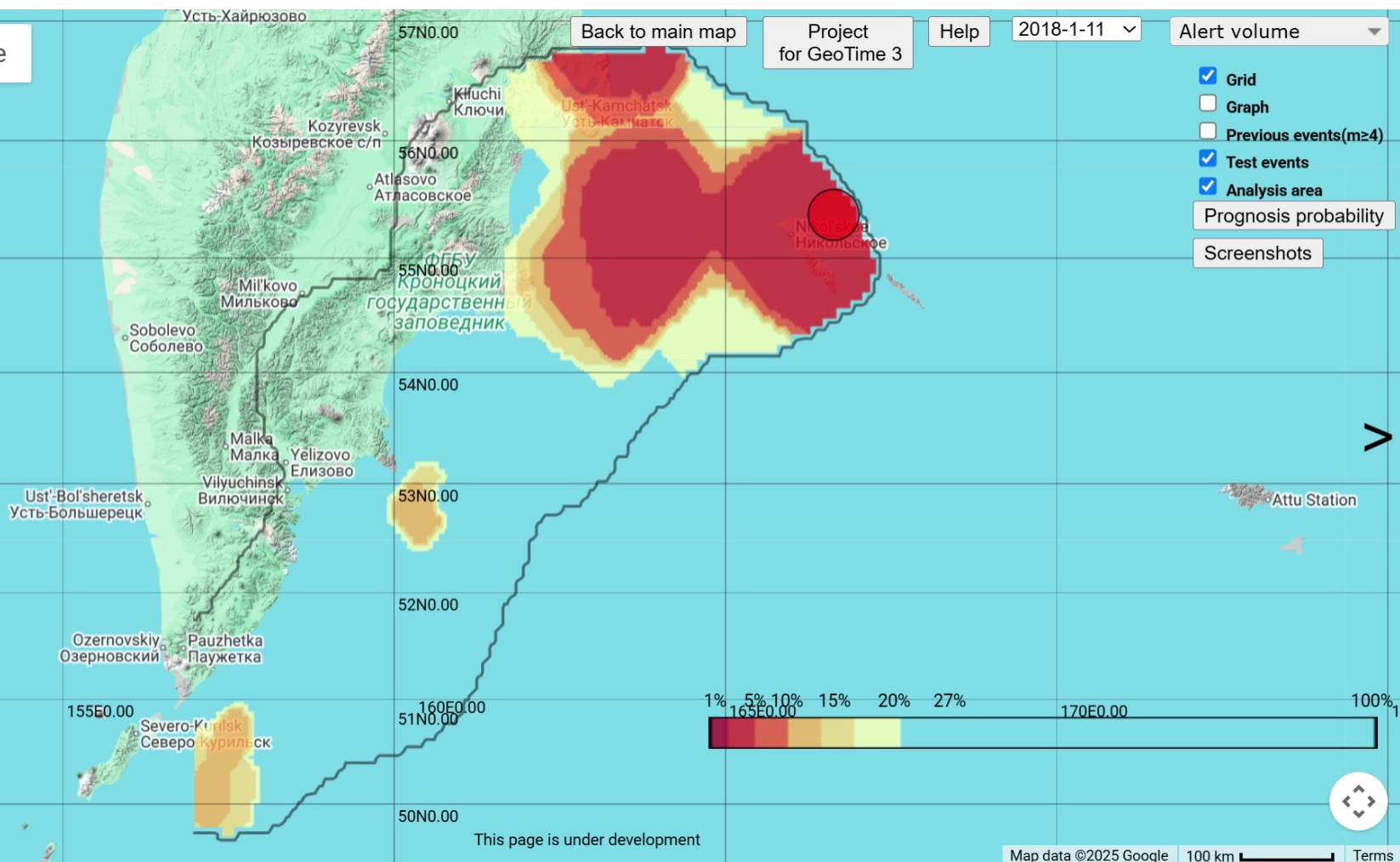
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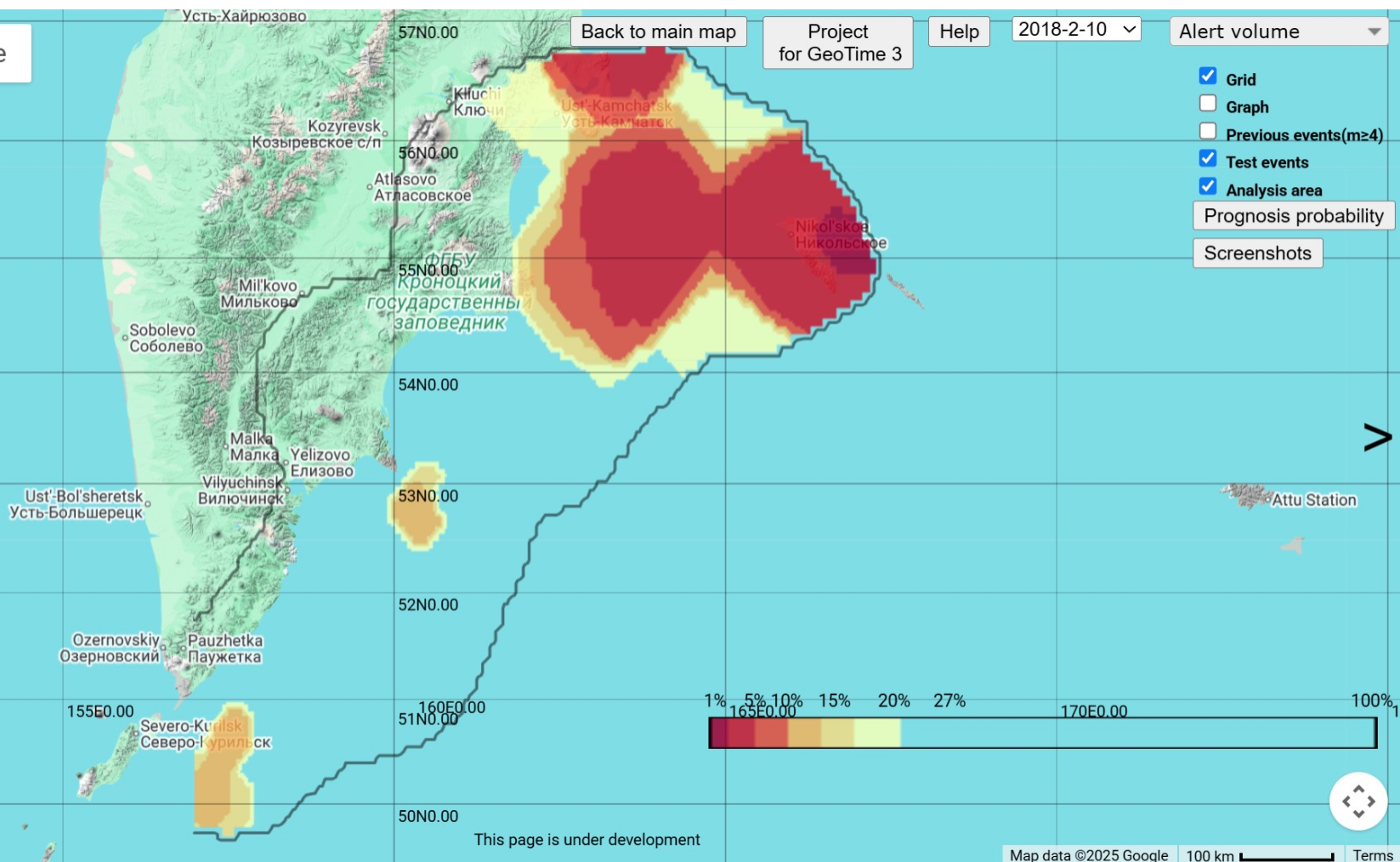
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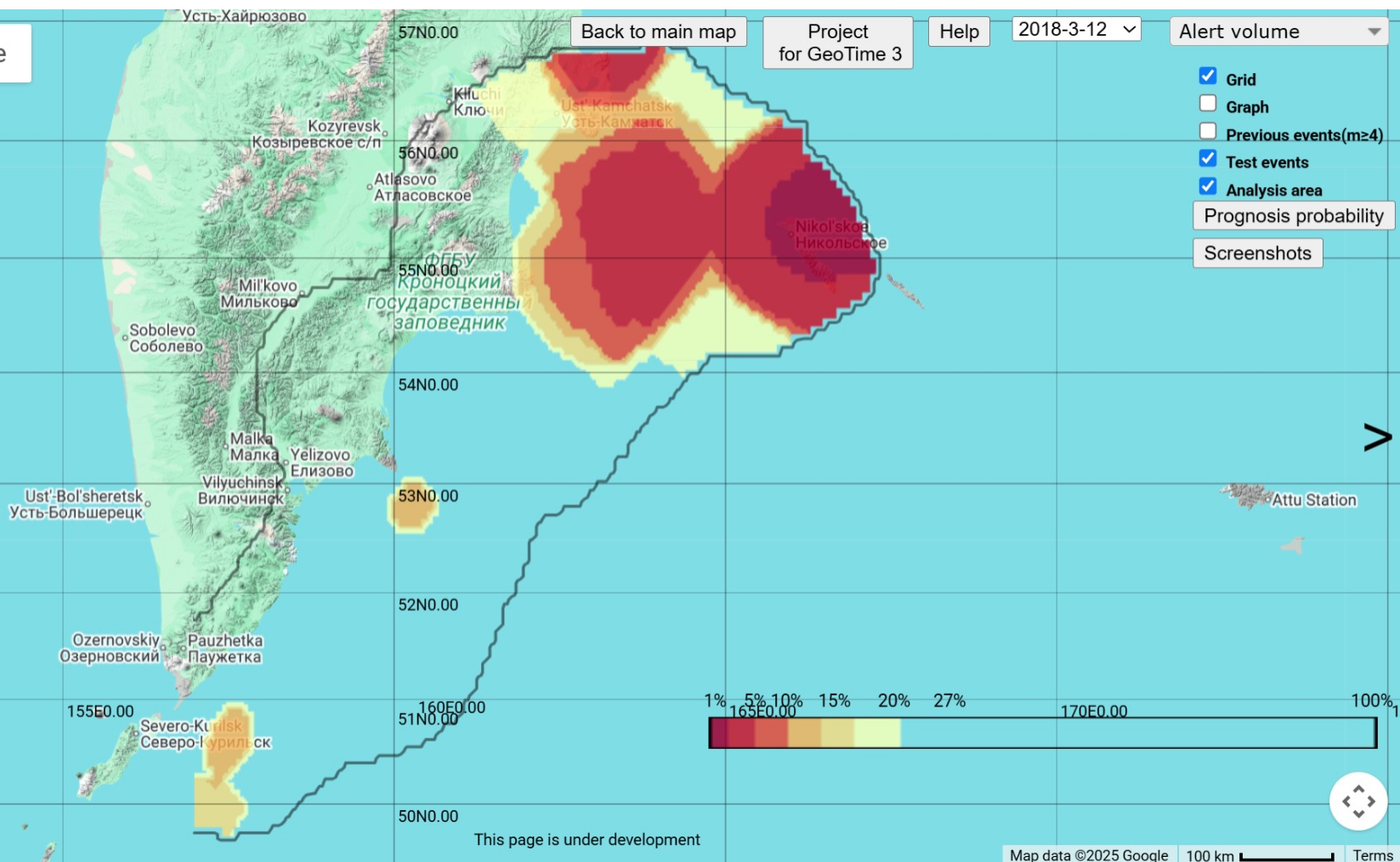
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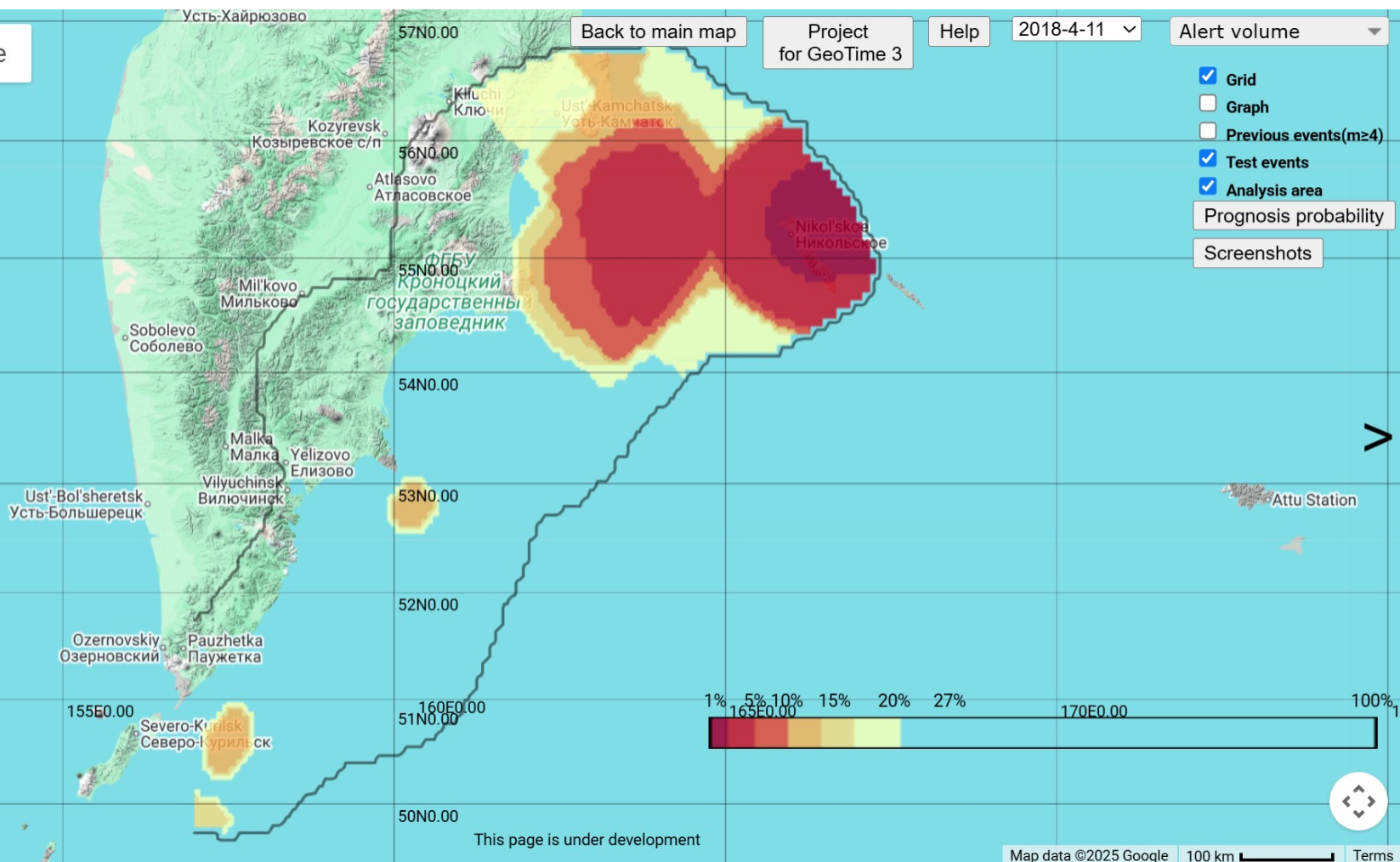
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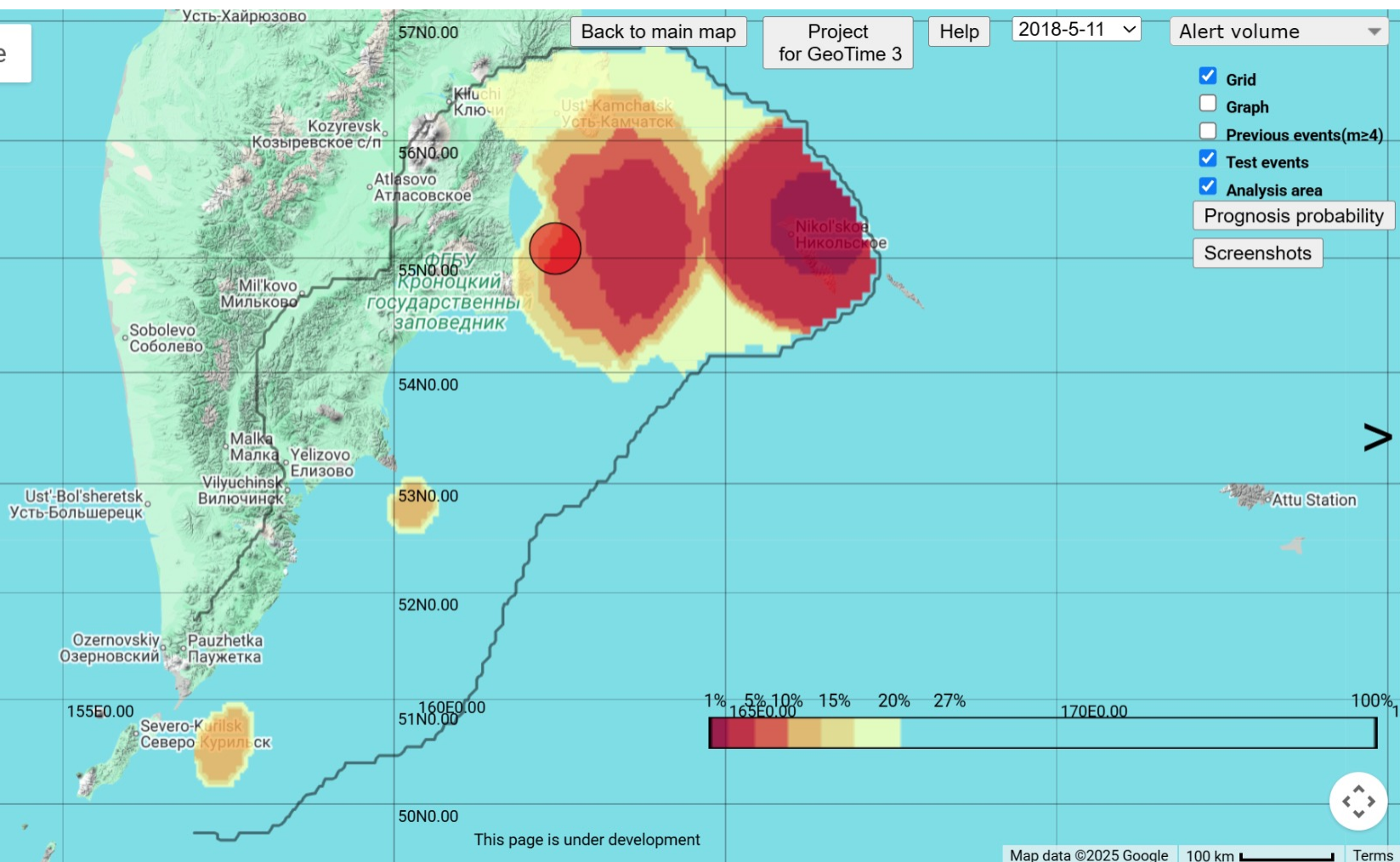
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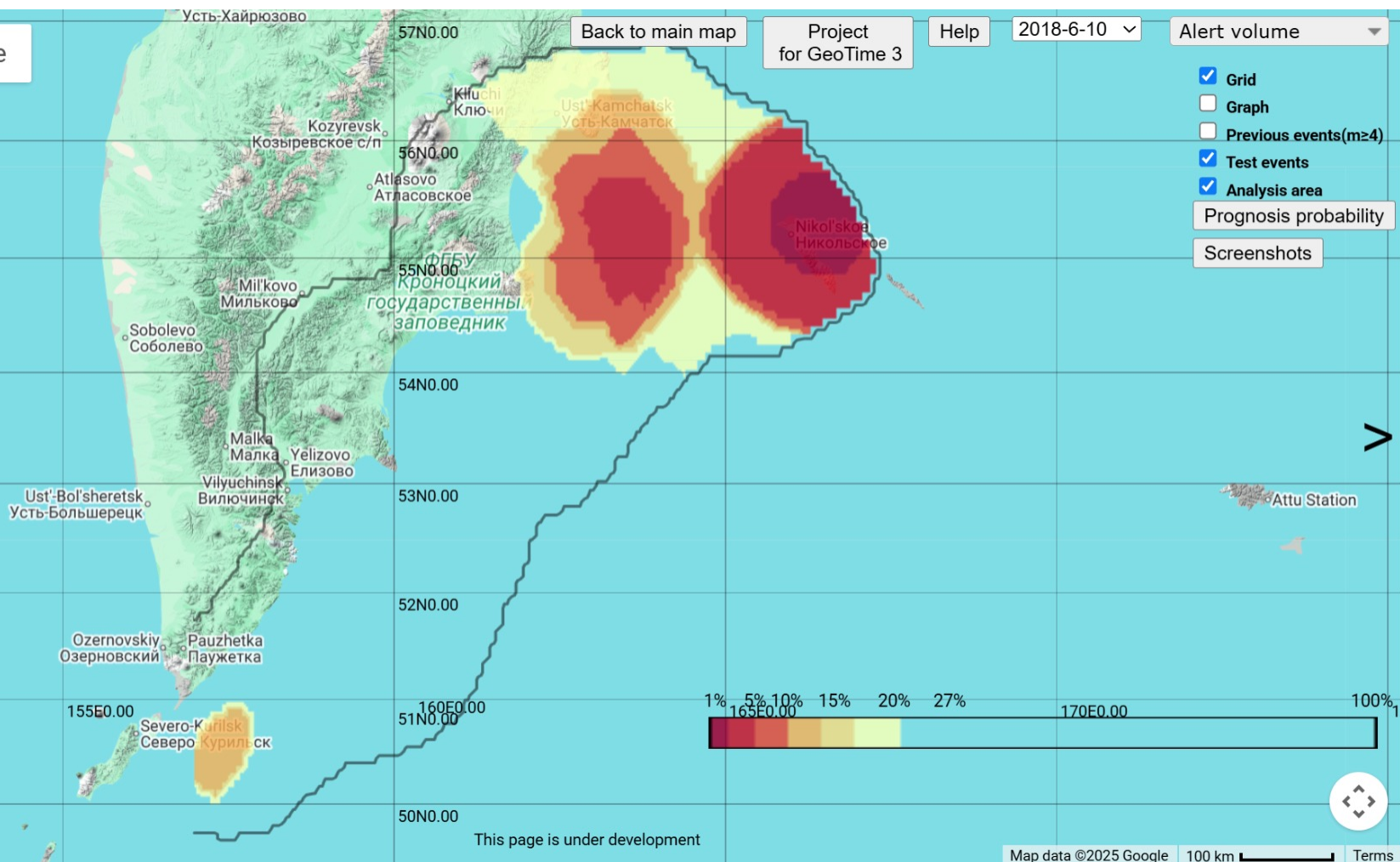
2018-6-10 ▾

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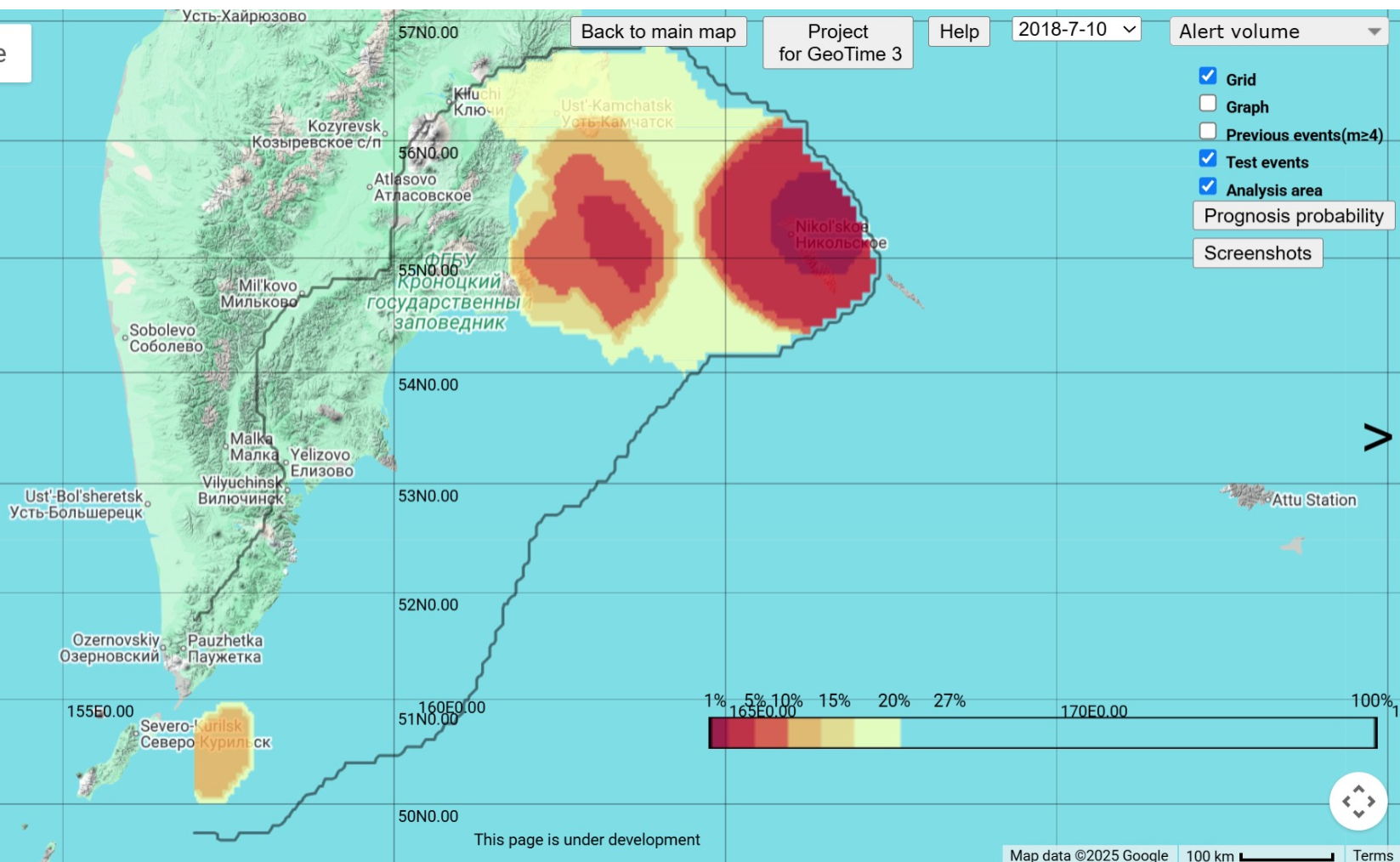
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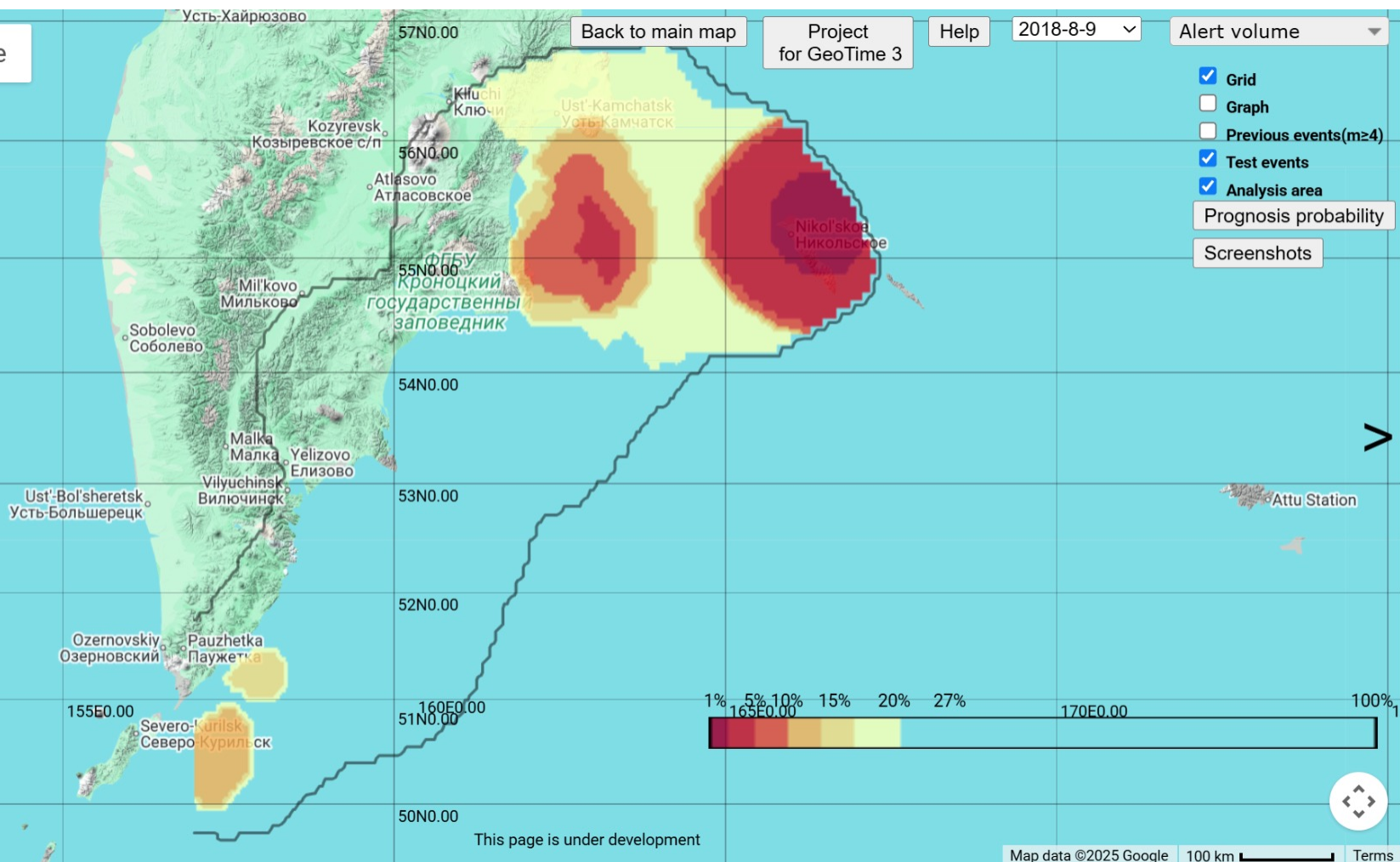
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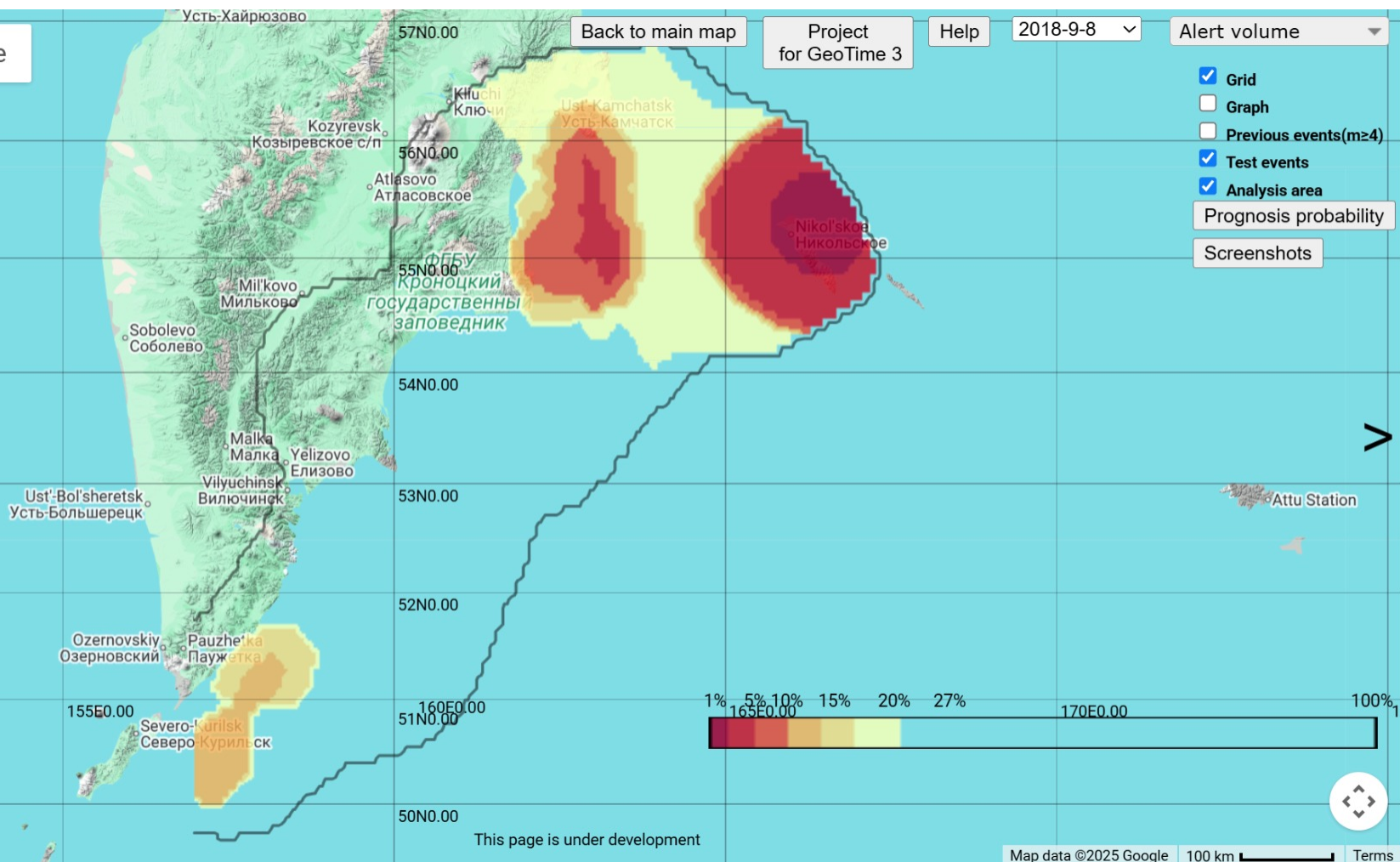
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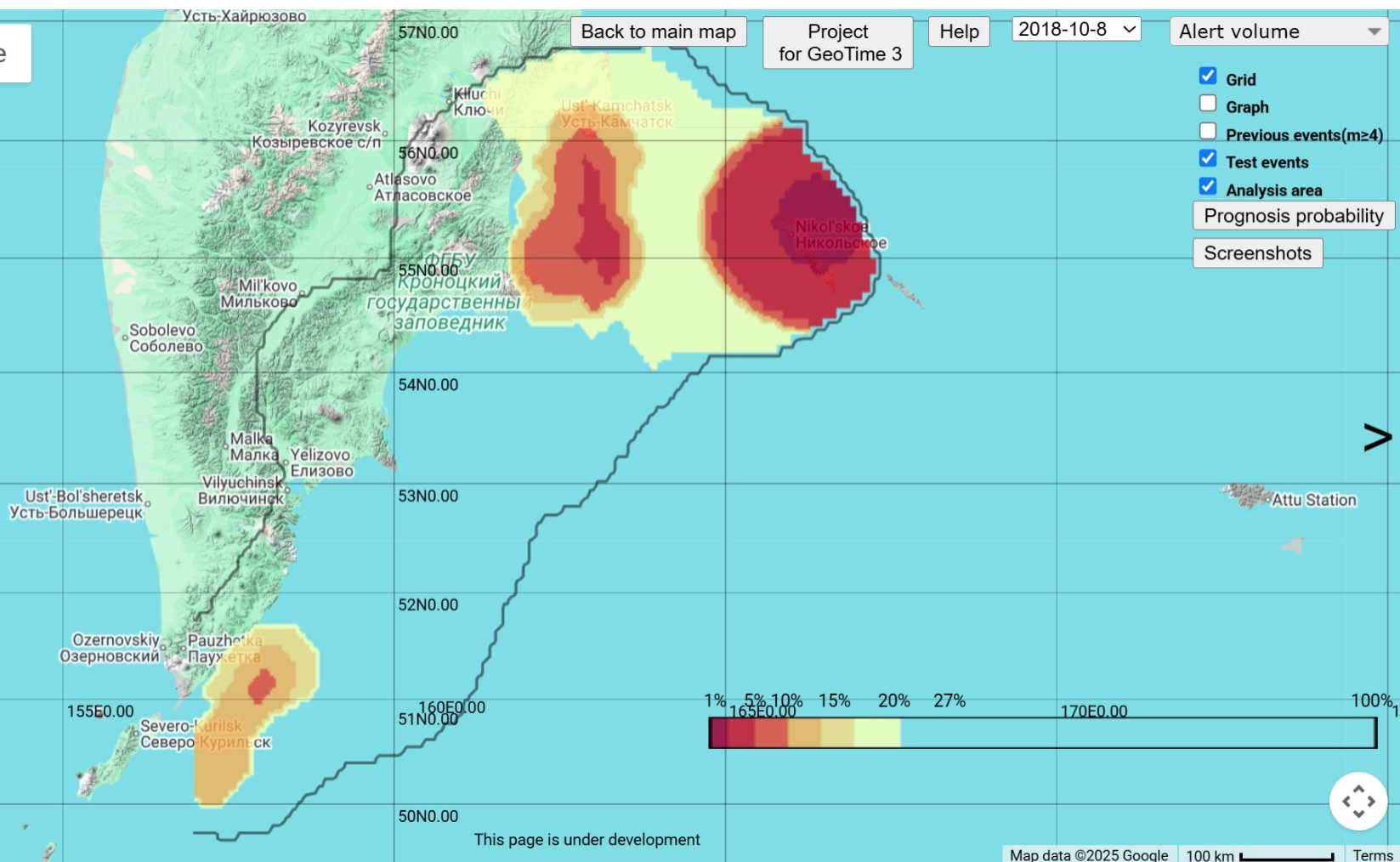
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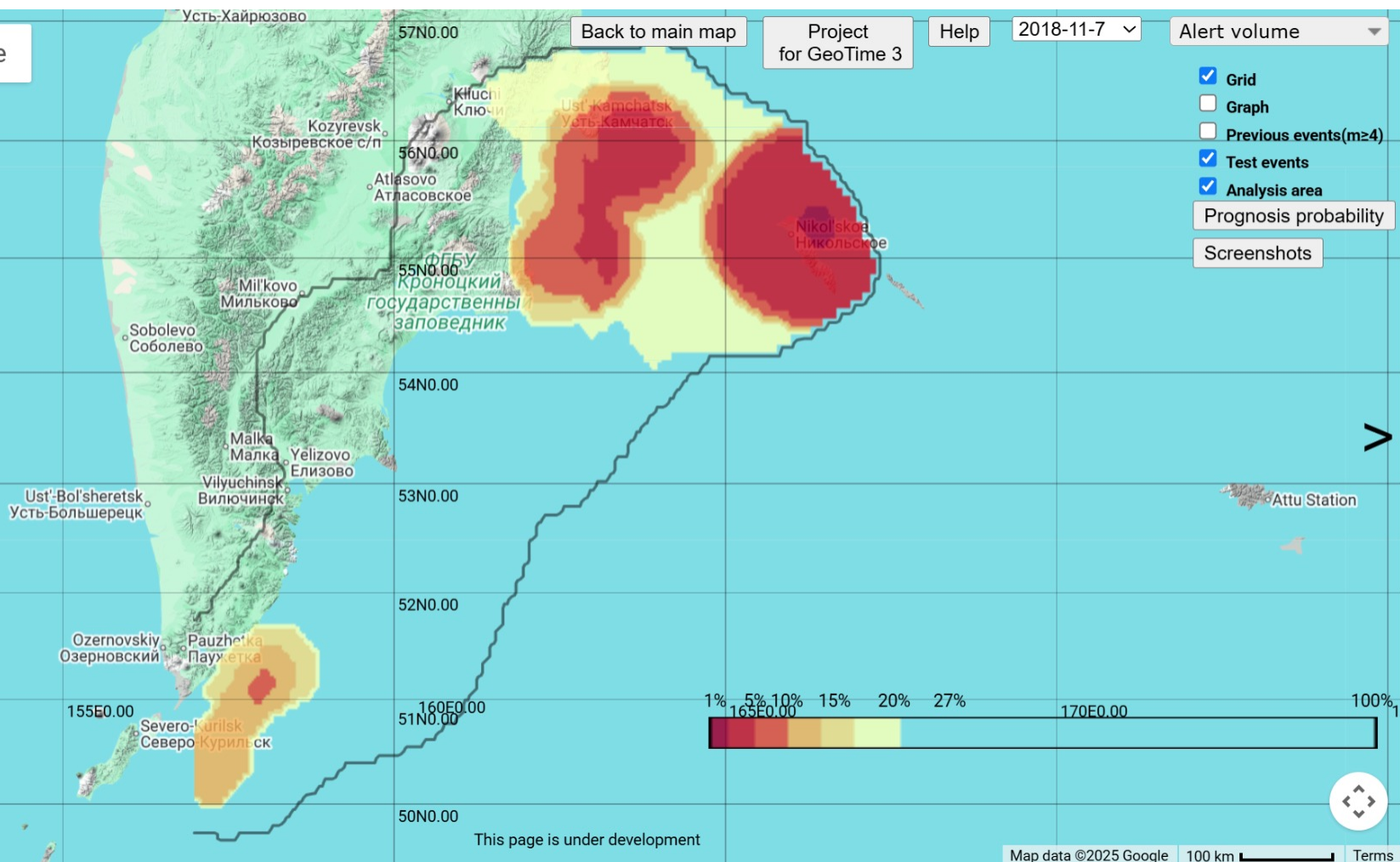
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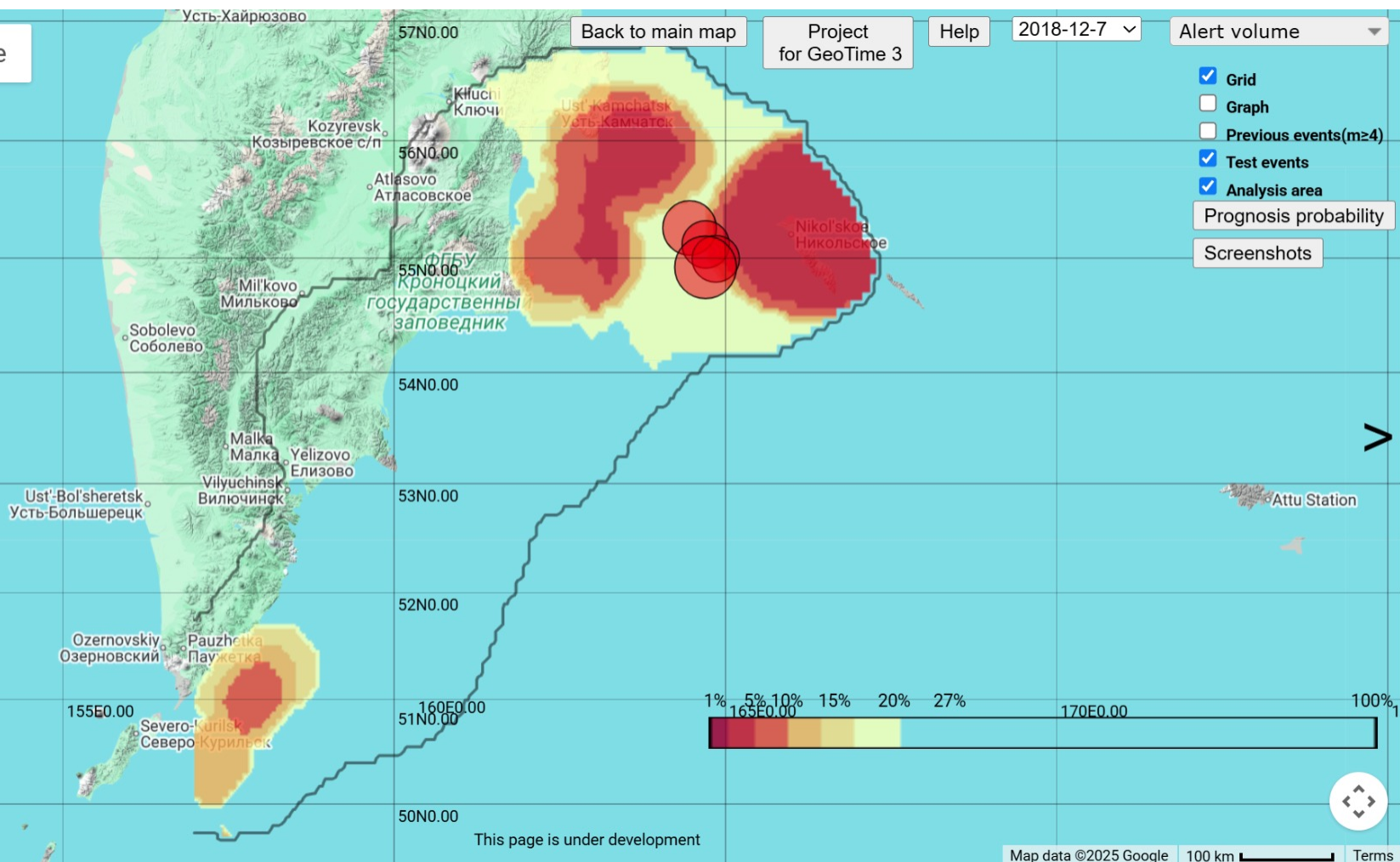
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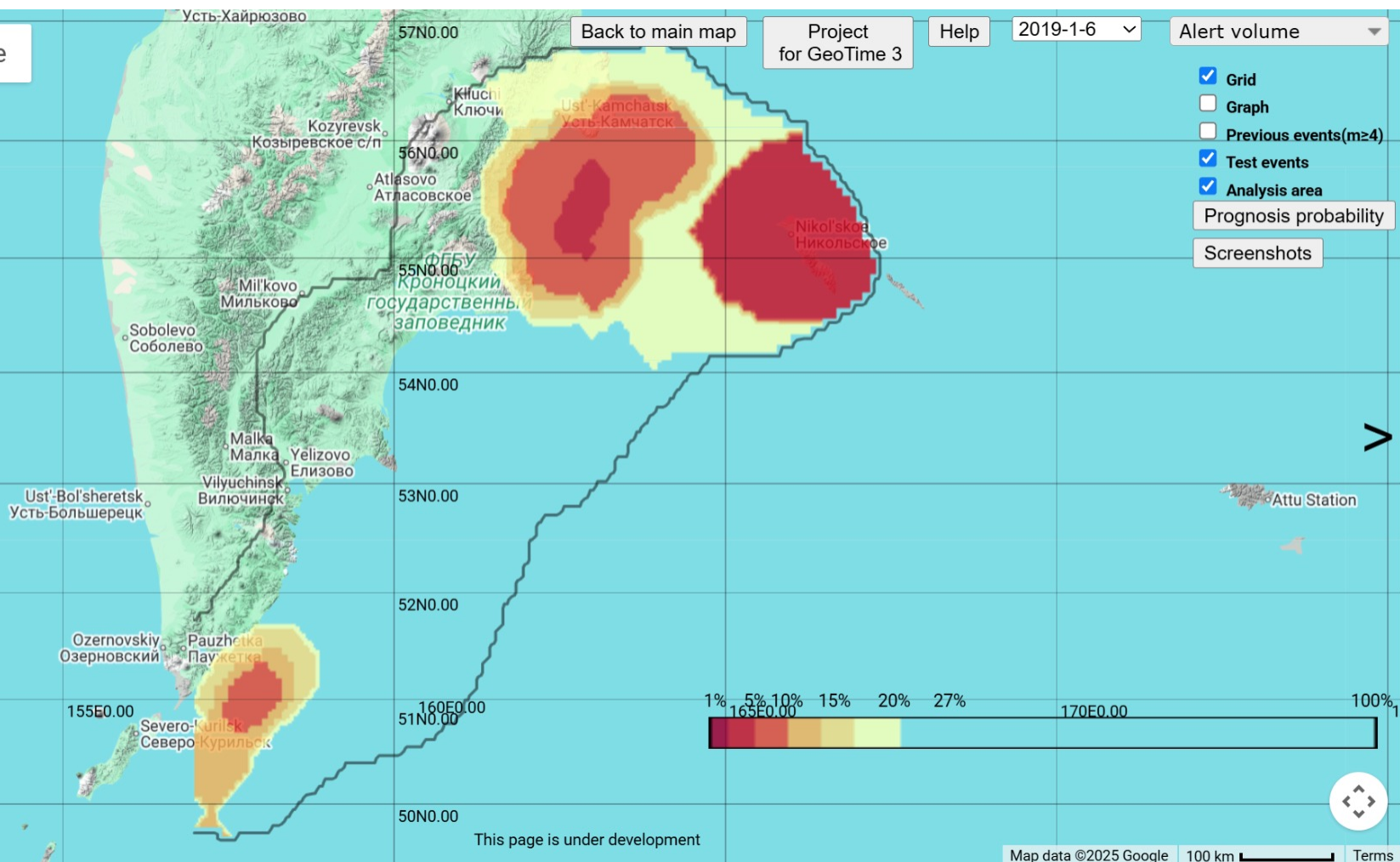
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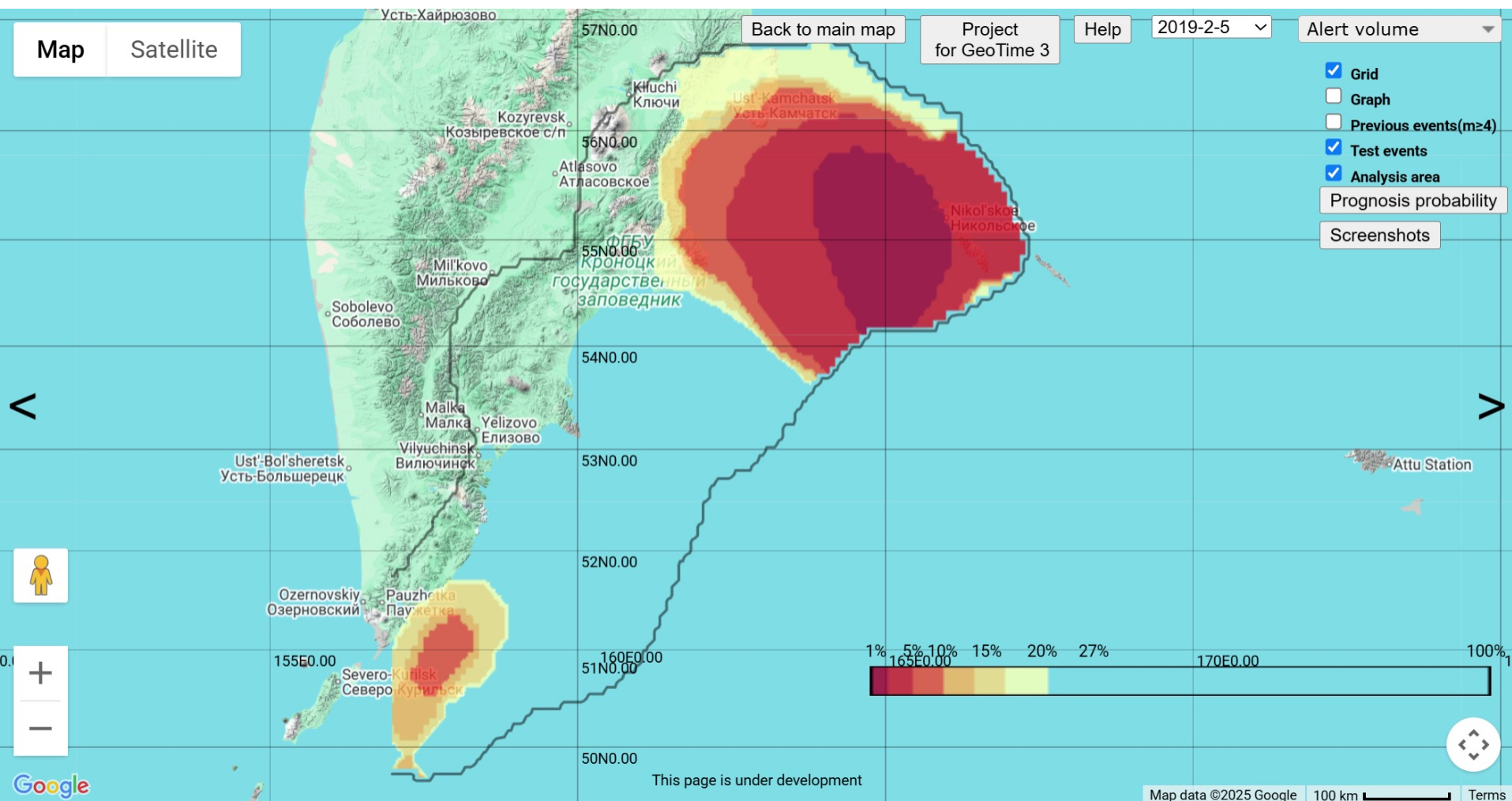
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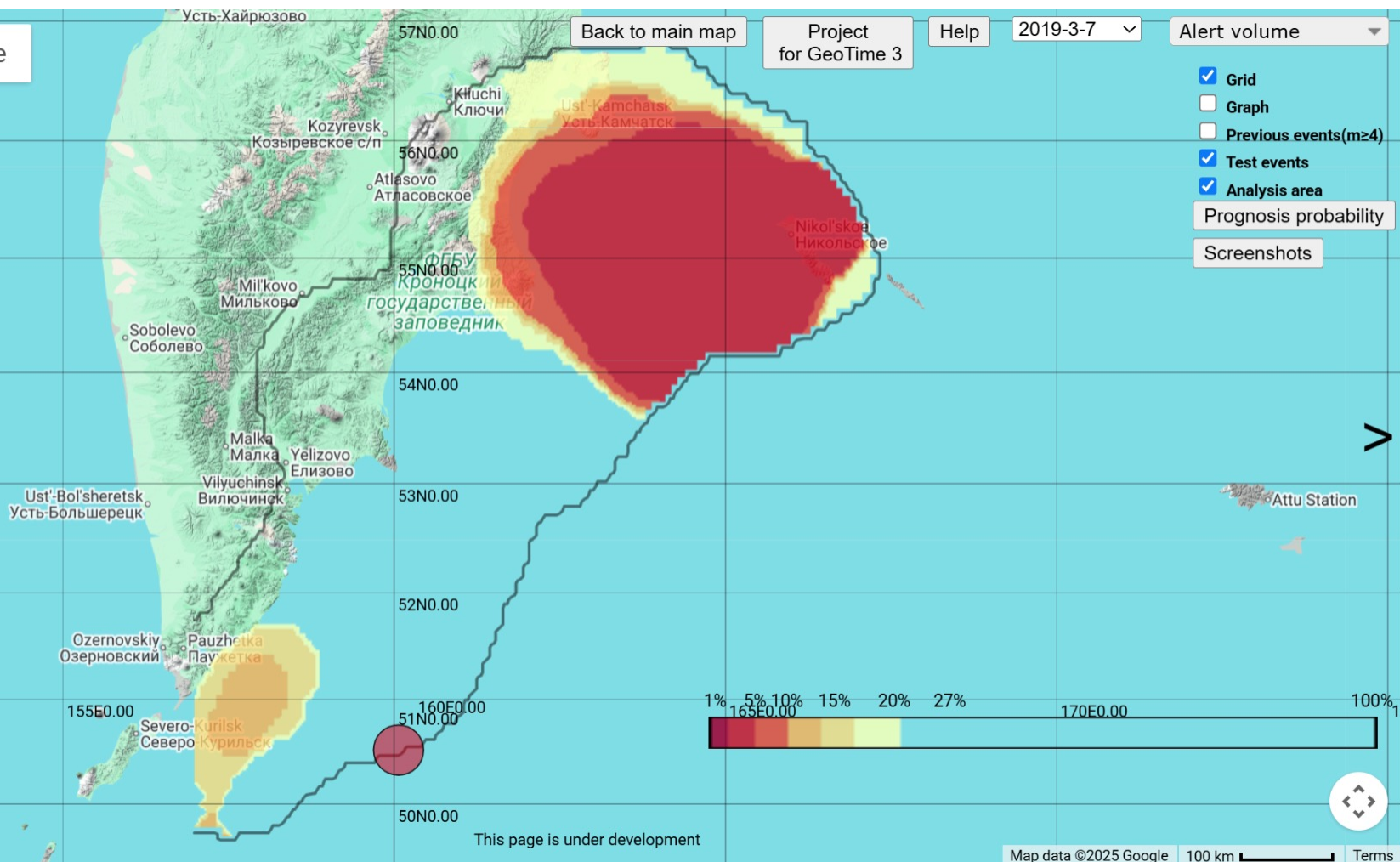
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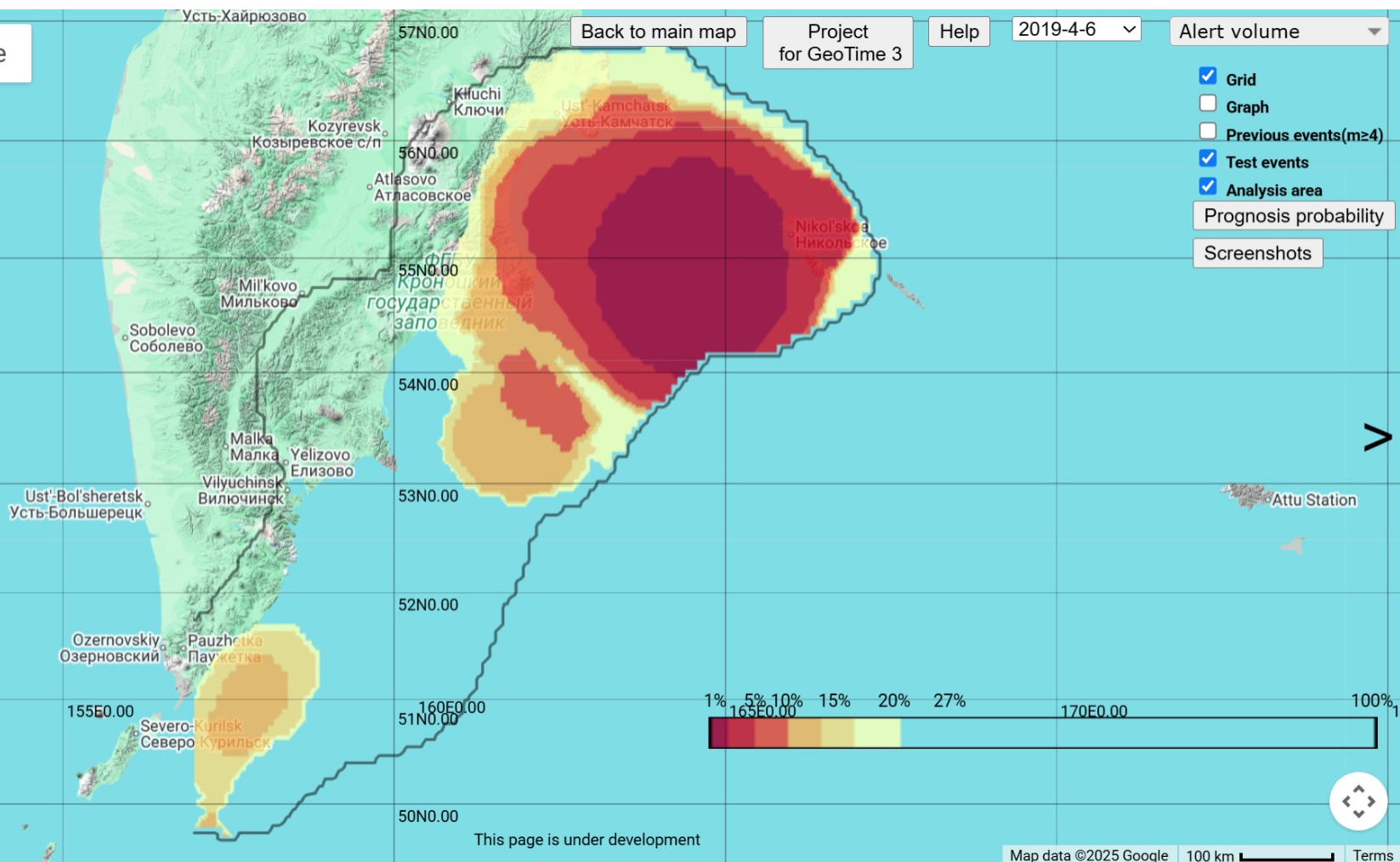
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☒ Grid

☐ **Graph**

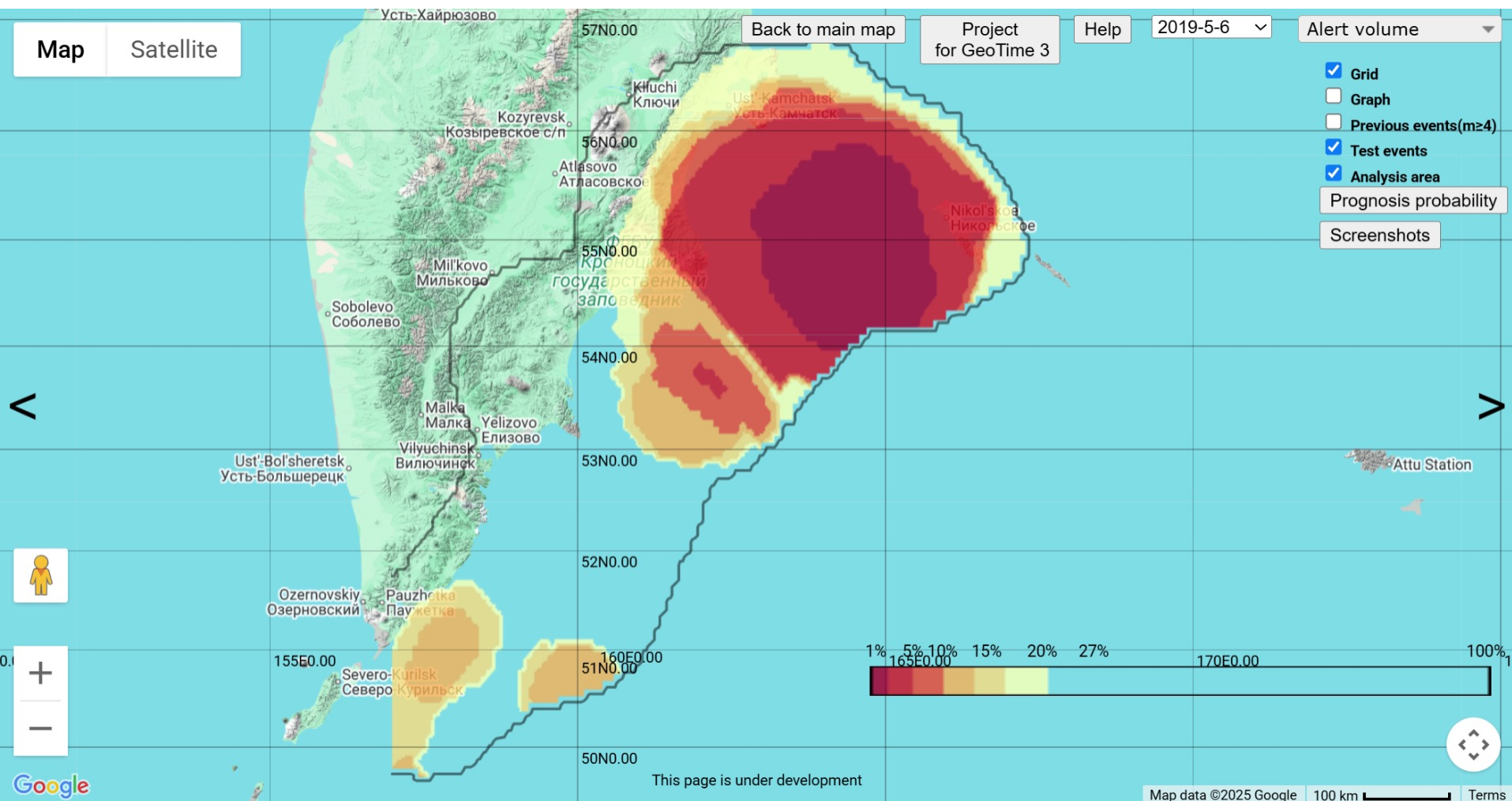
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- ✓ **Test events**

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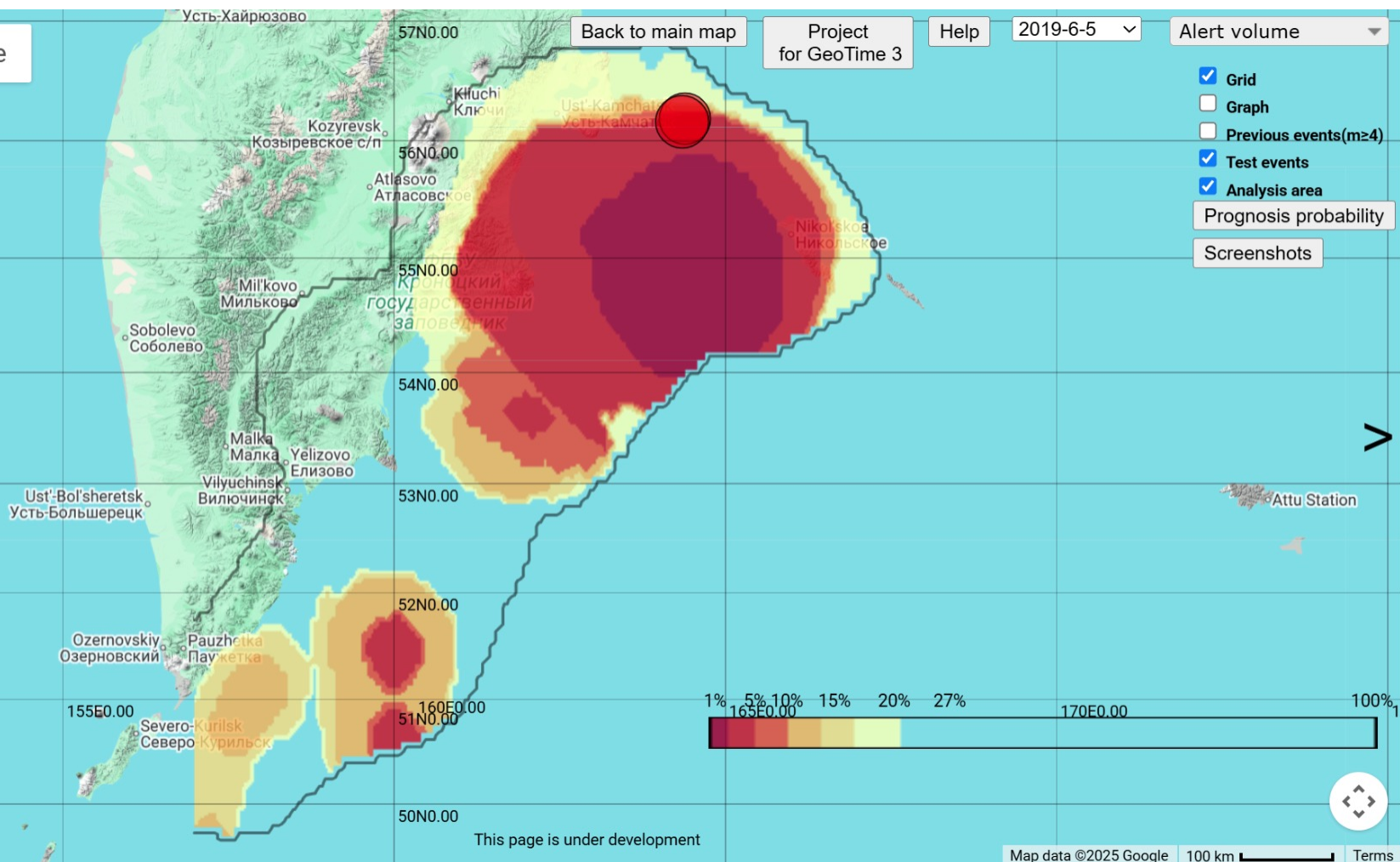
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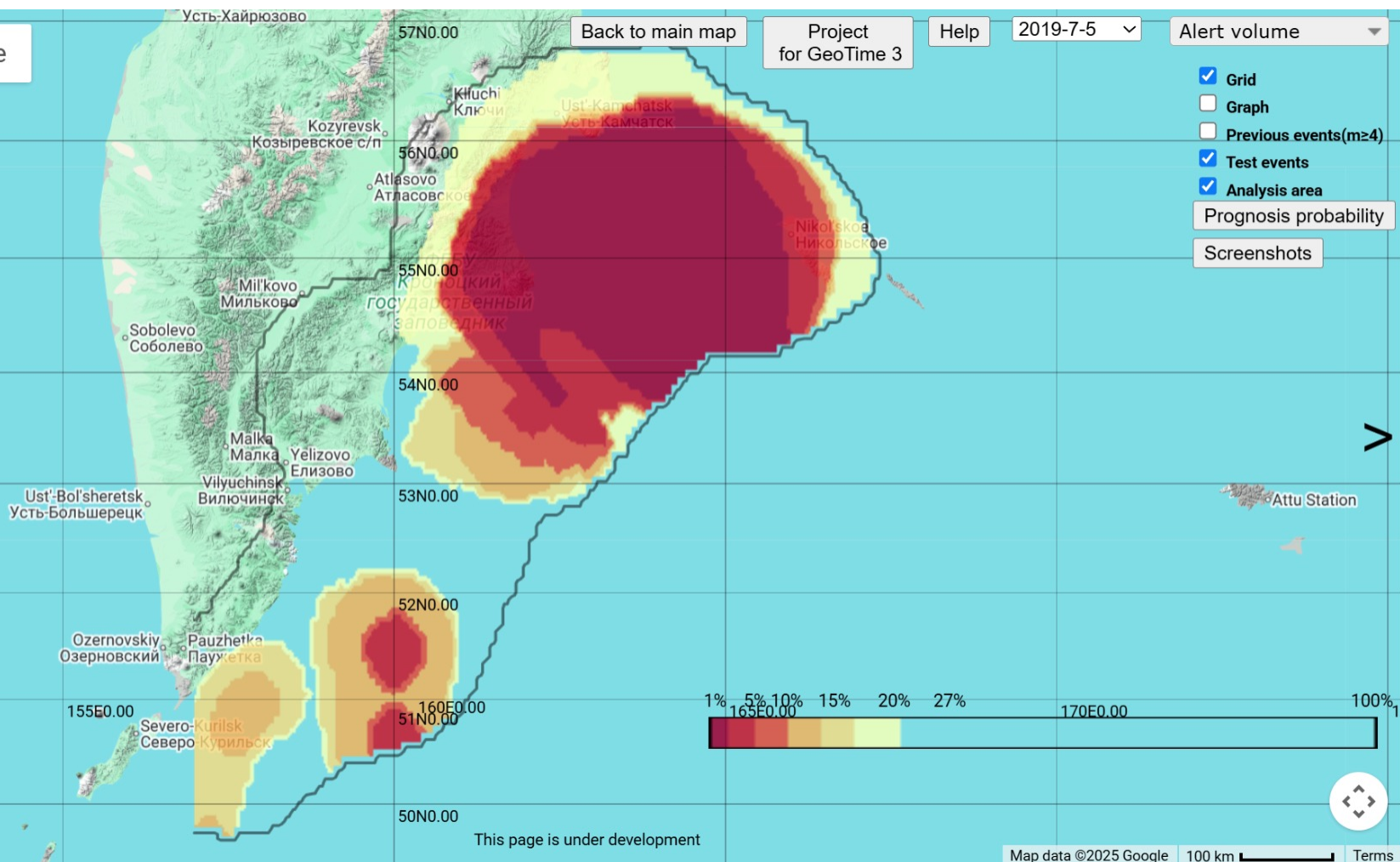
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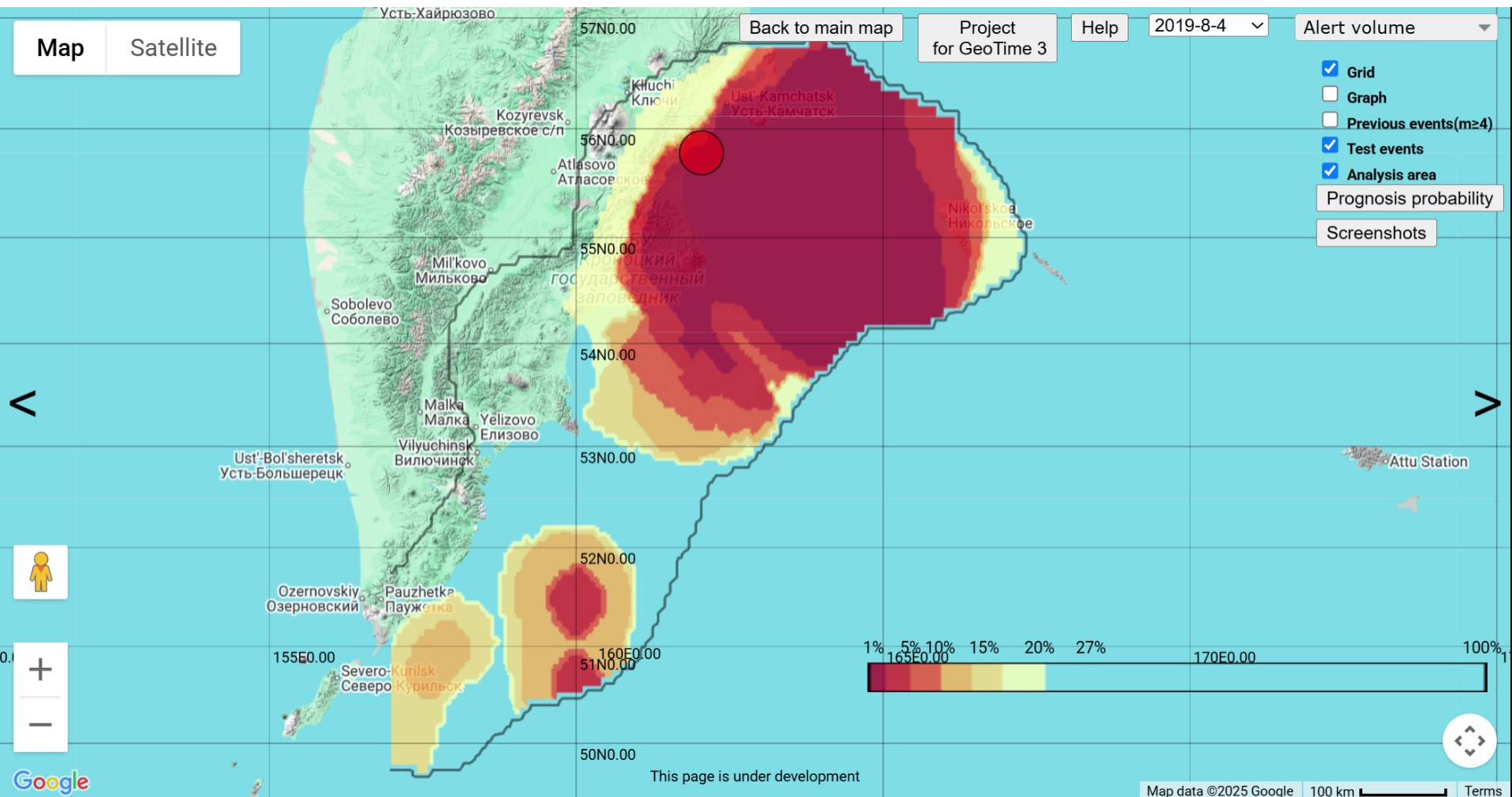
2019-8-4 ▾

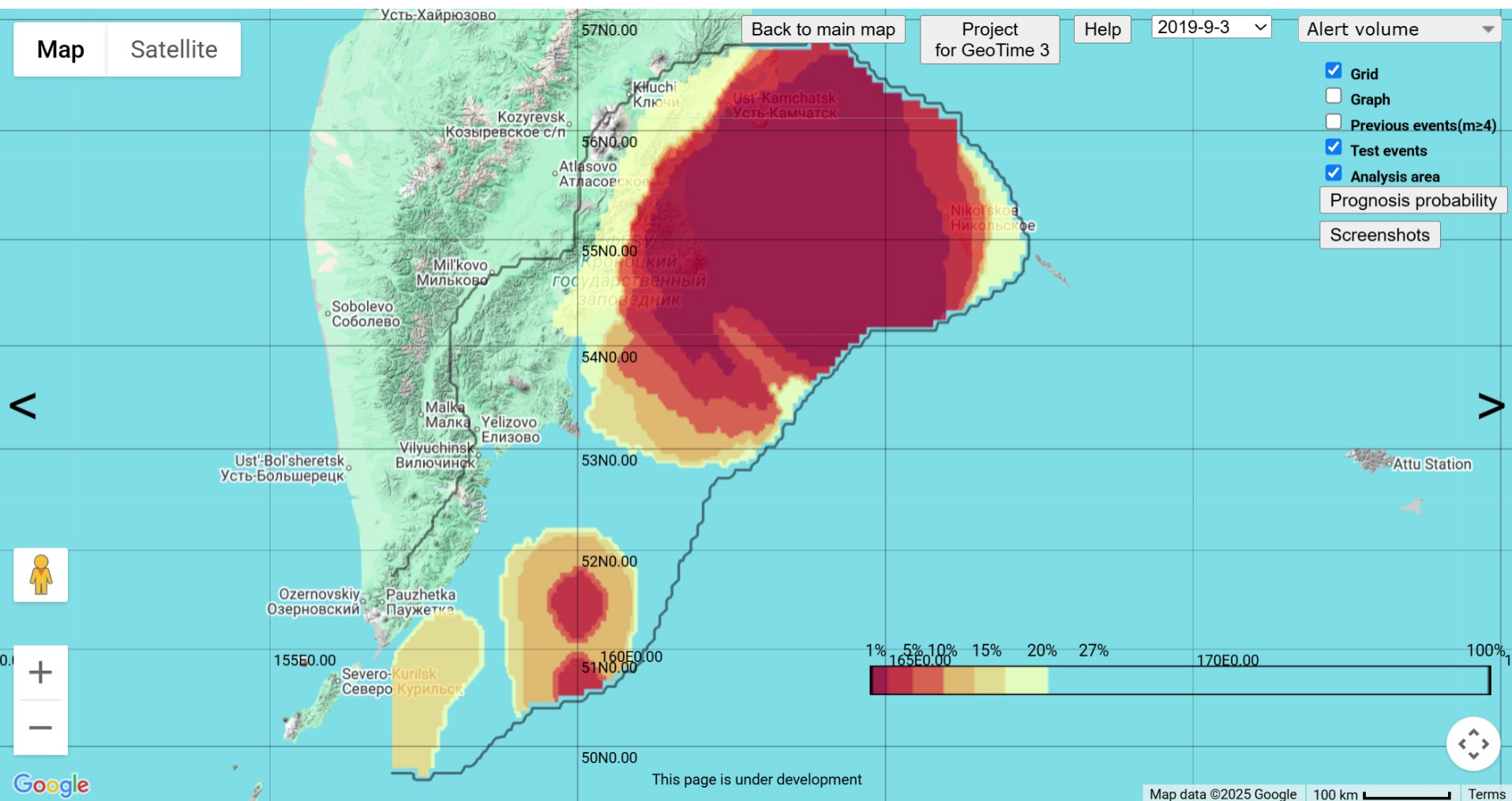
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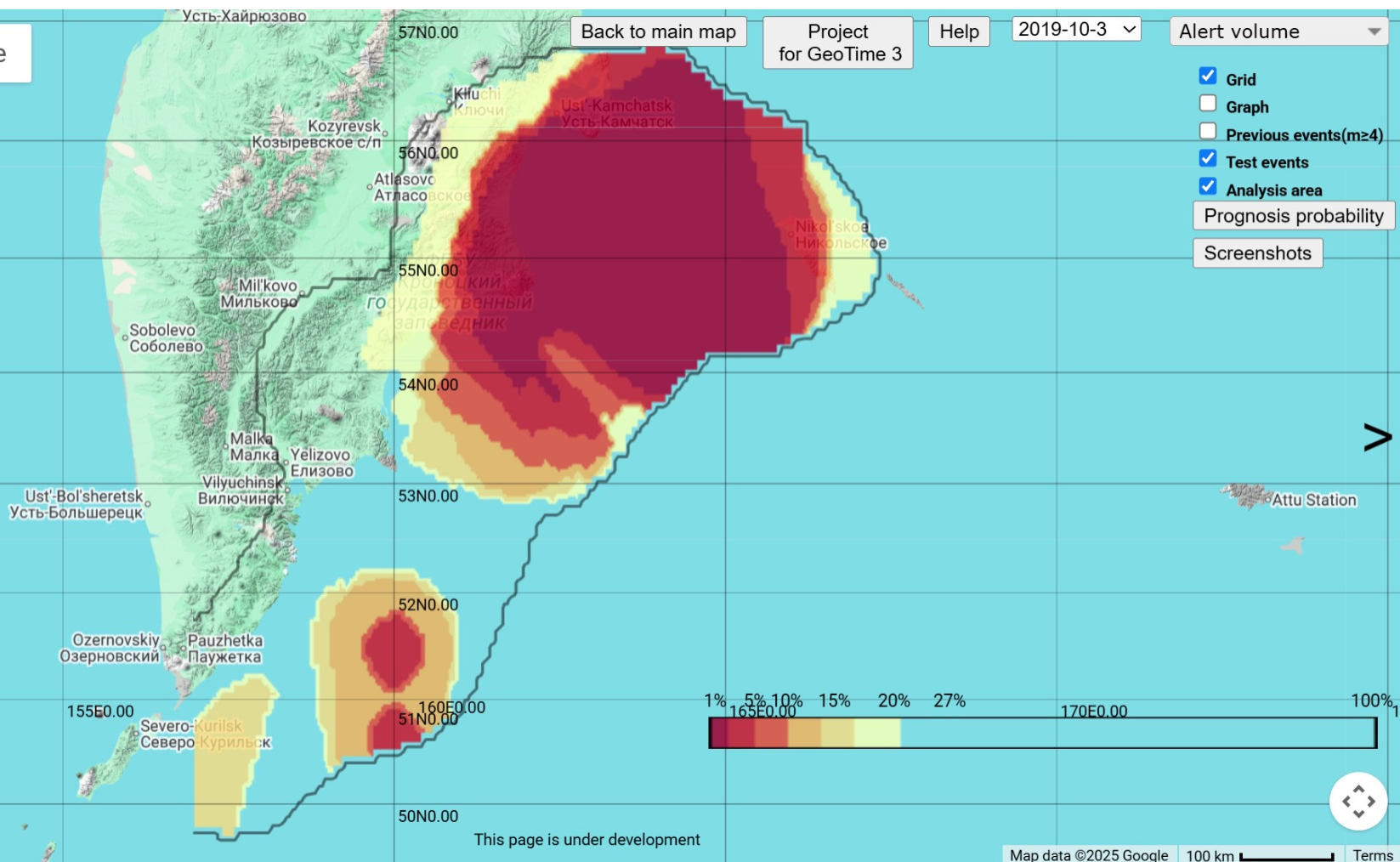
2019-10-3 ▾

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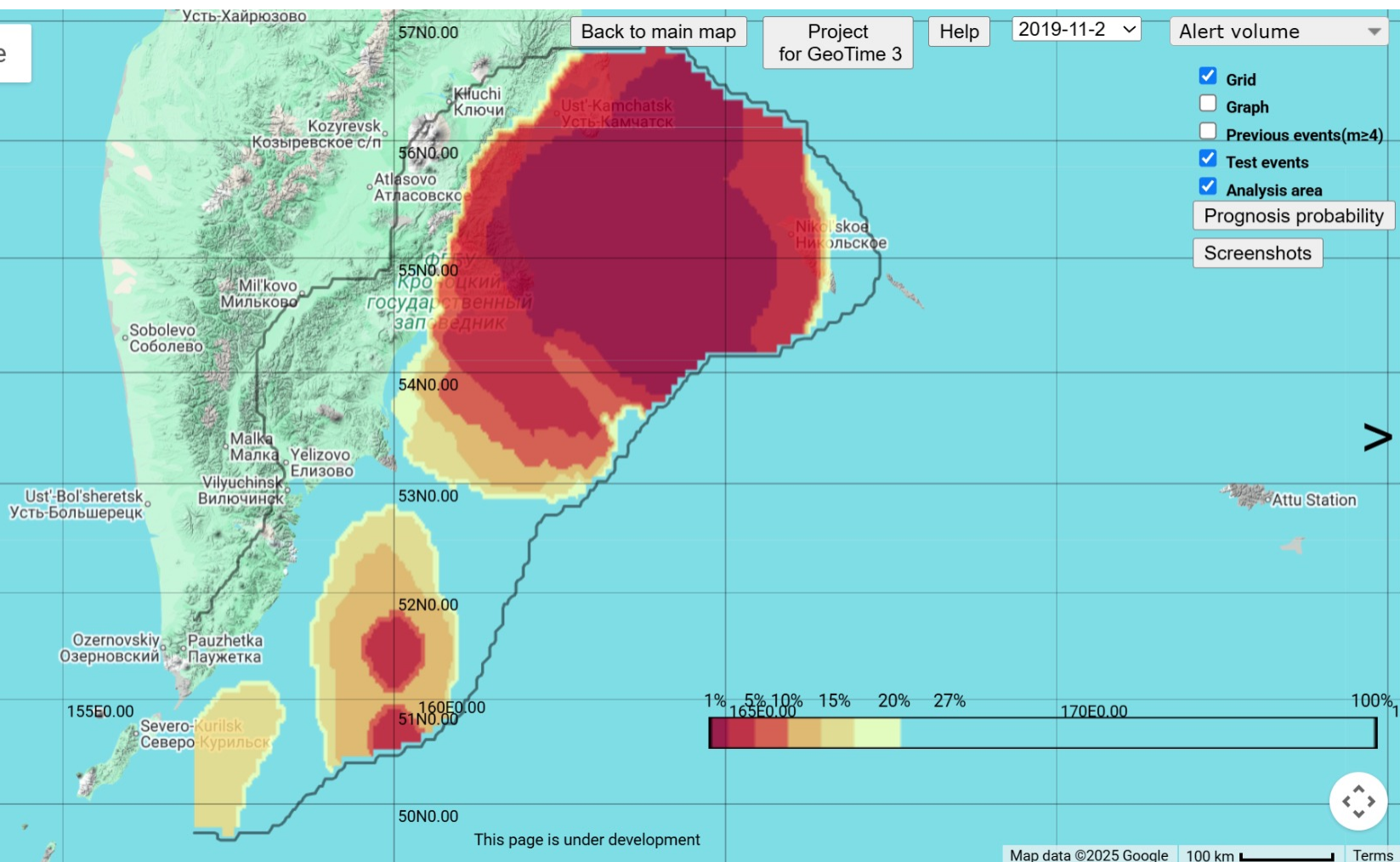
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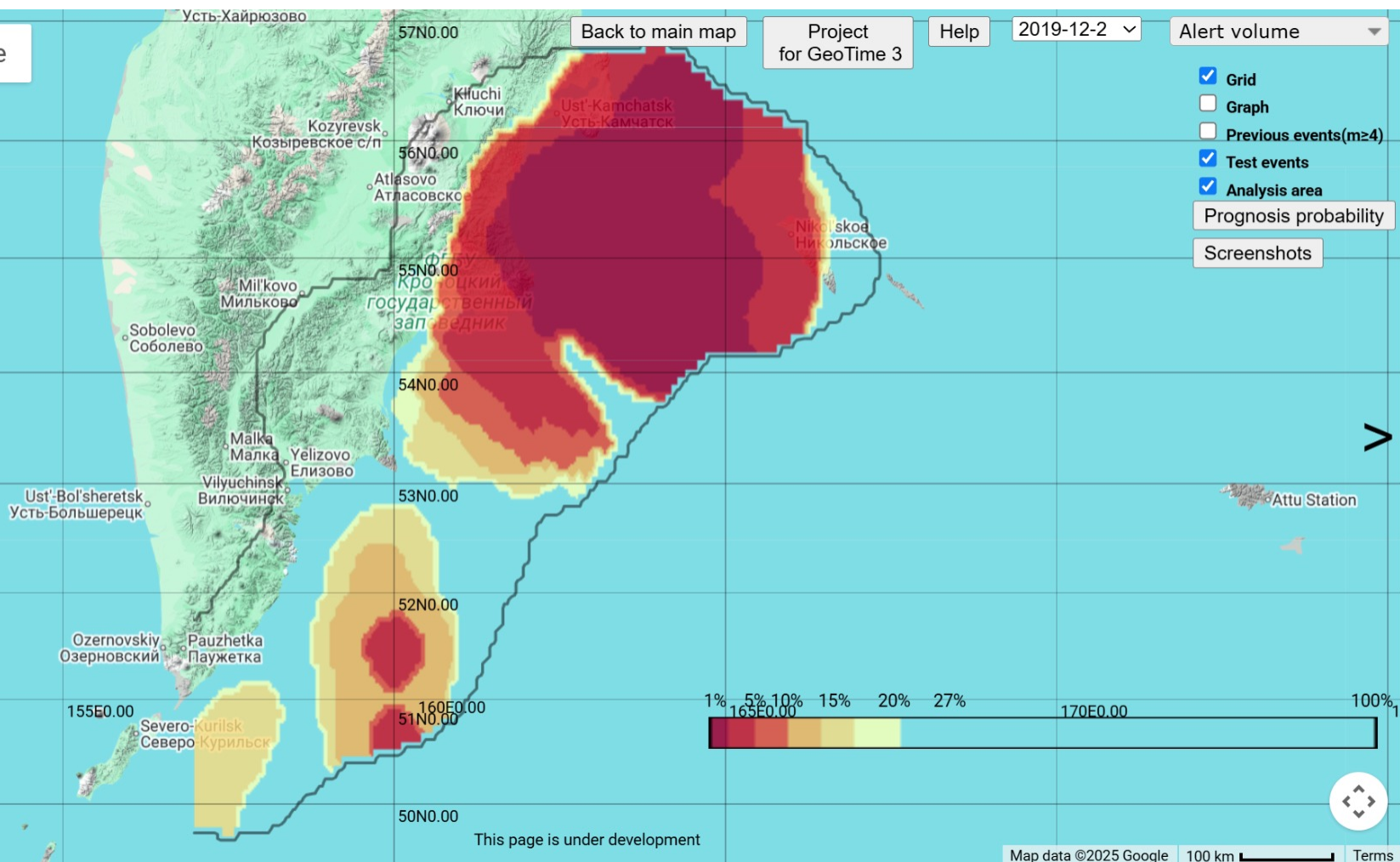
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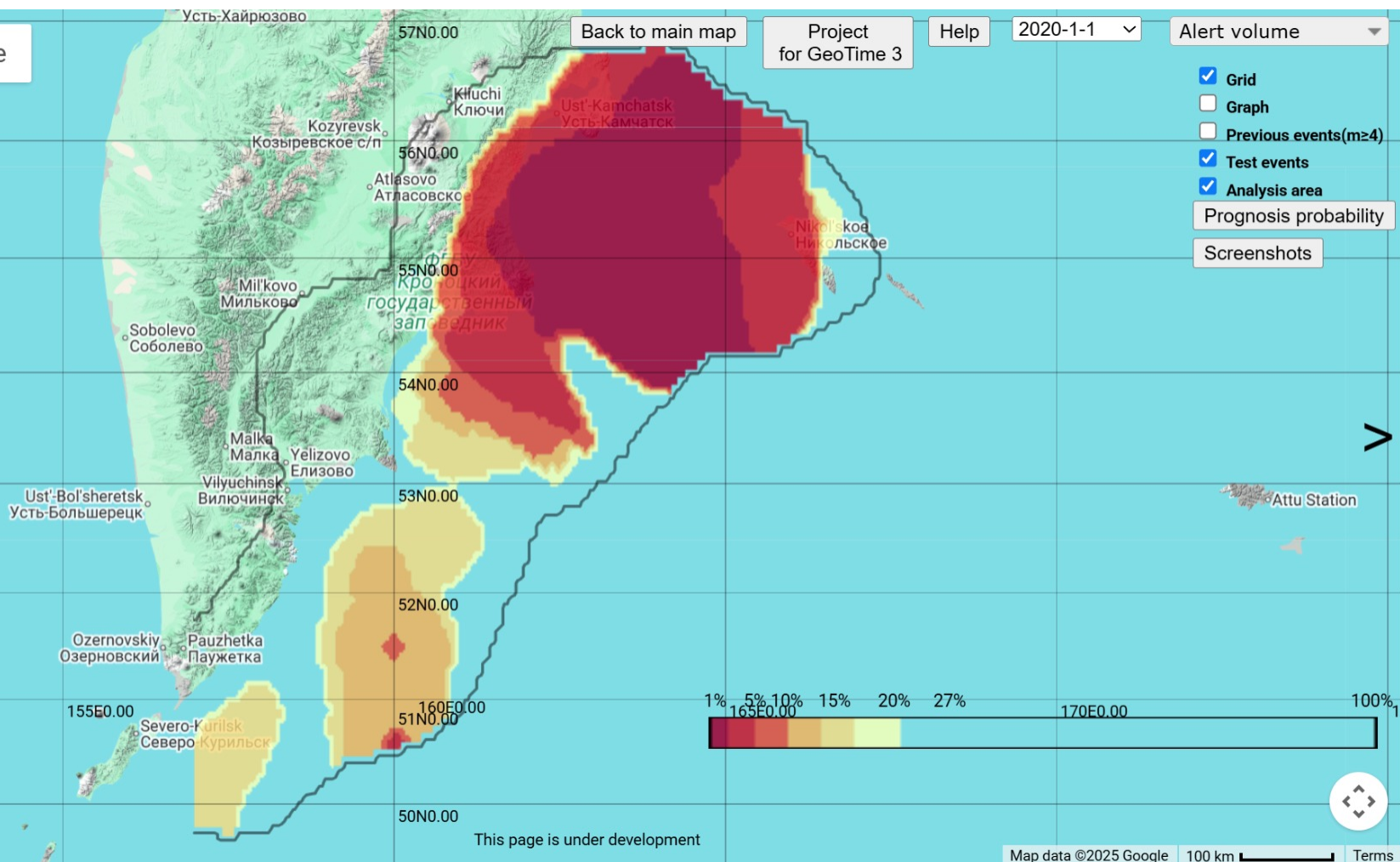
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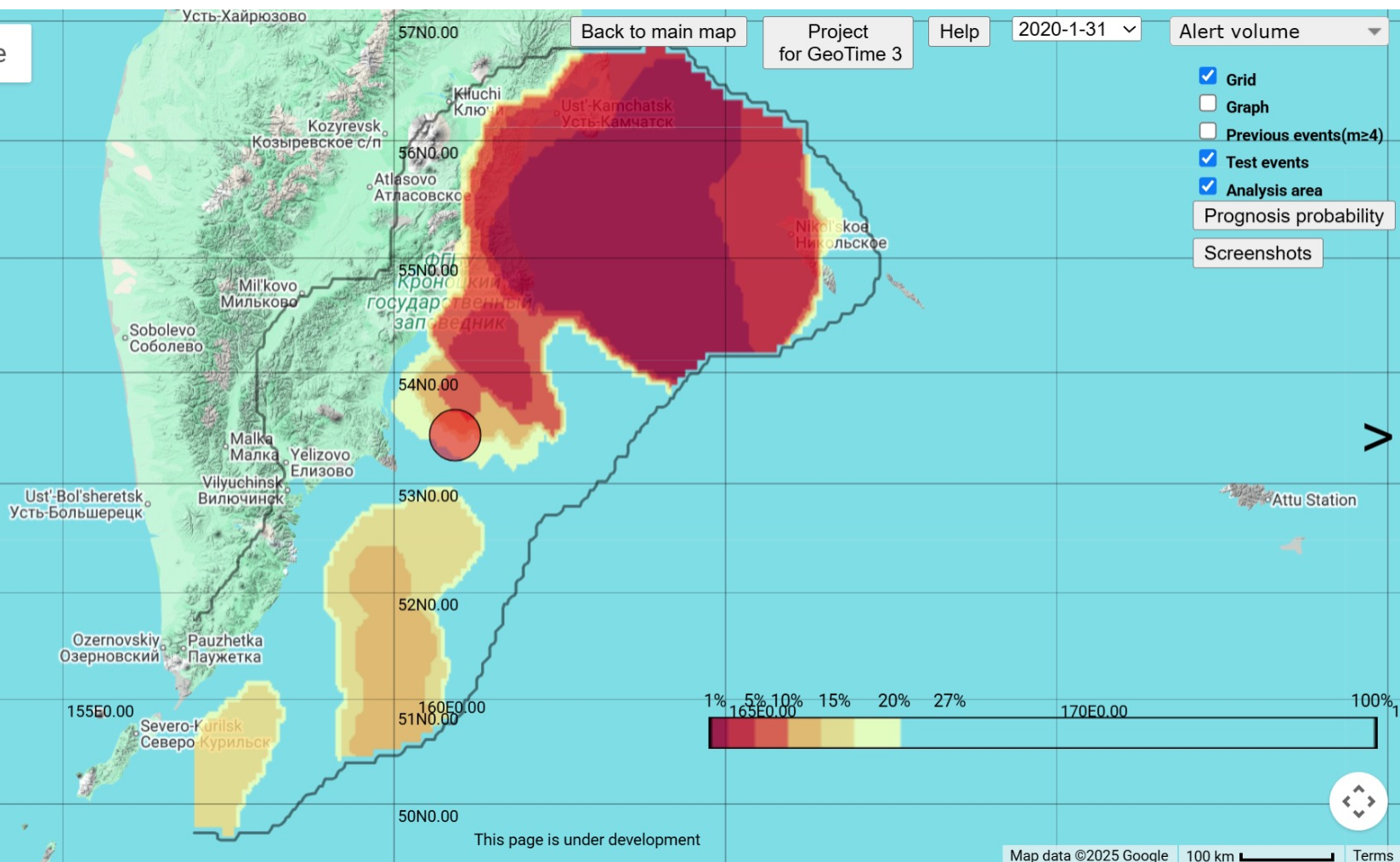
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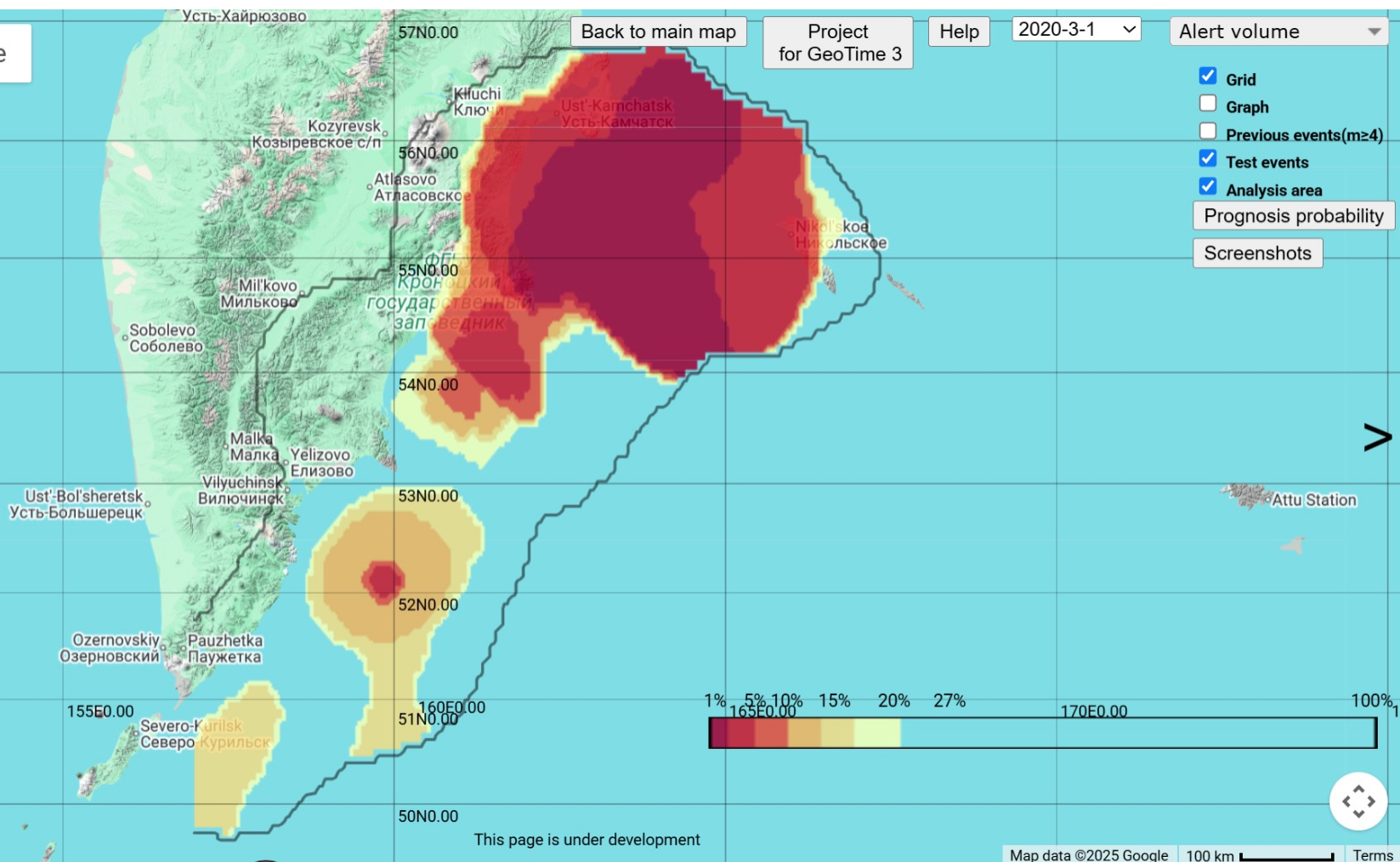
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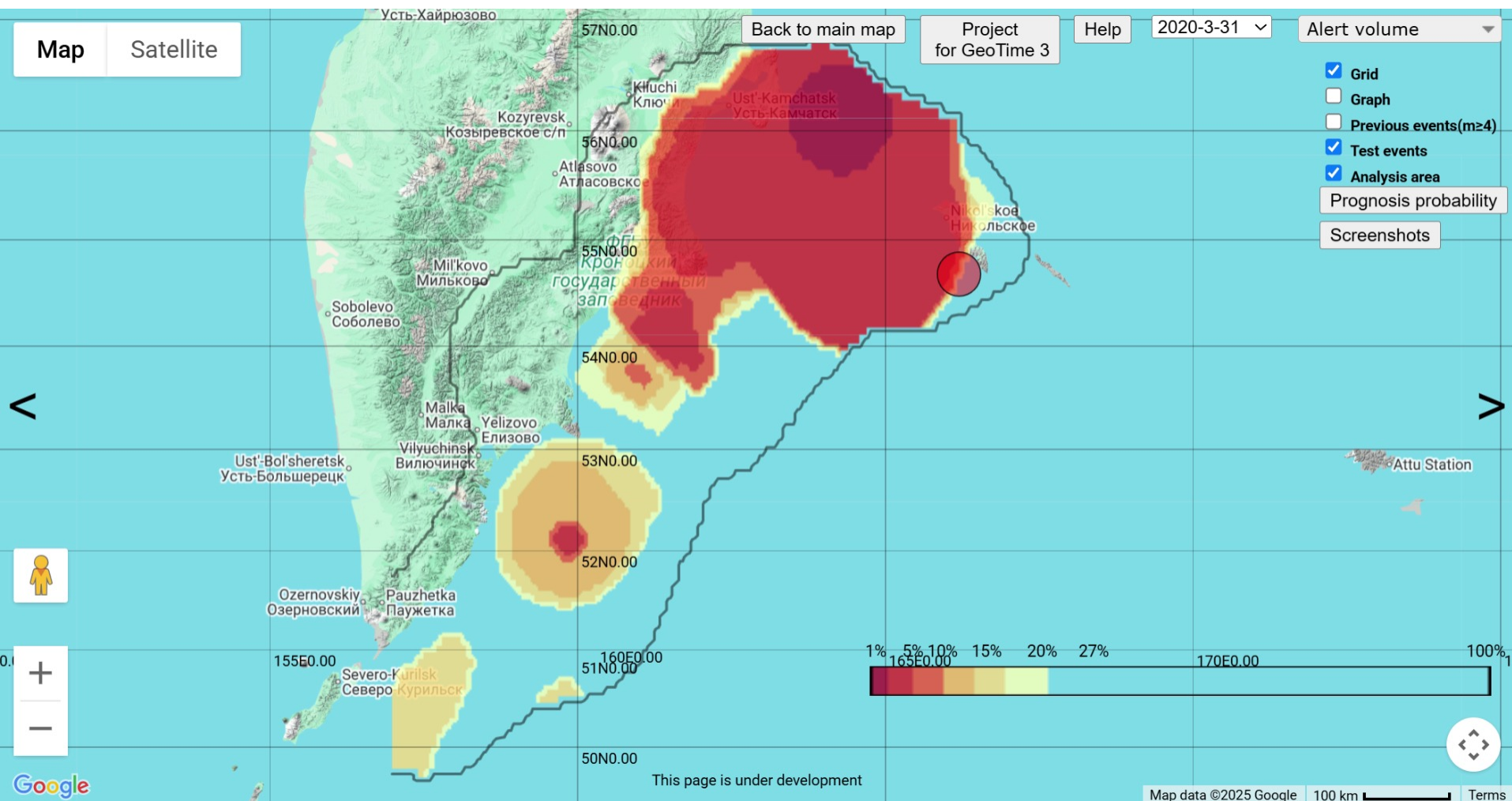
- ✓ **Test events**

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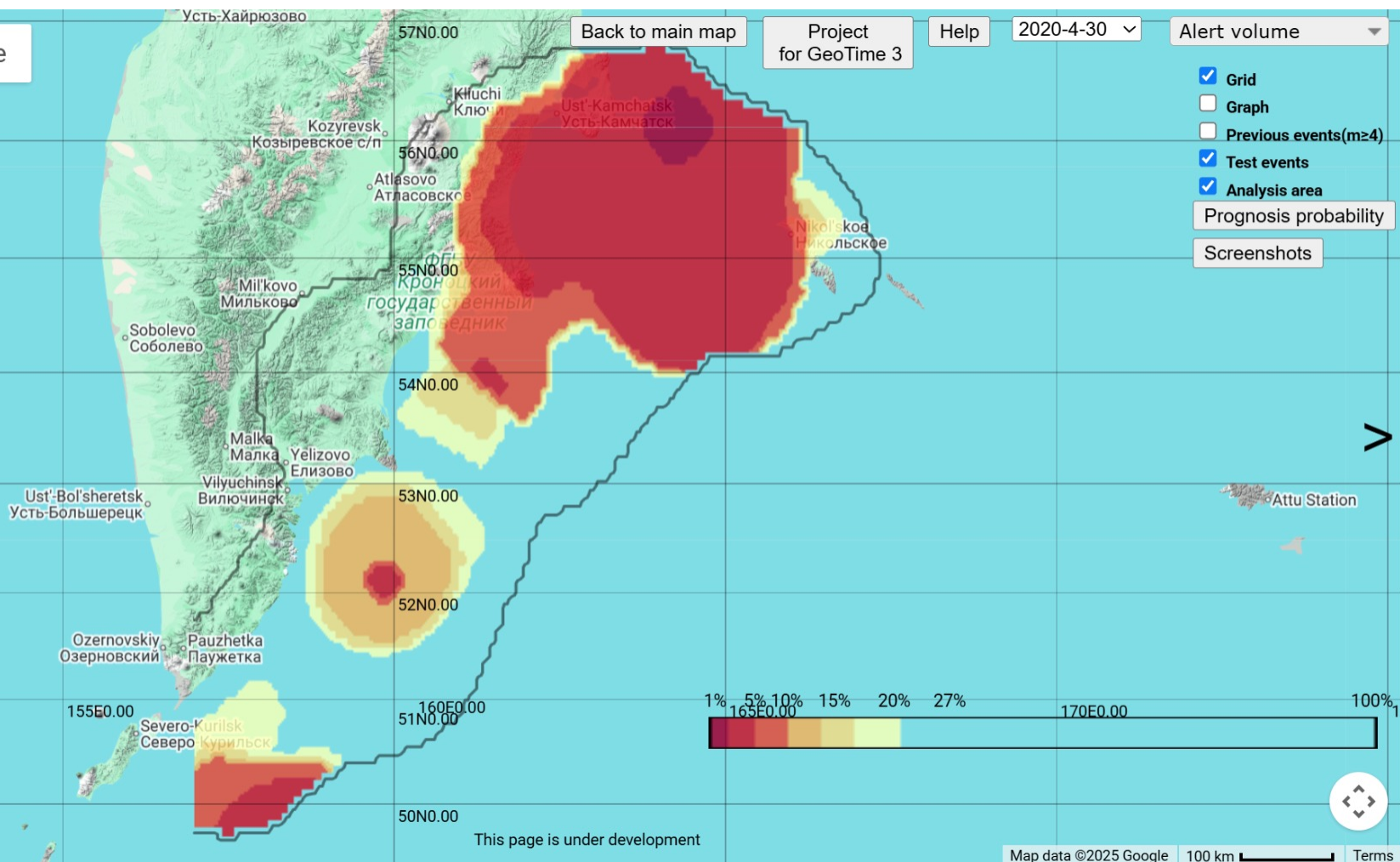
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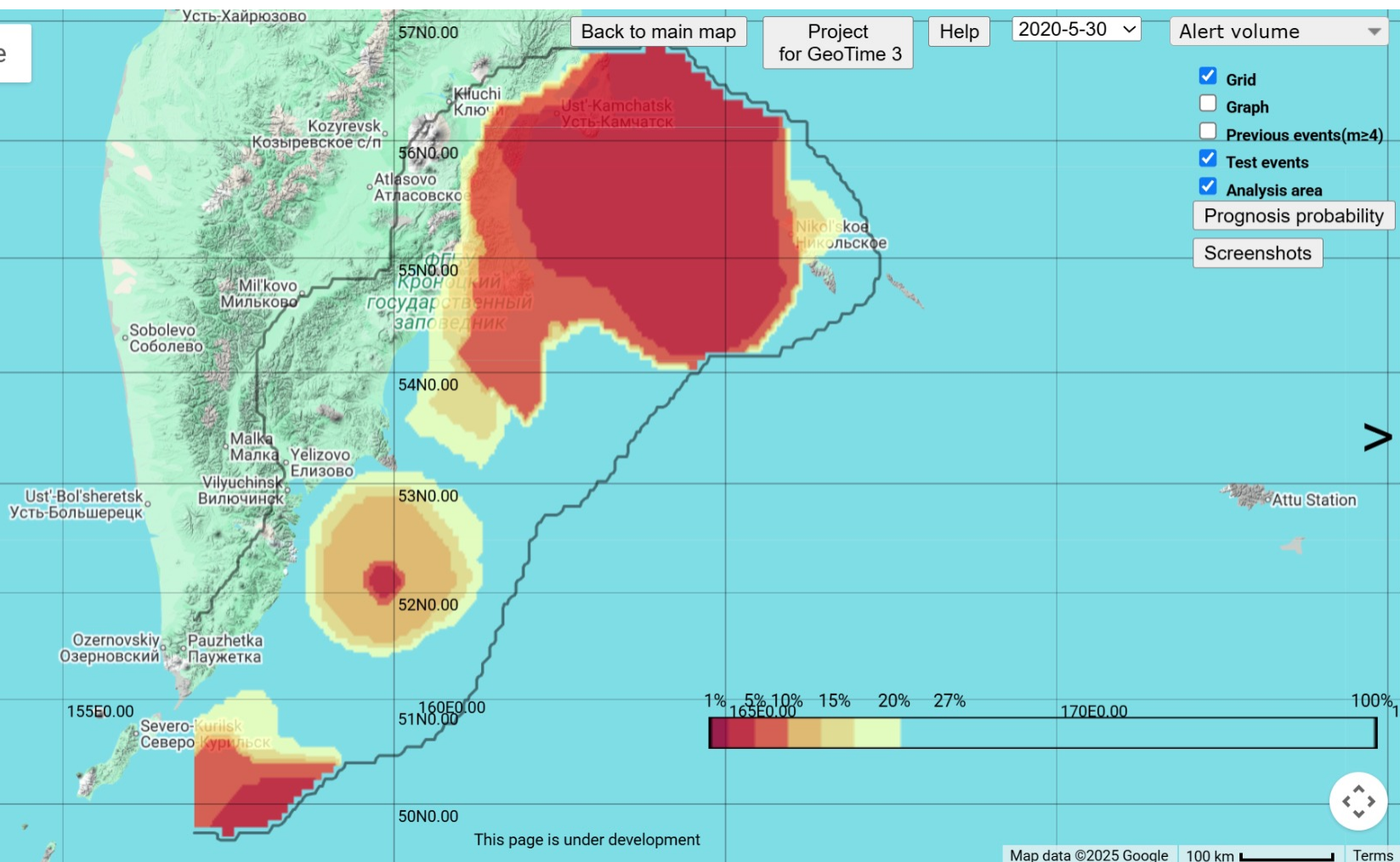
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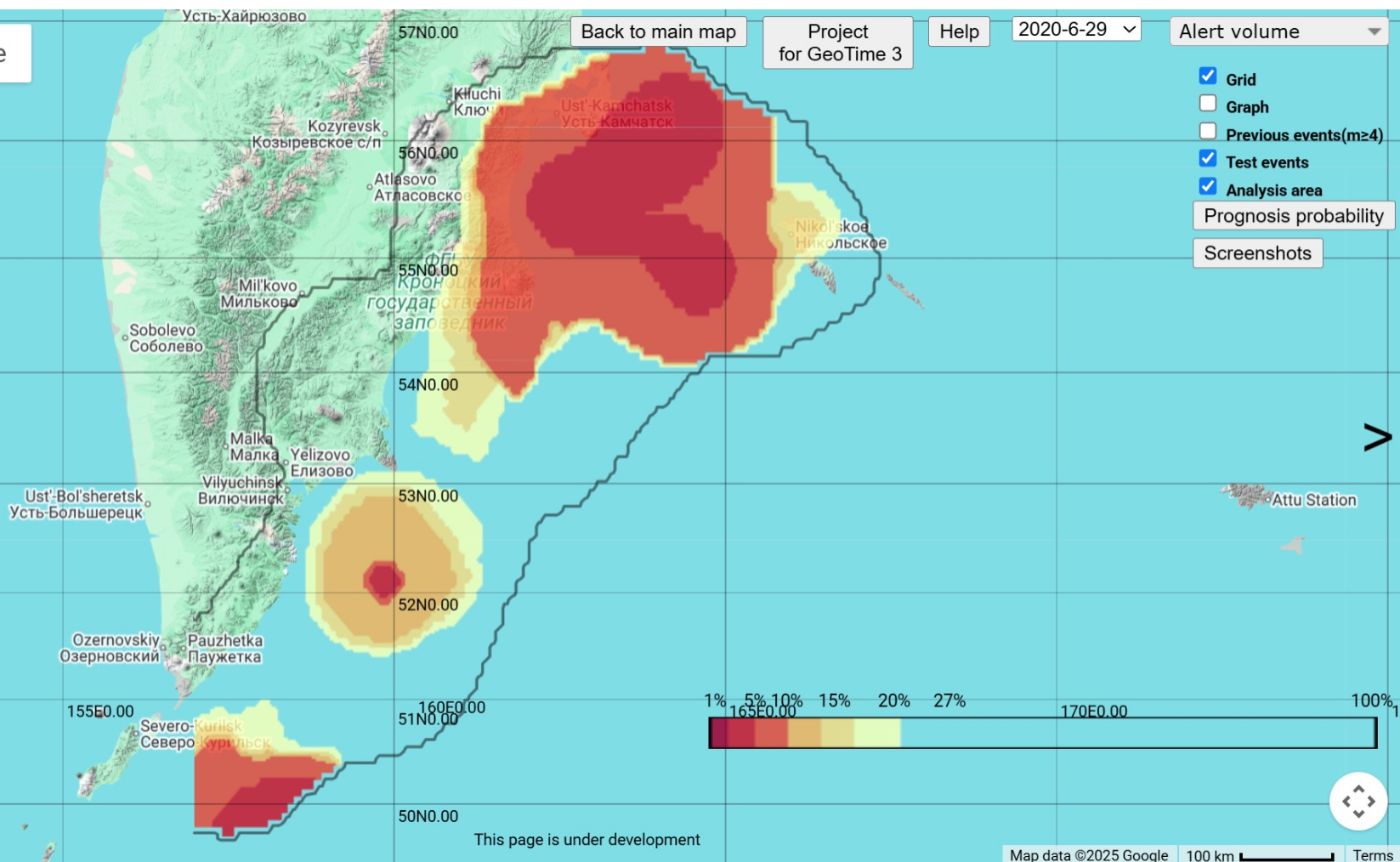
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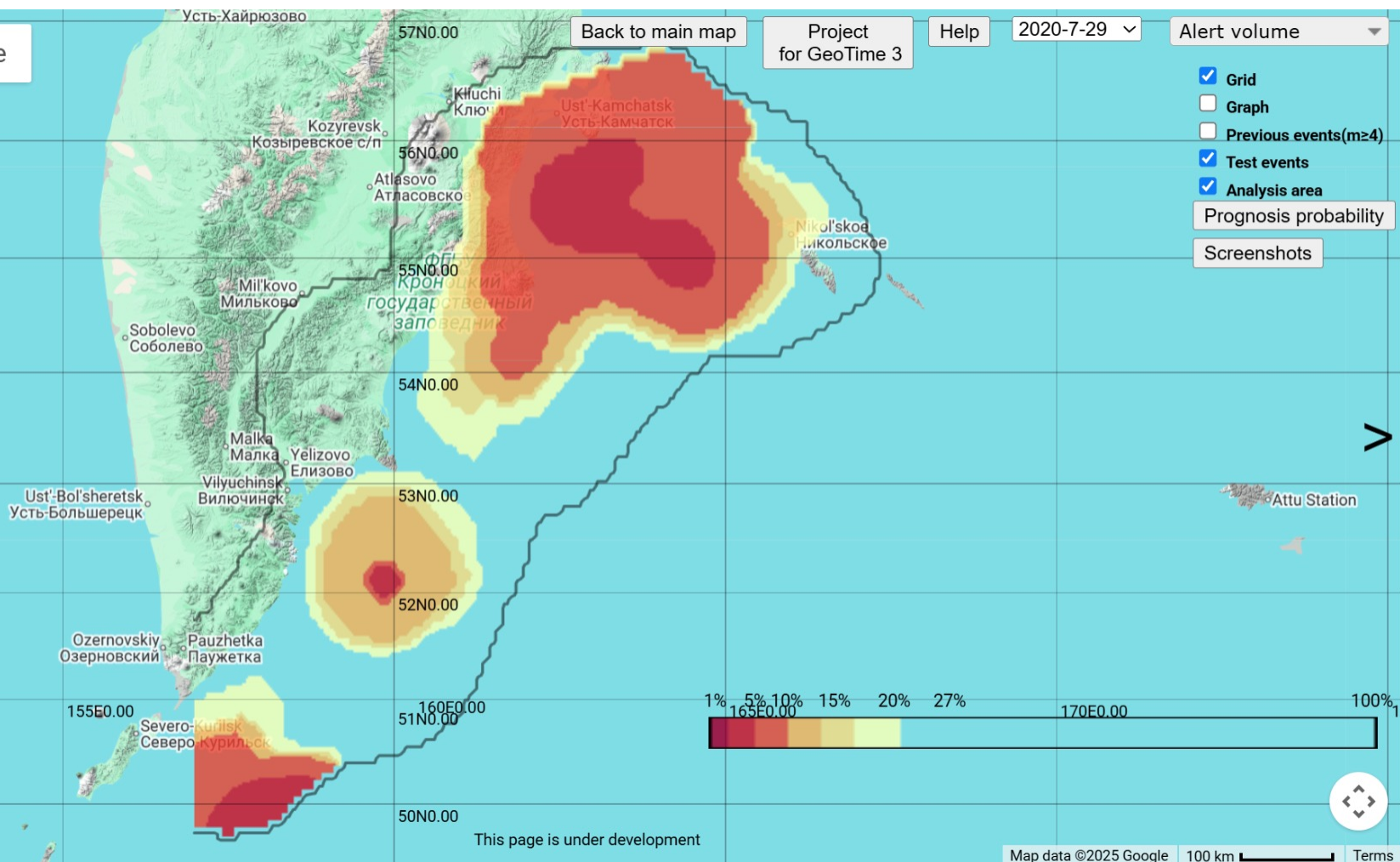
2020-7-29 ▾

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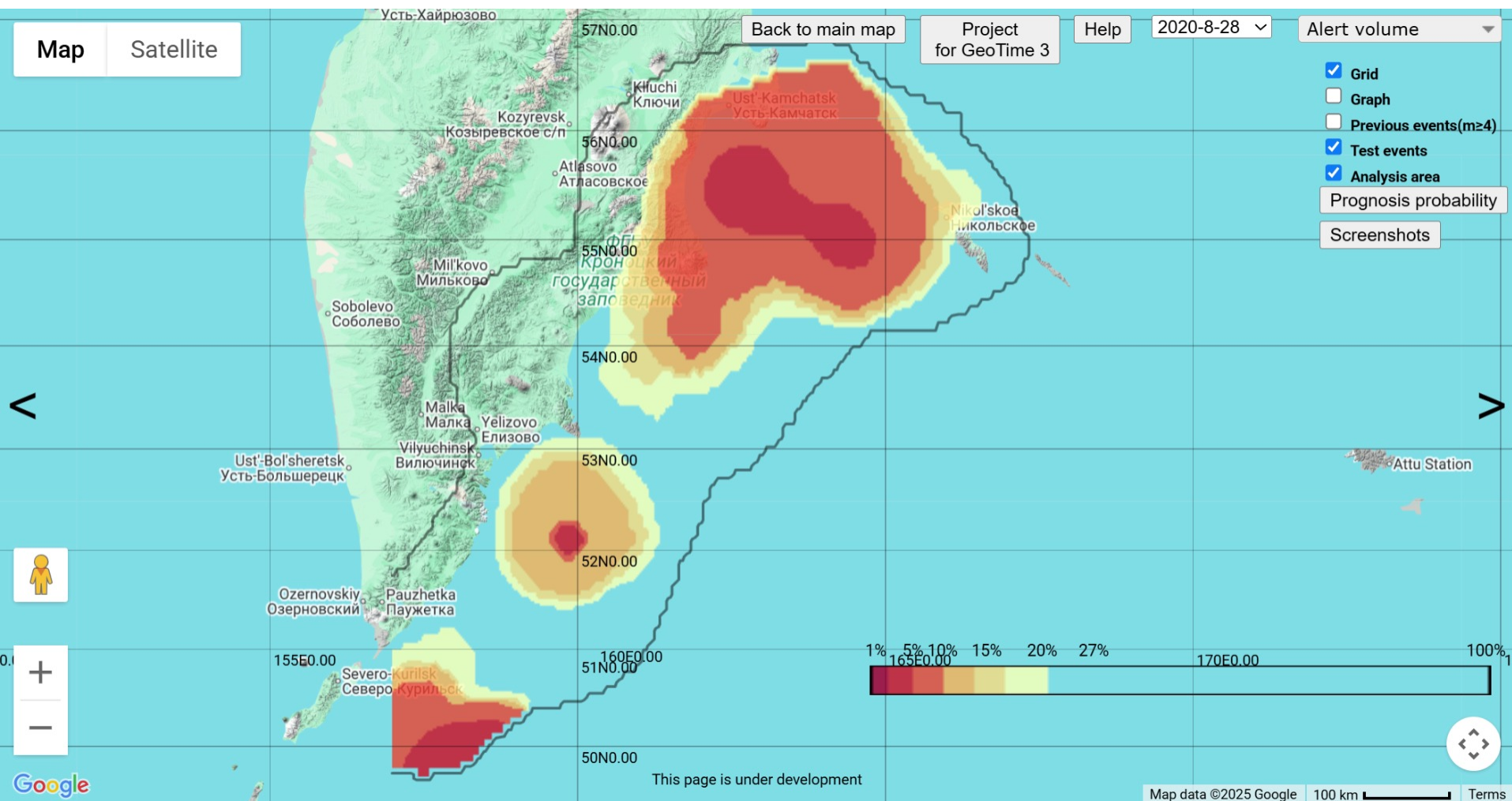
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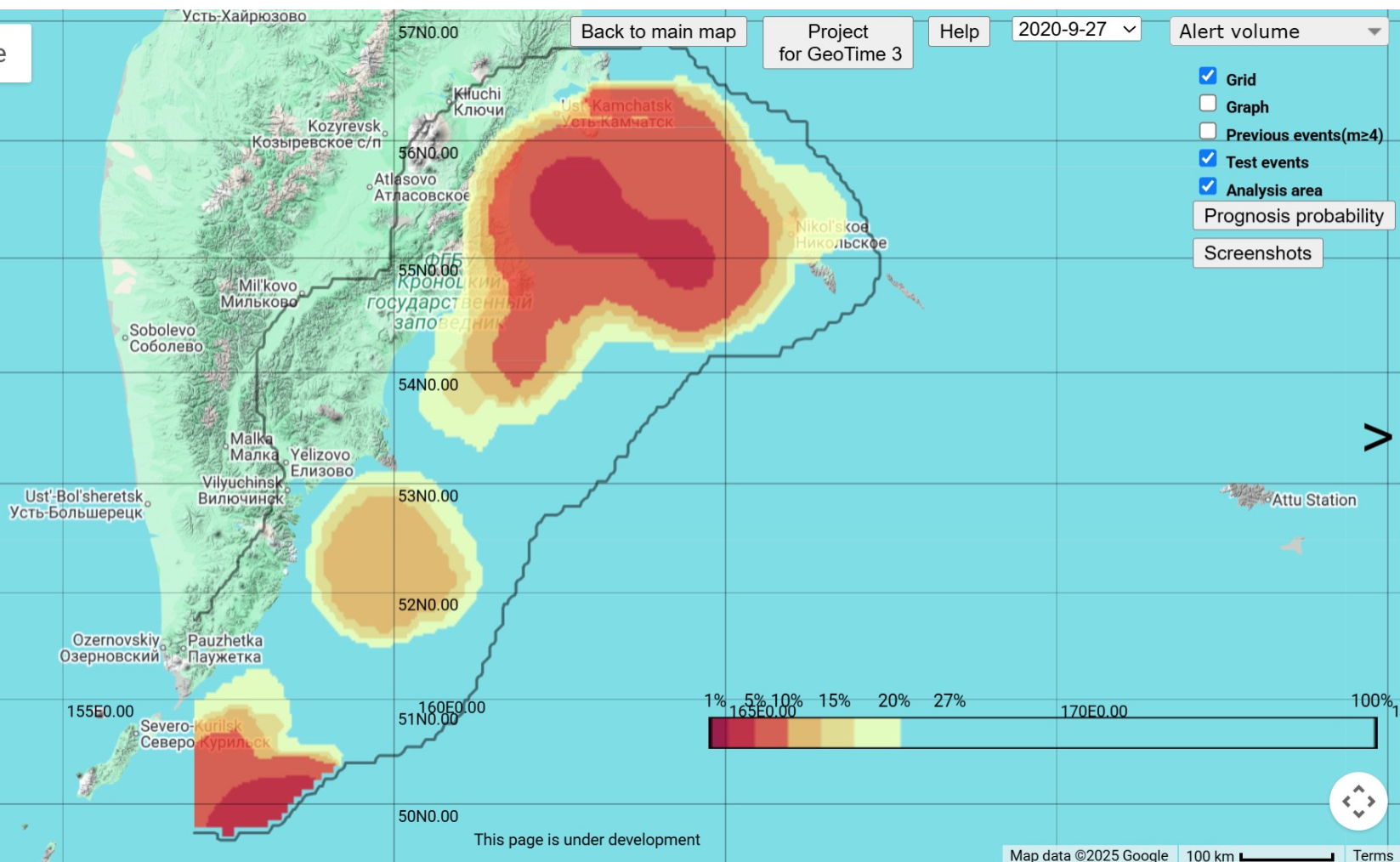
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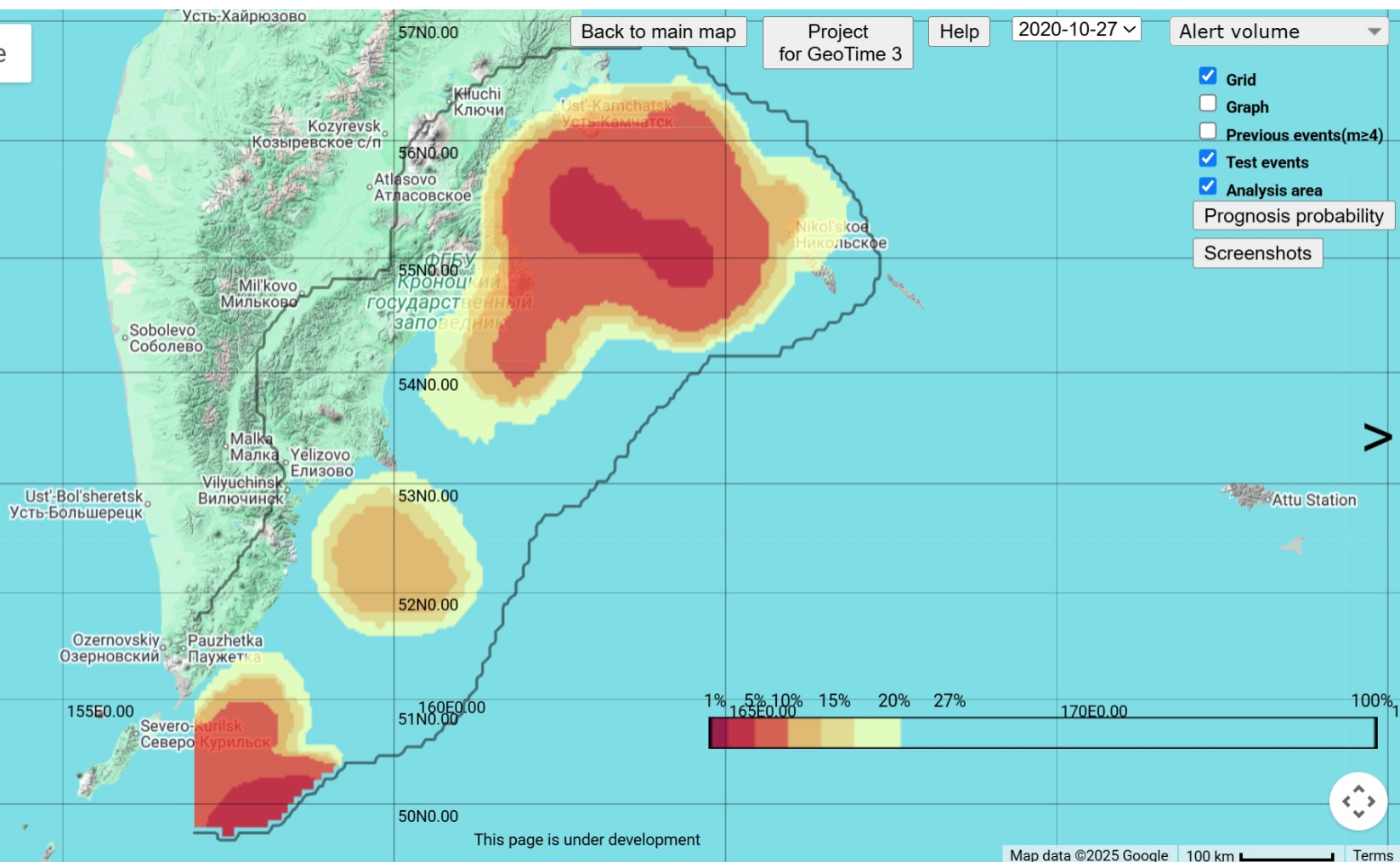
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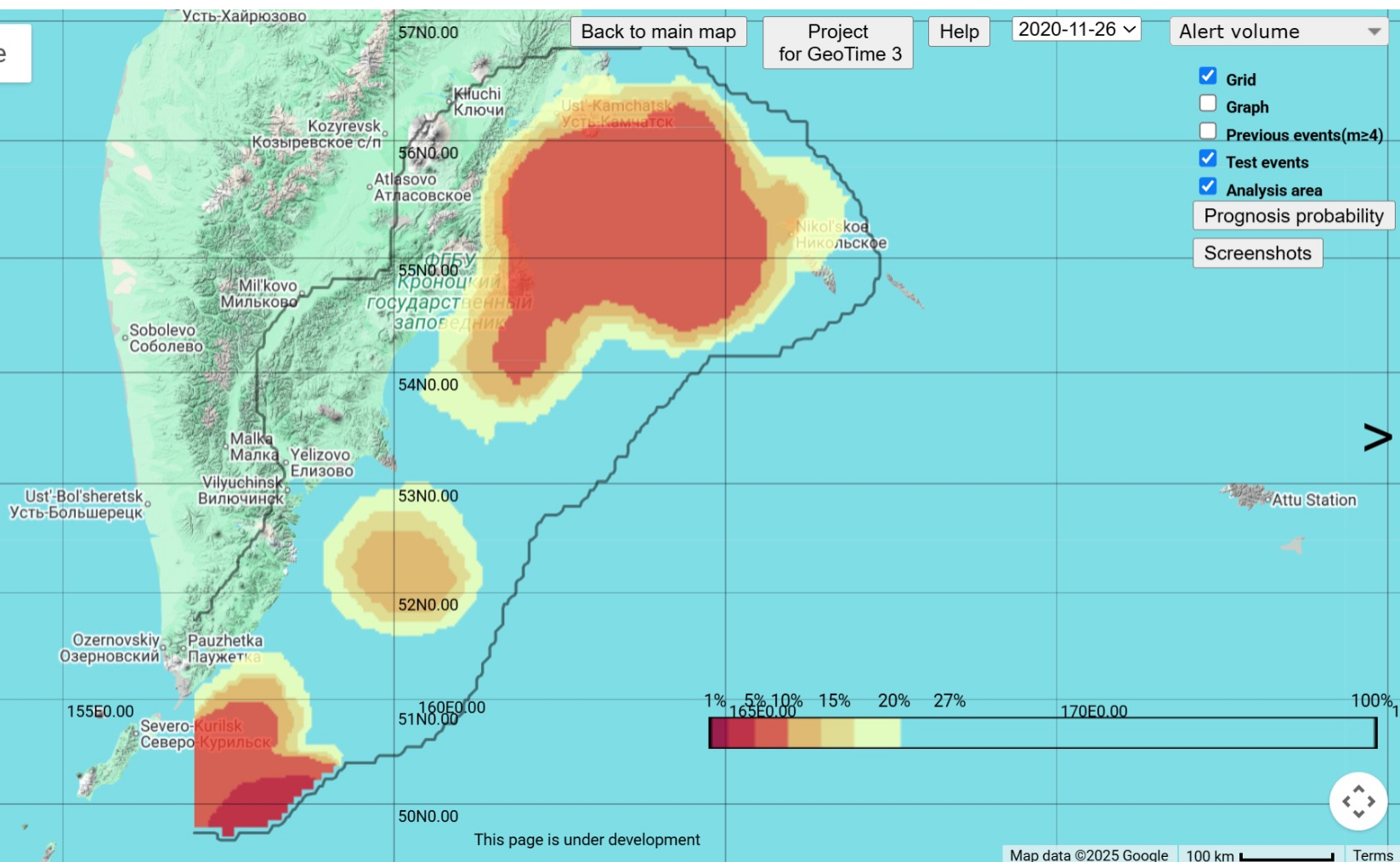
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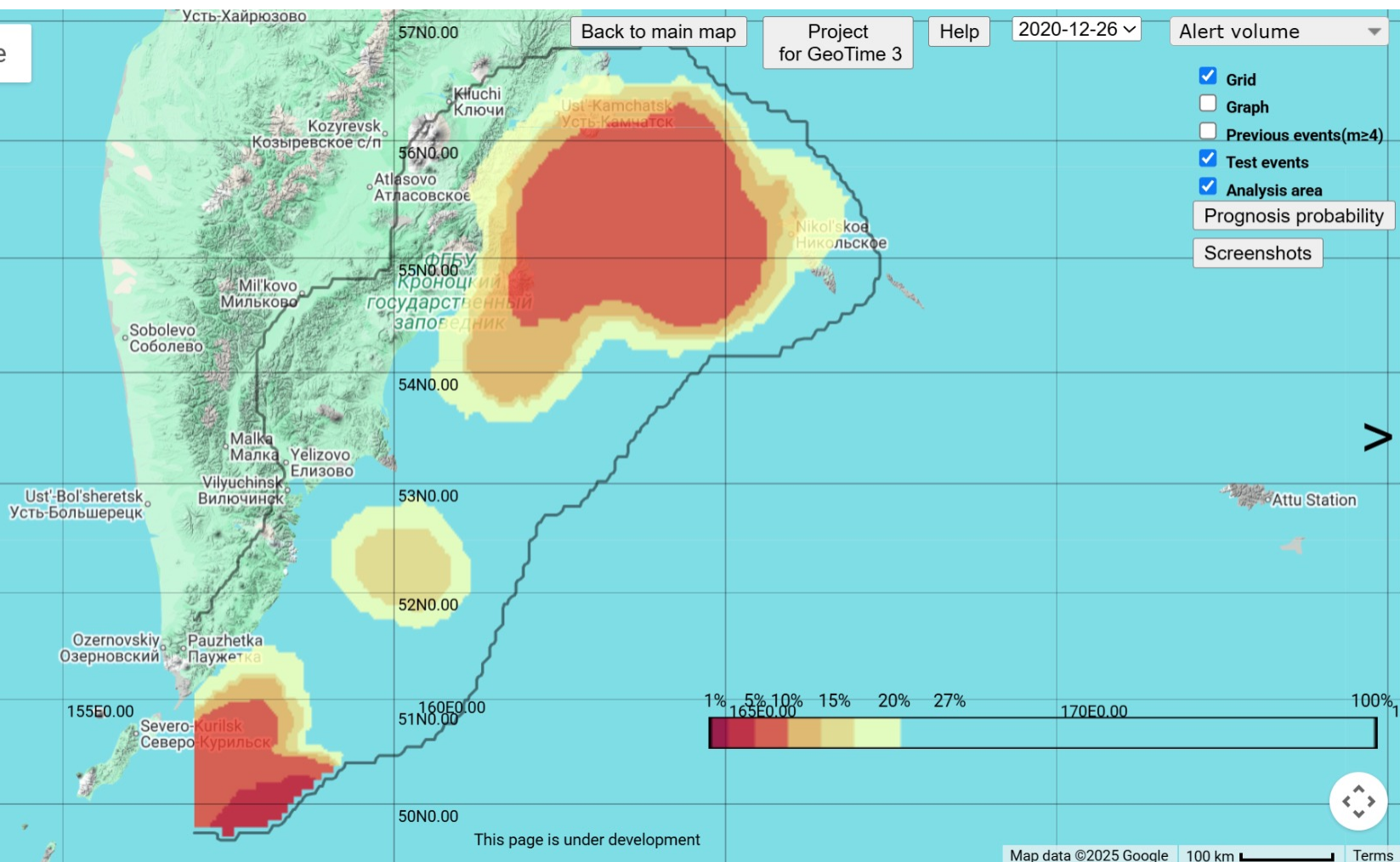
2020-12-26 ▾

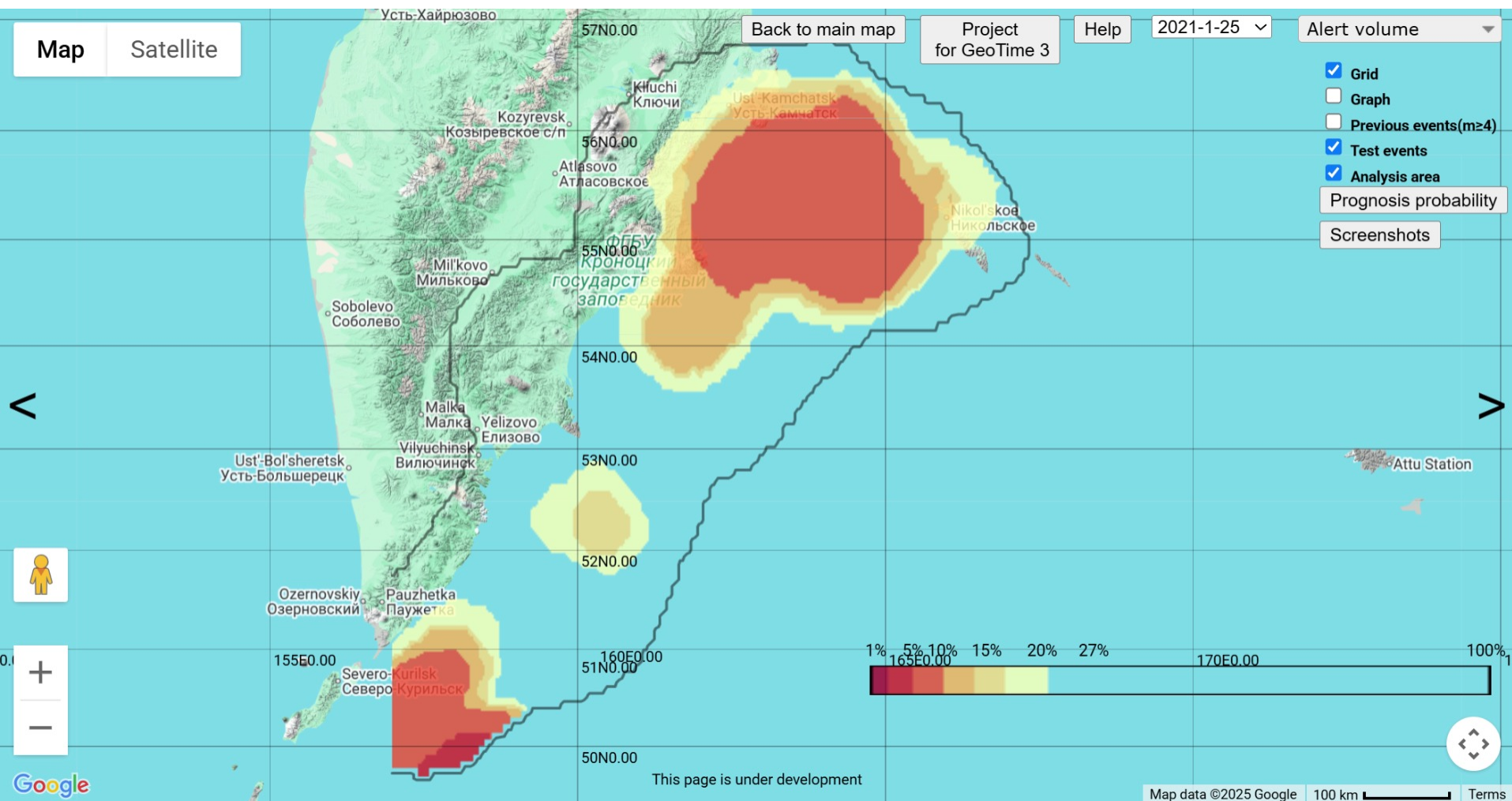
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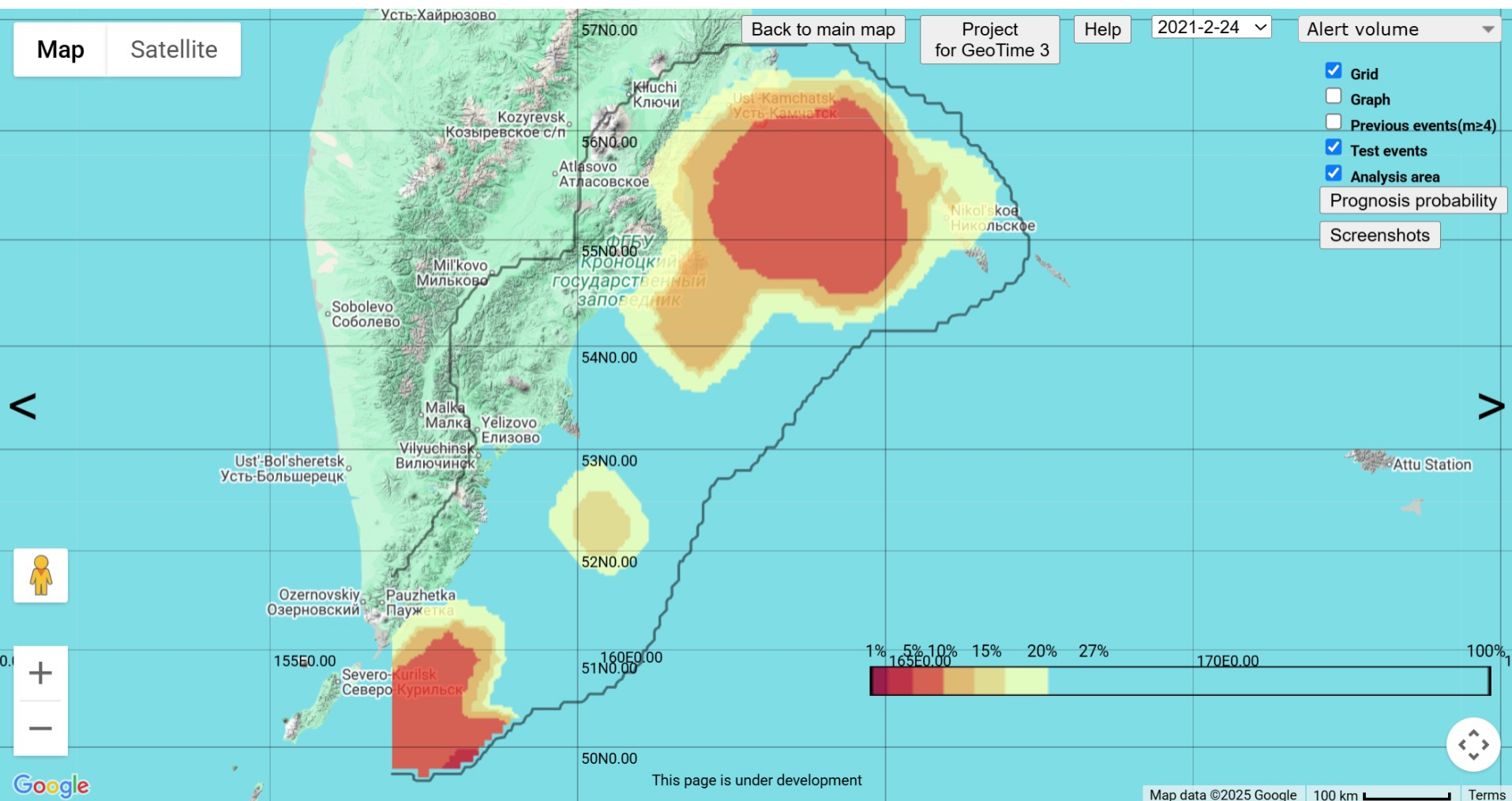
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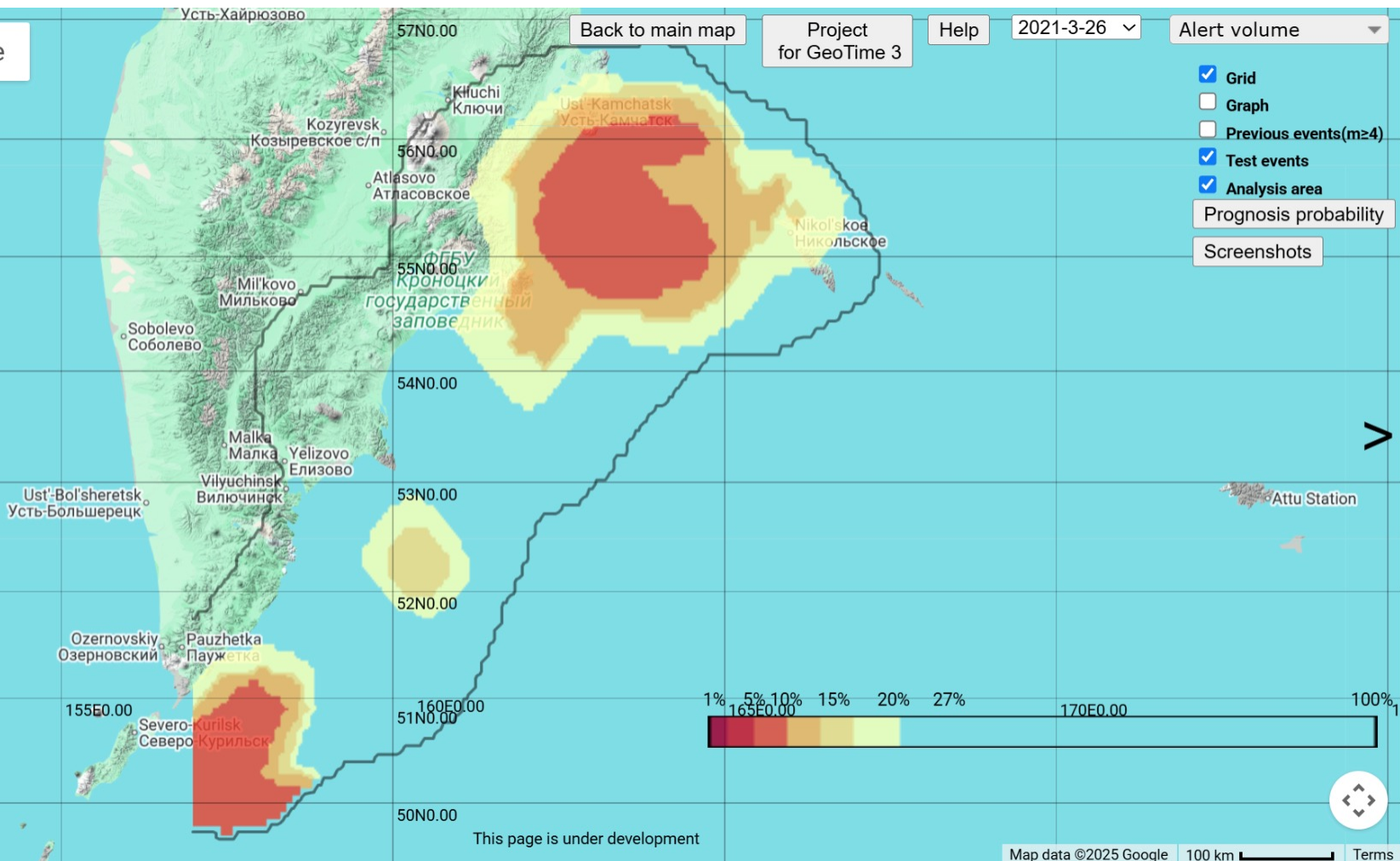
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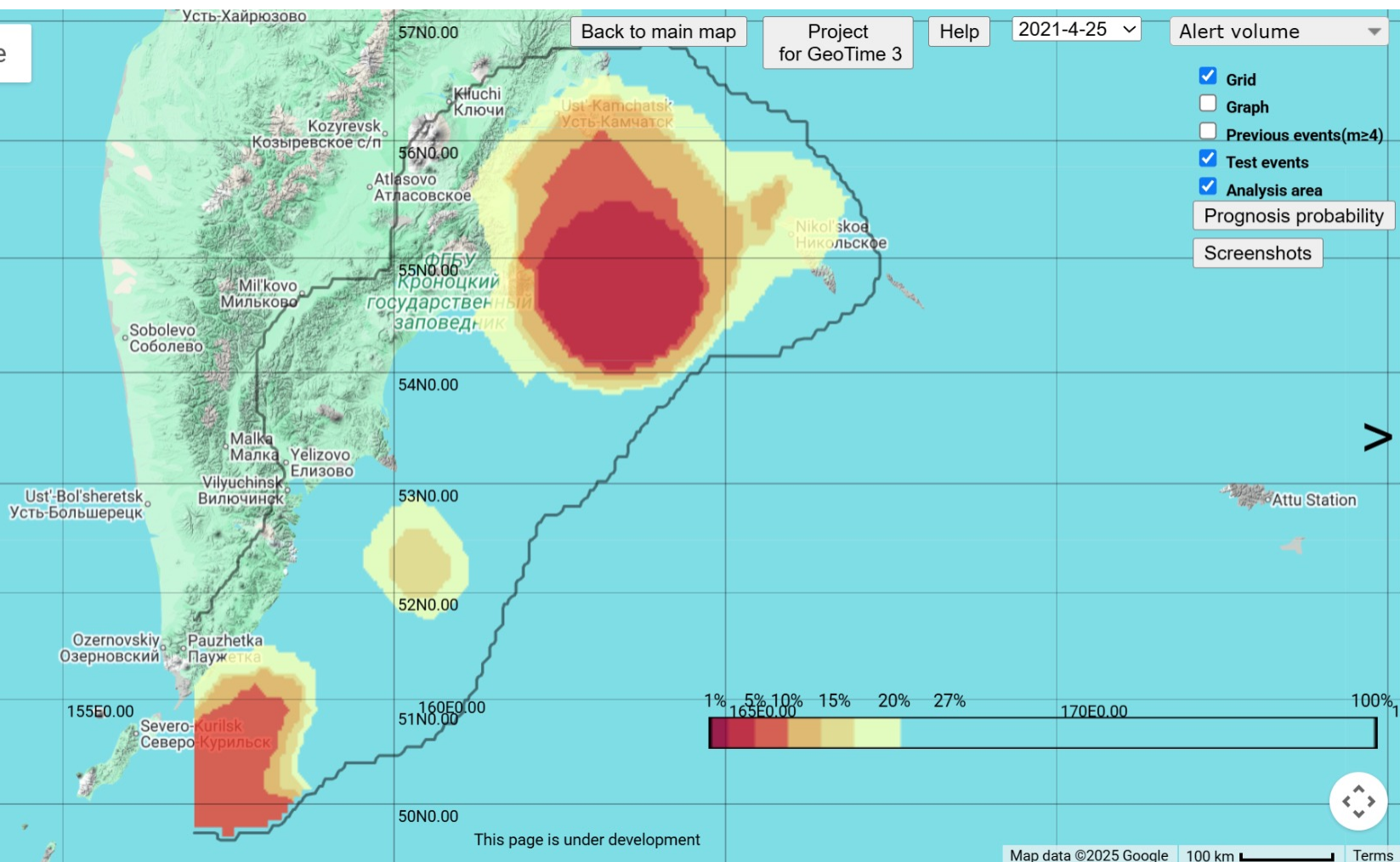
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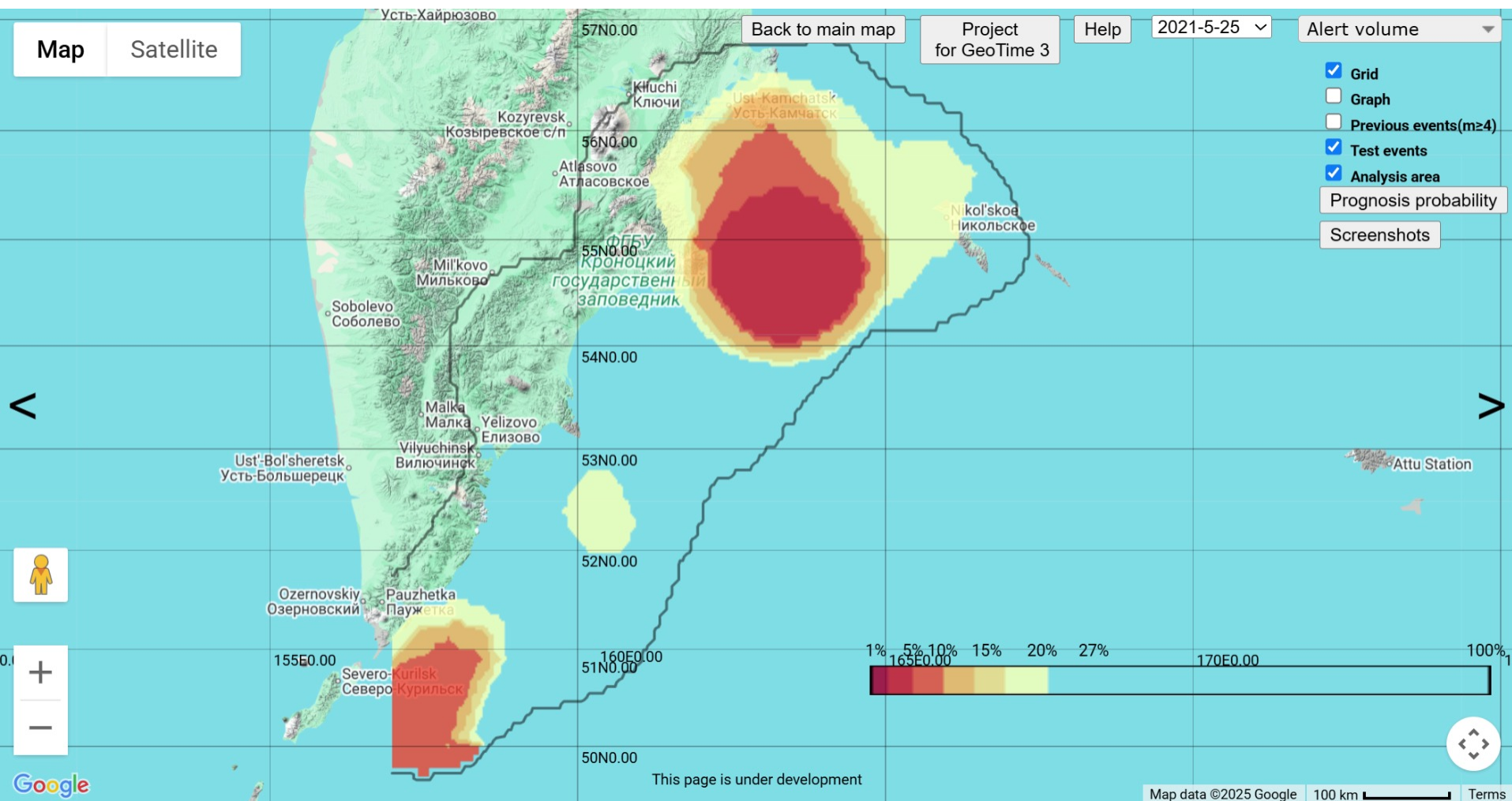
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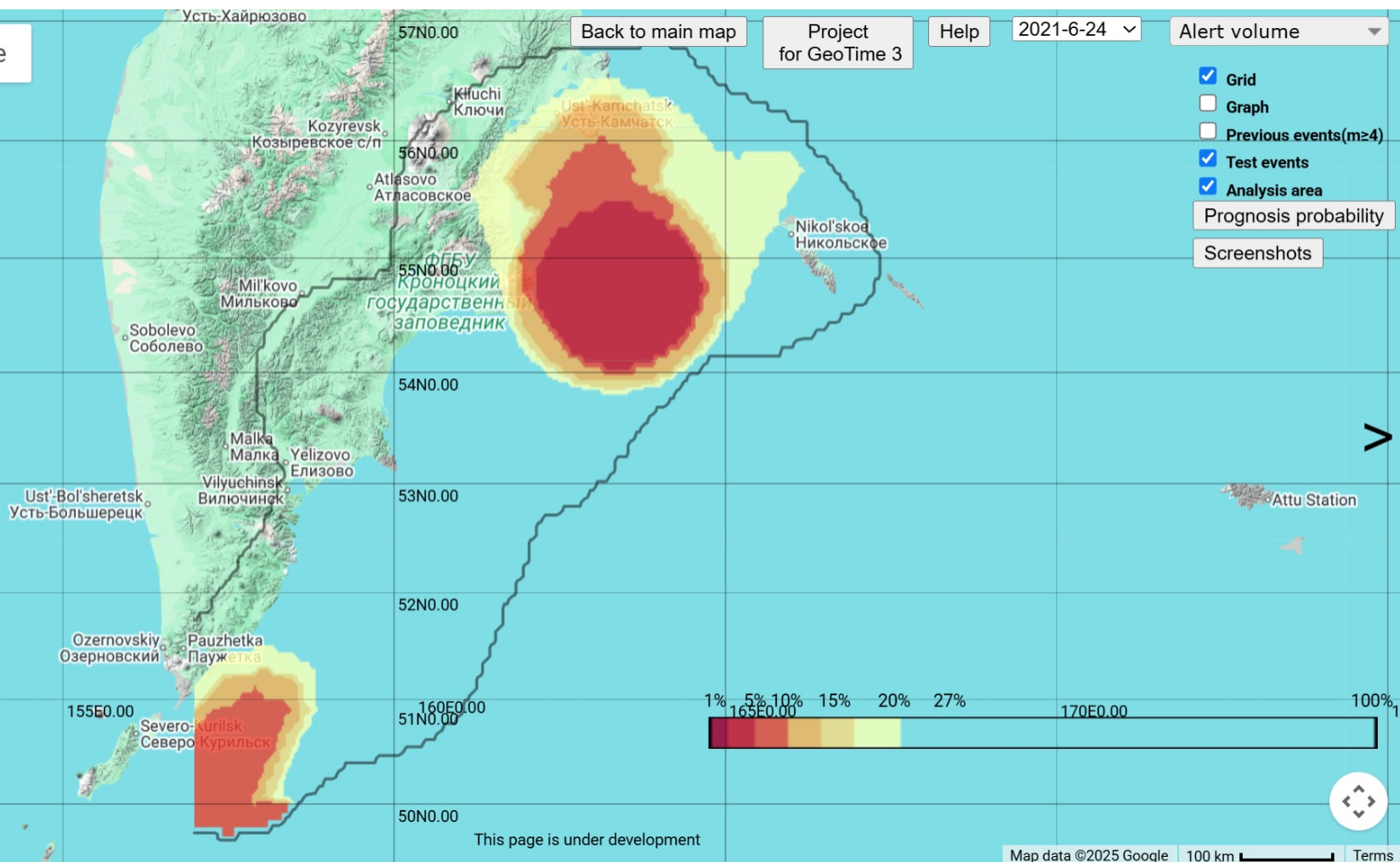
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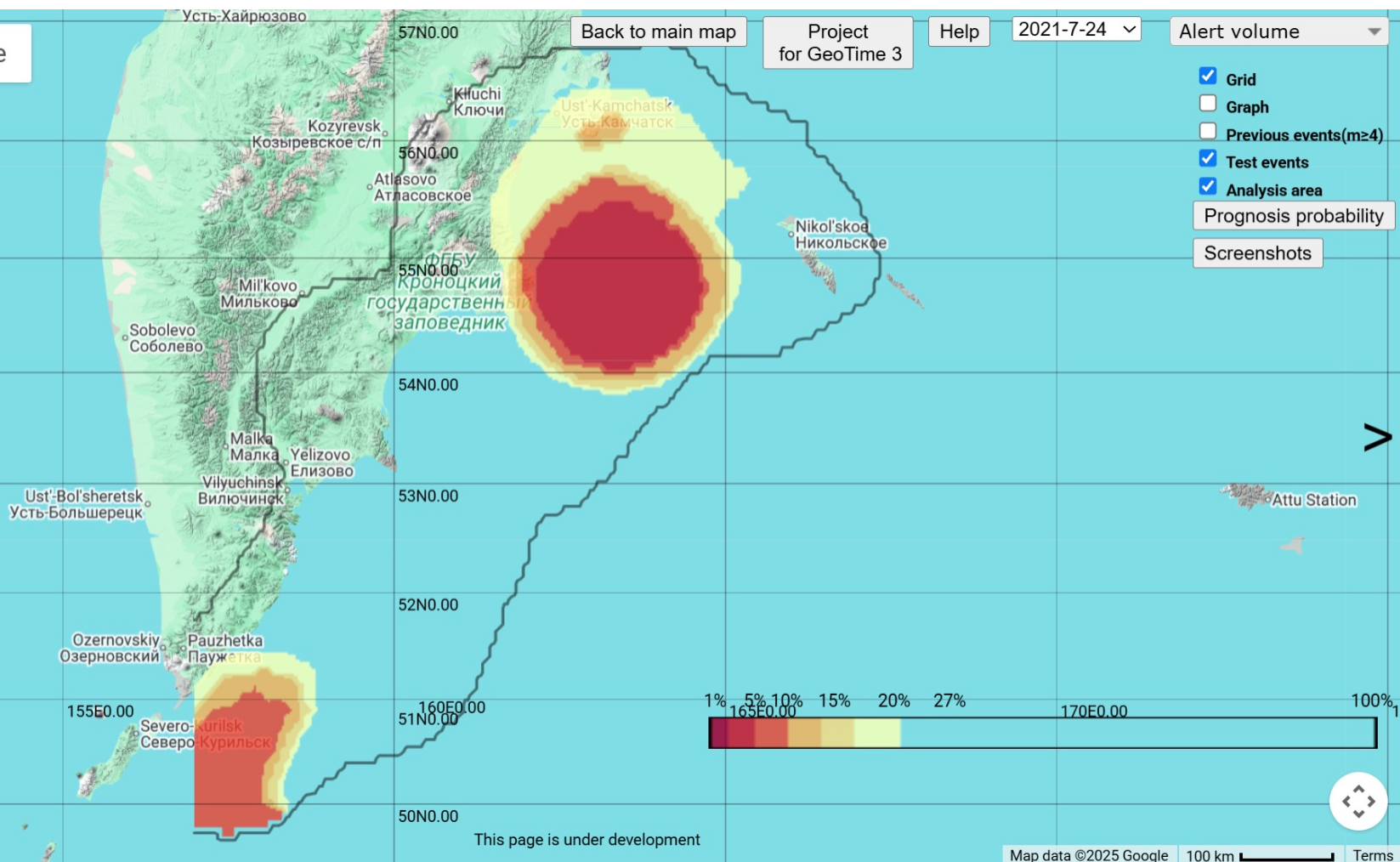
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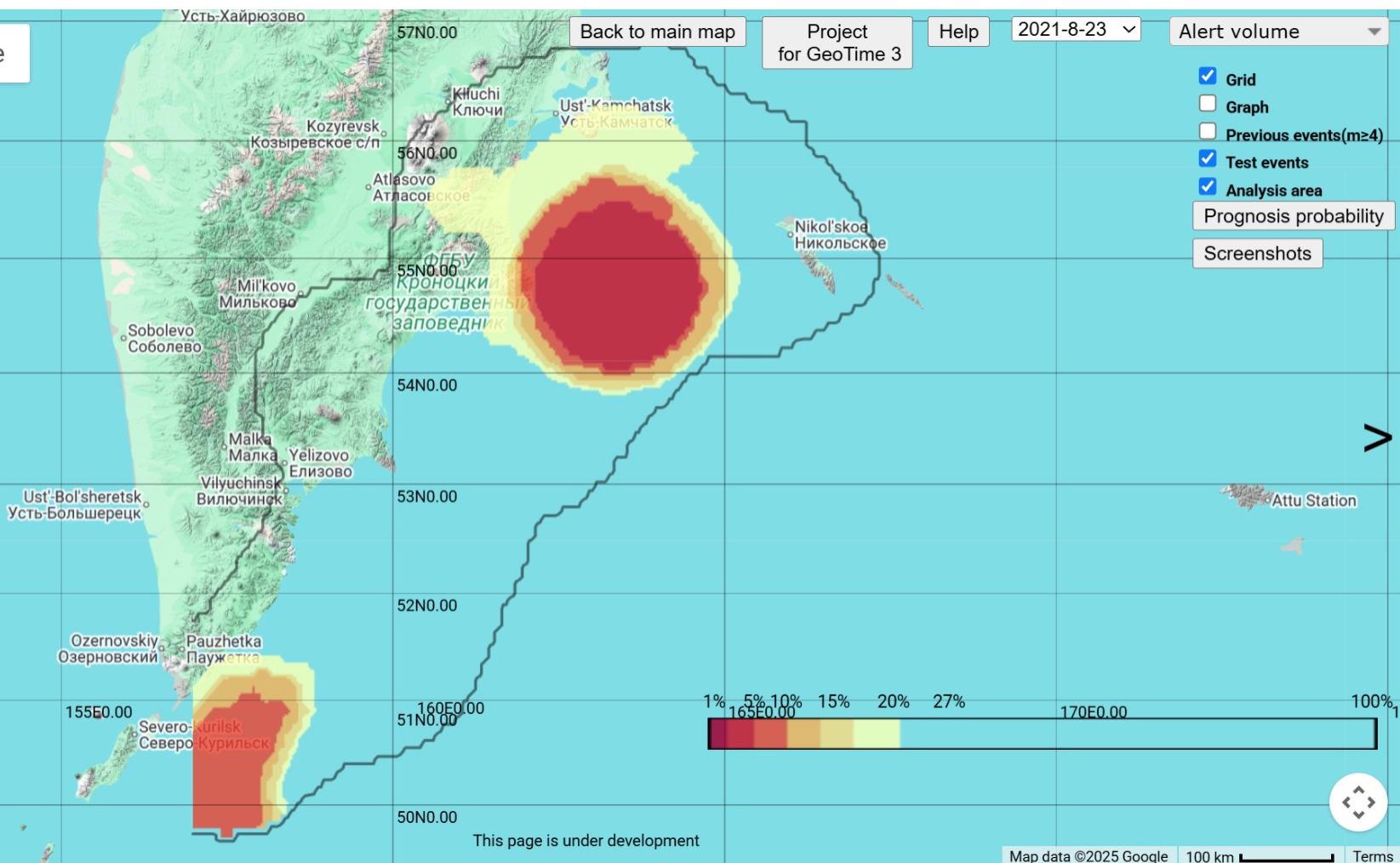
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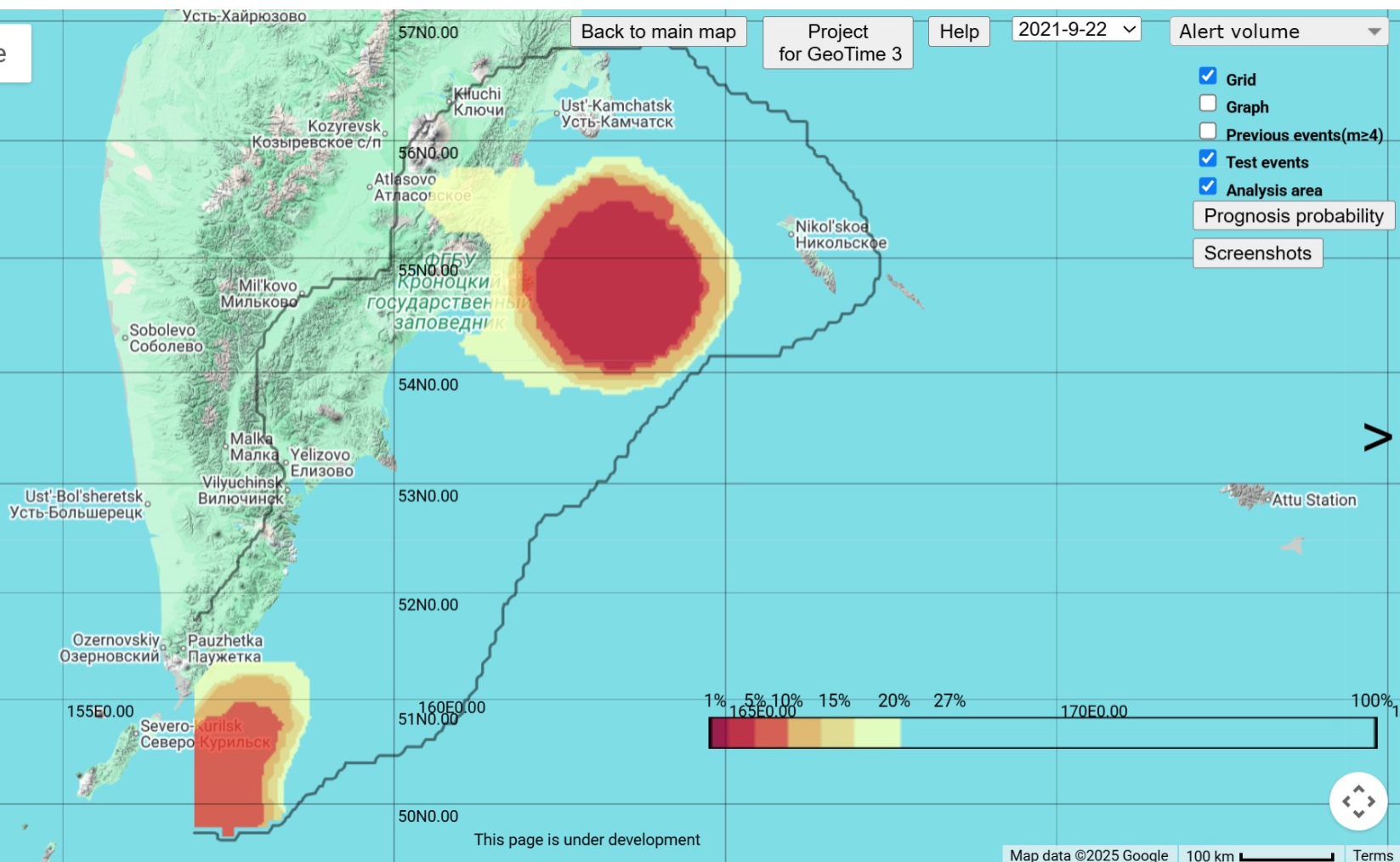
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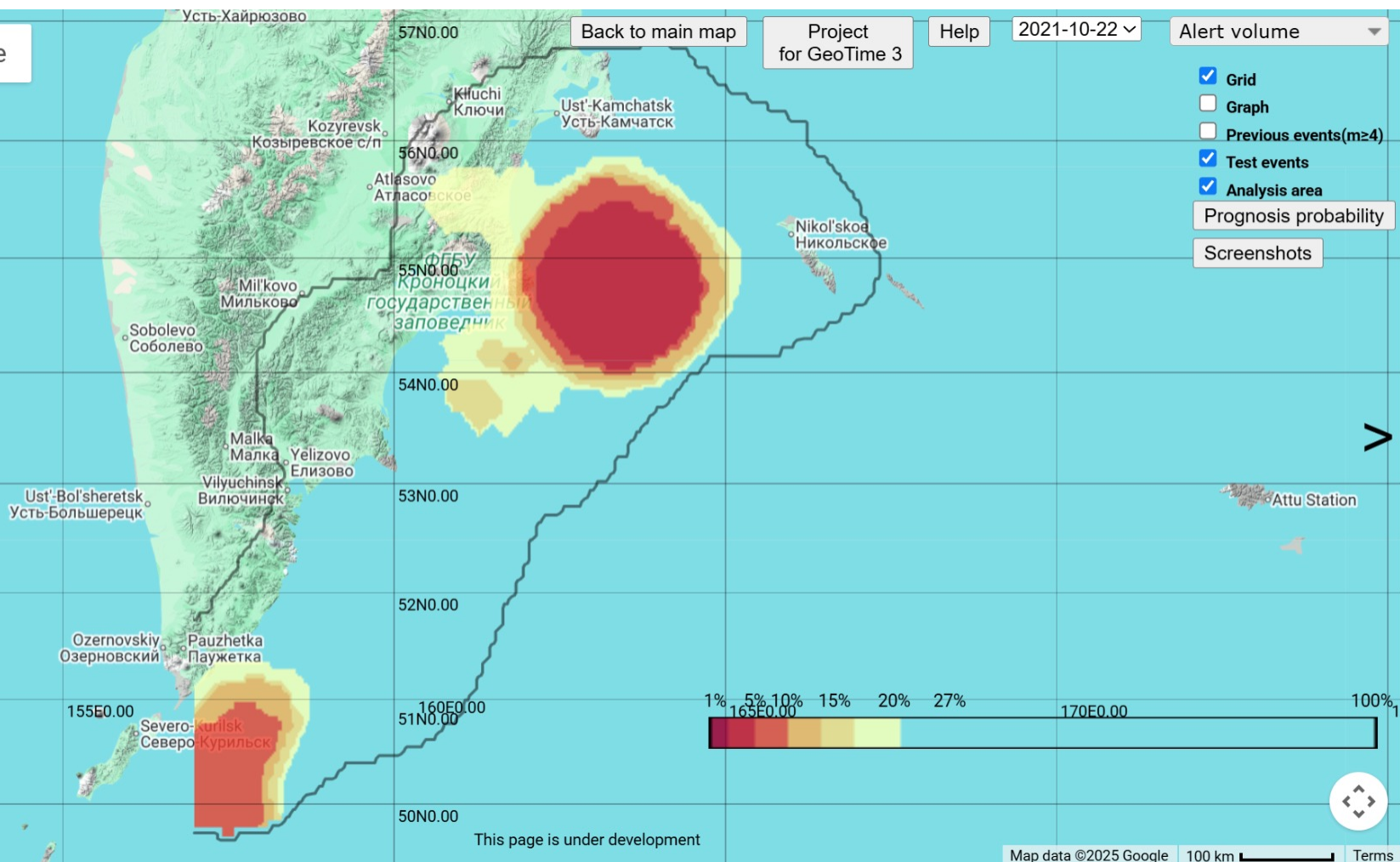
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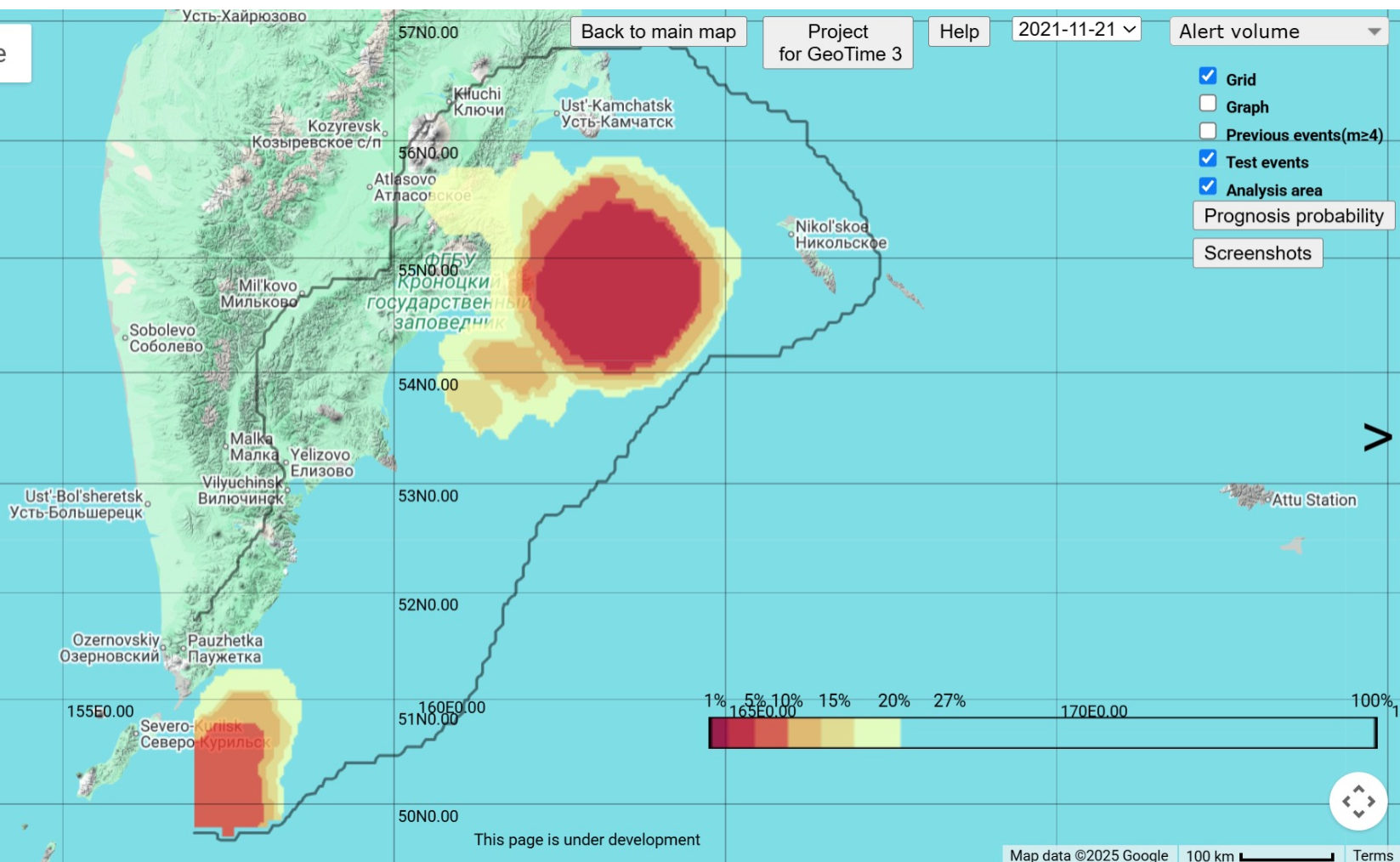
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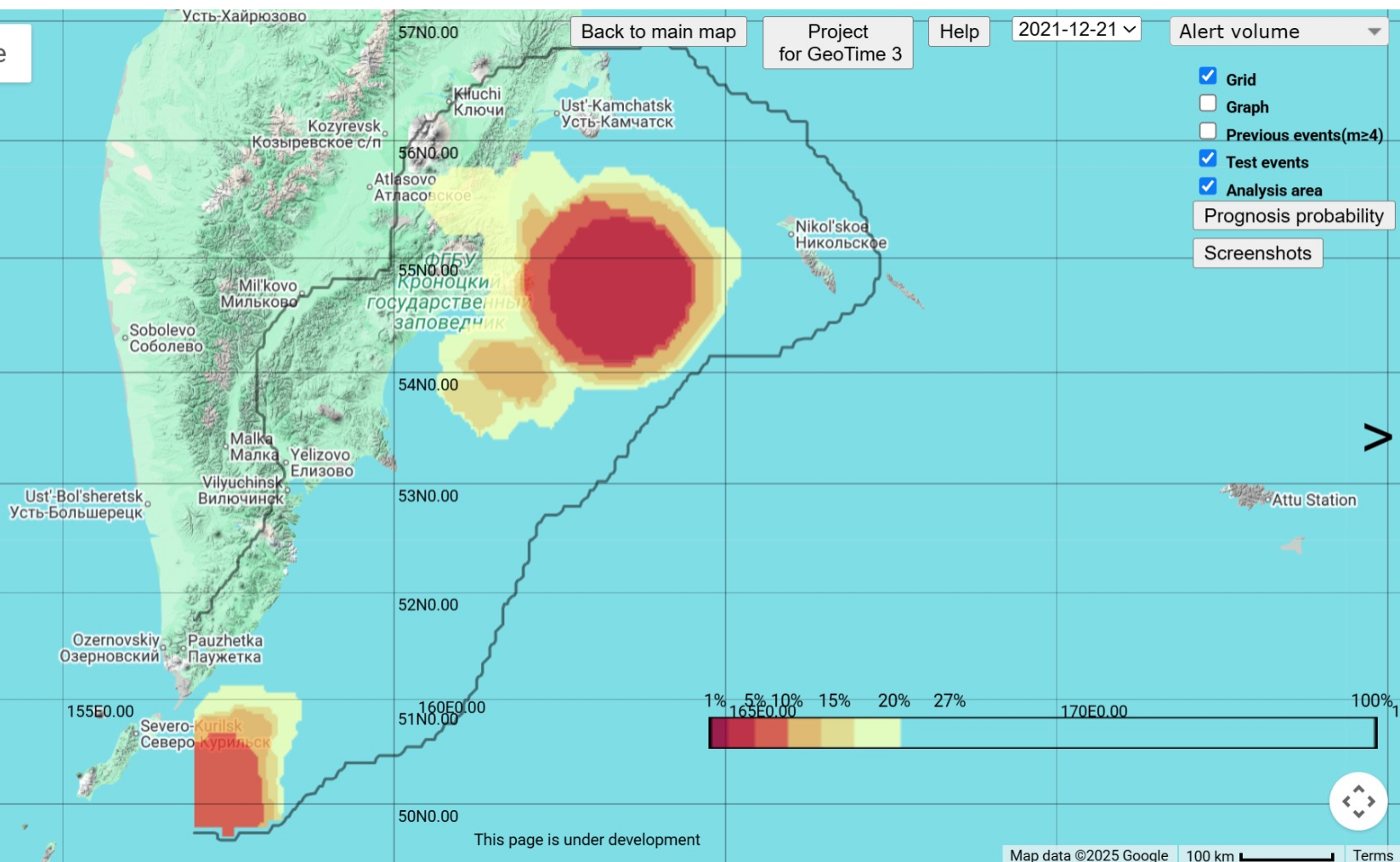
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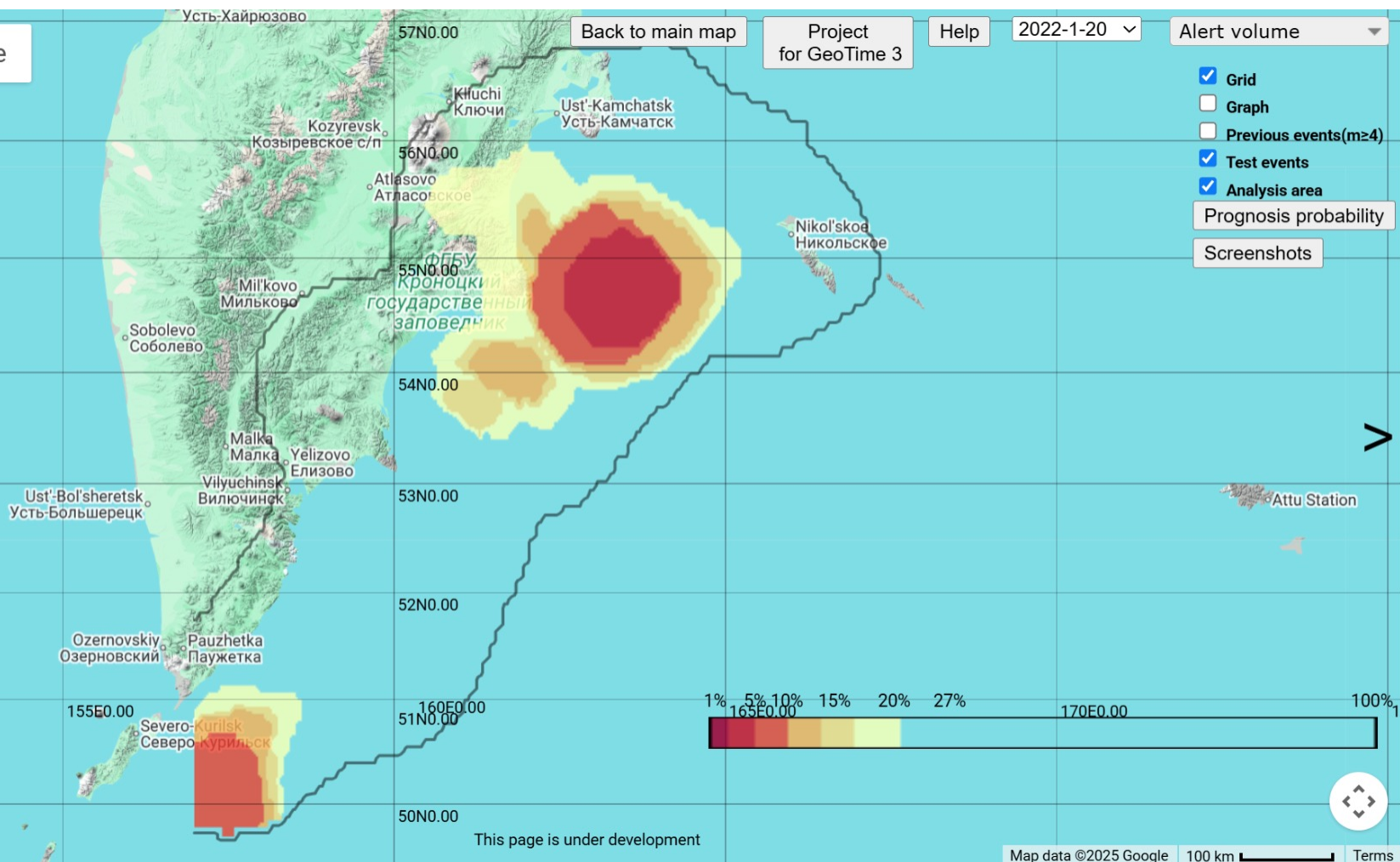
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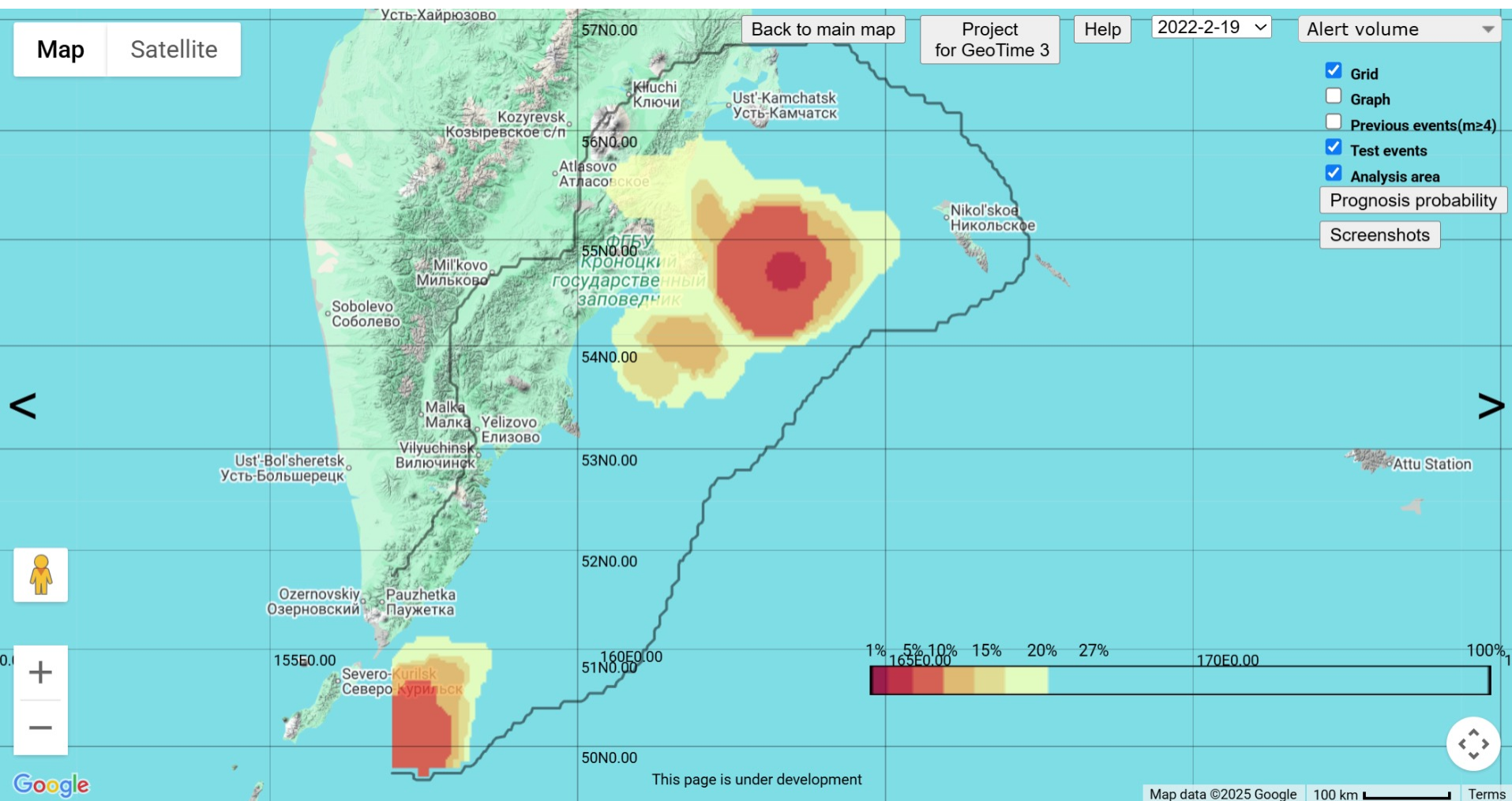
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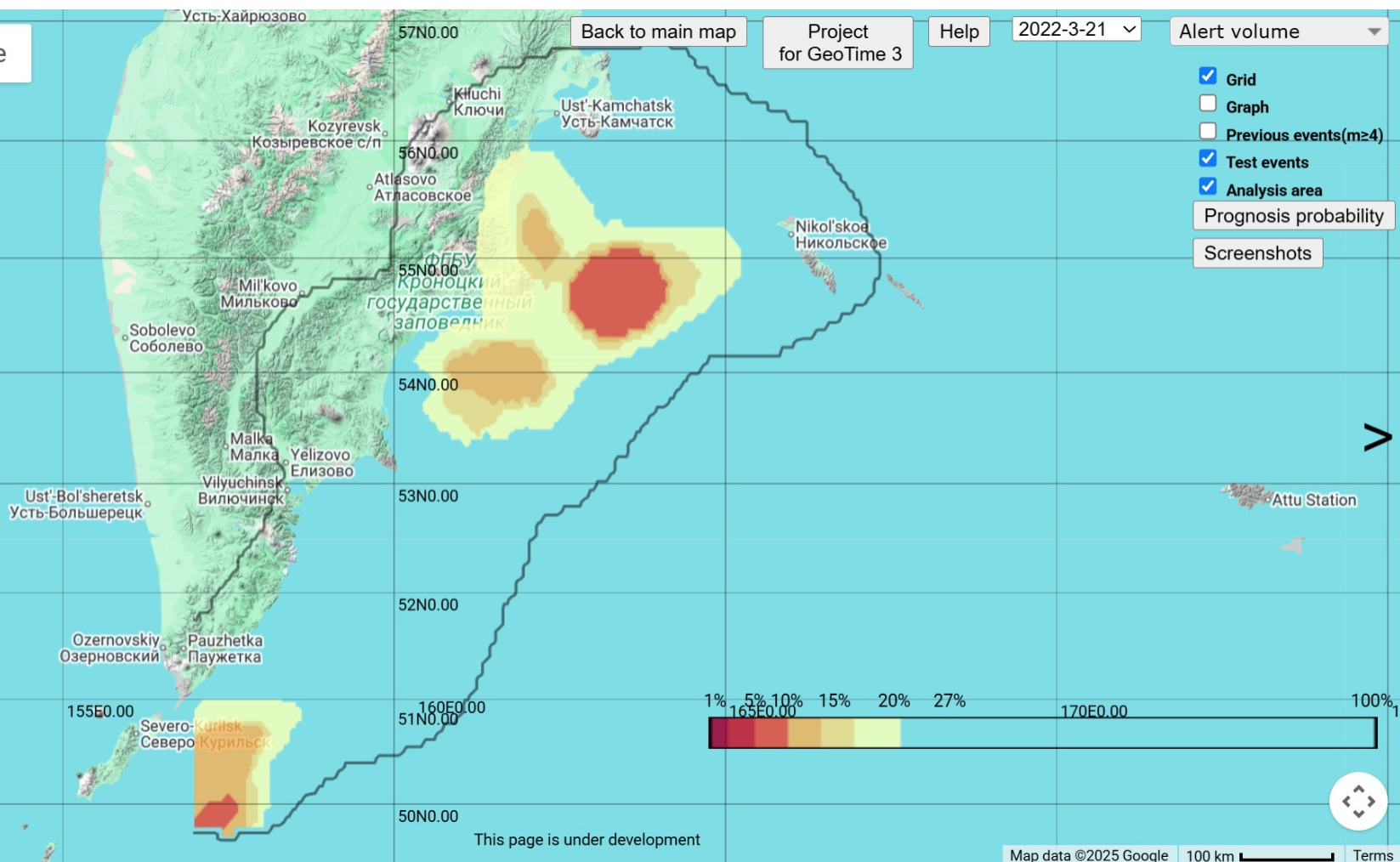
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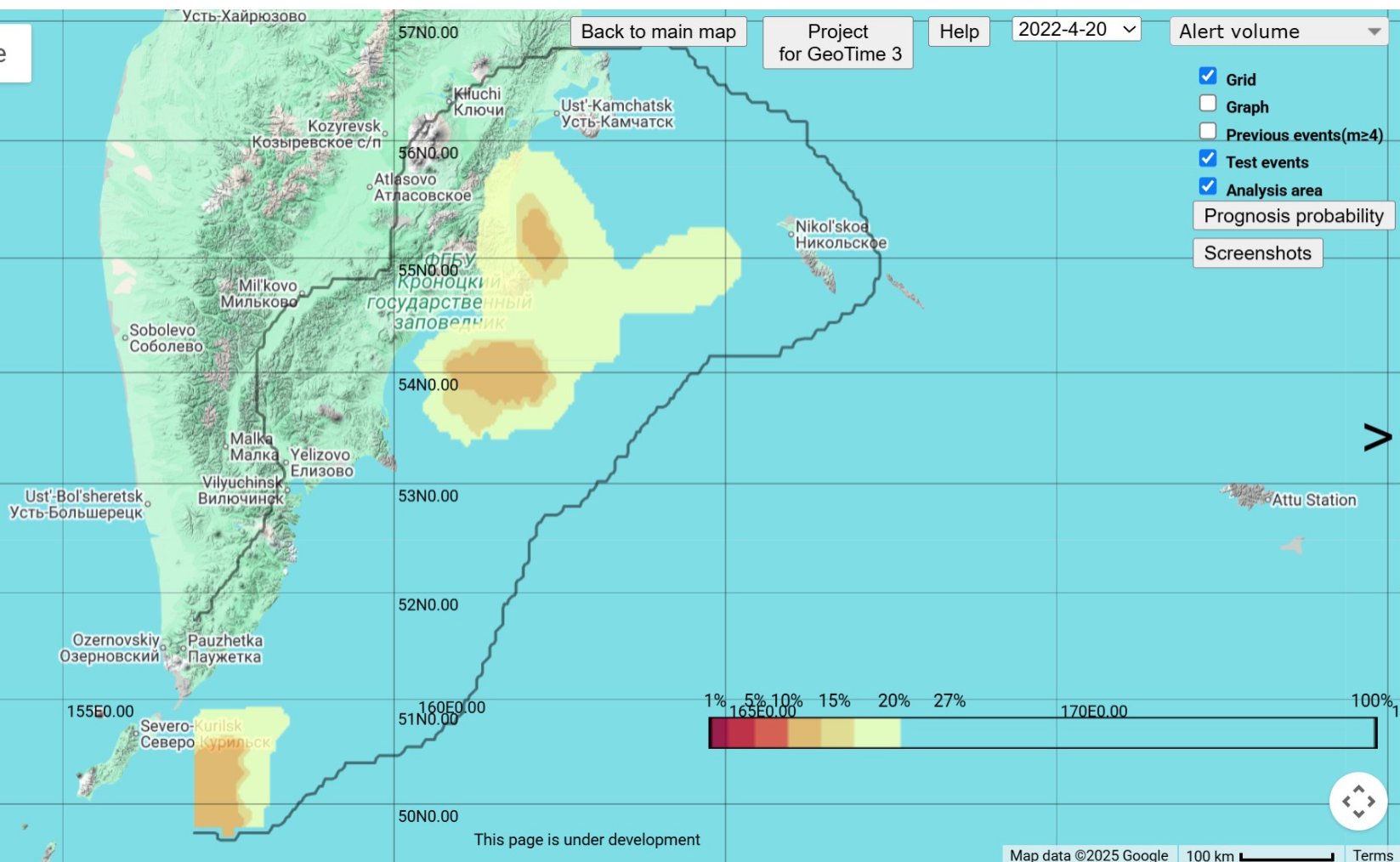
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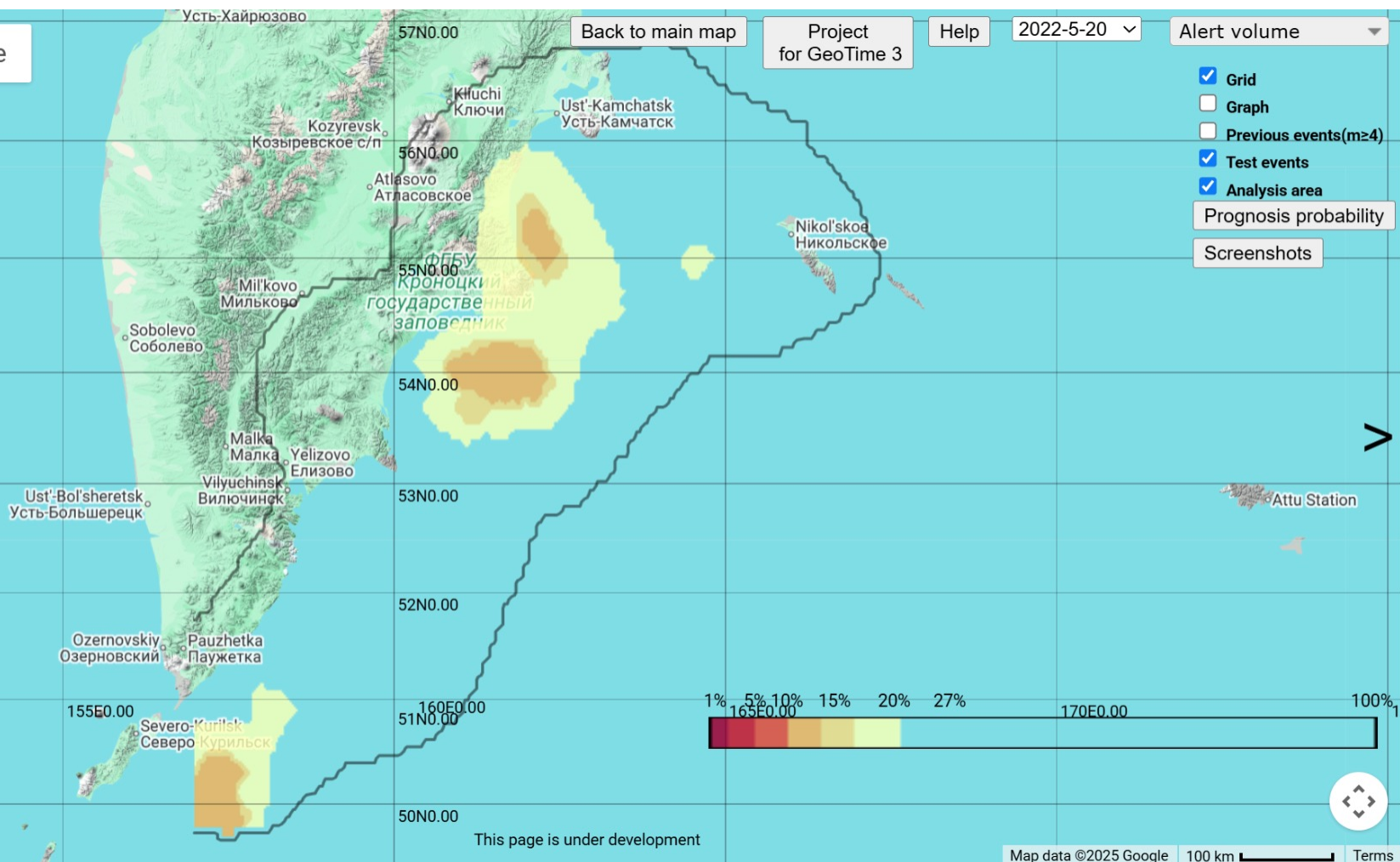
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100 km h⁻¹

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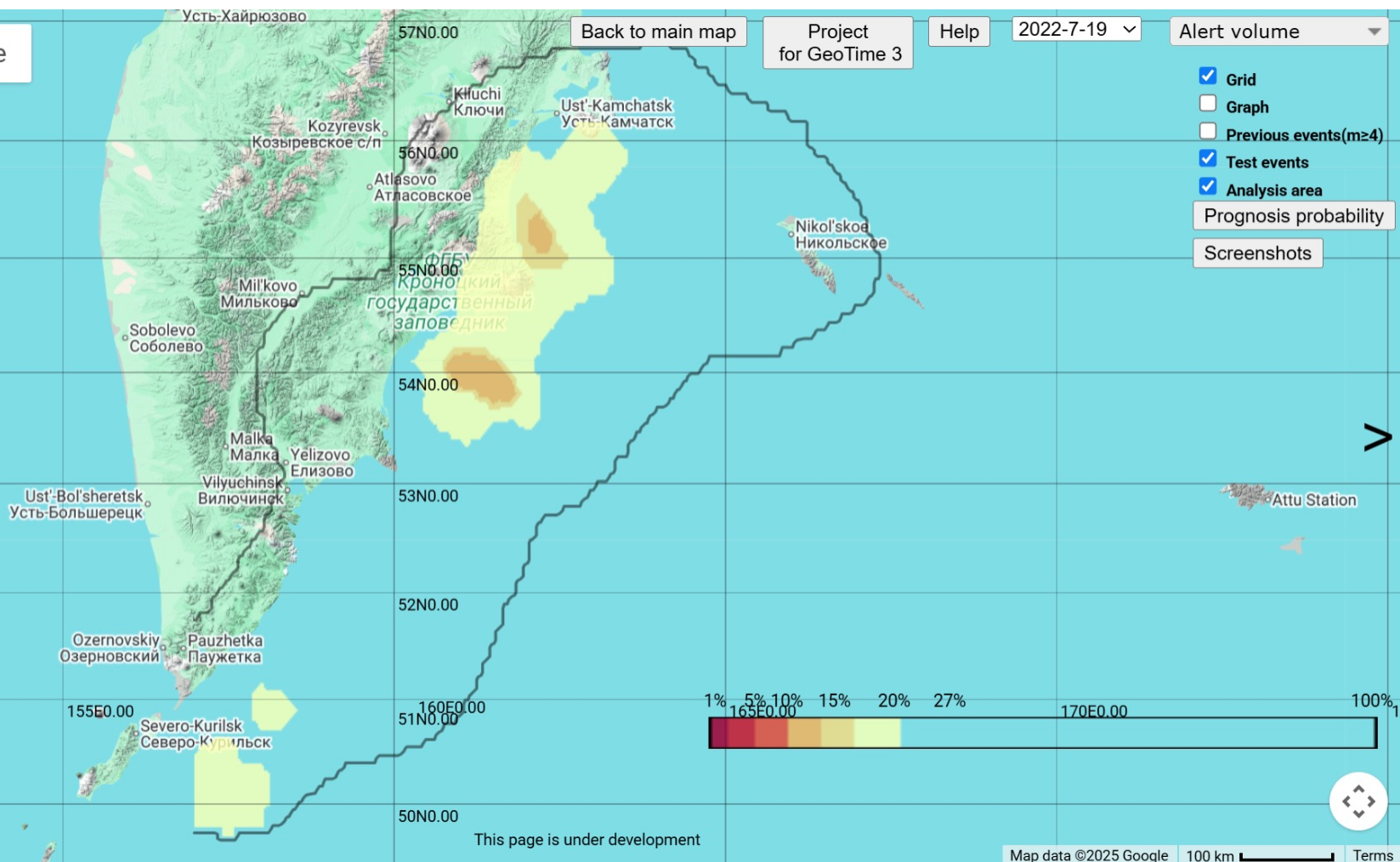
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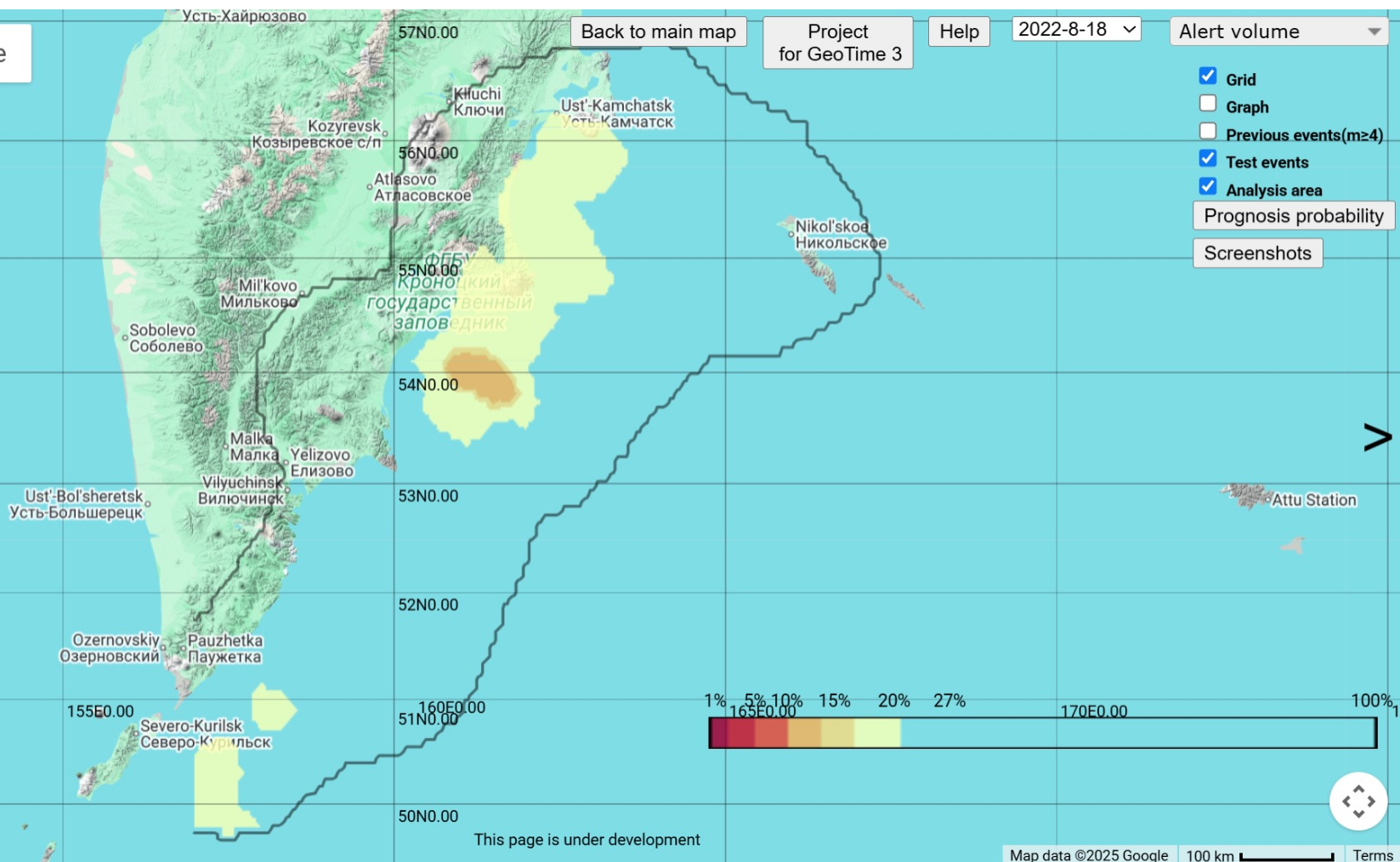
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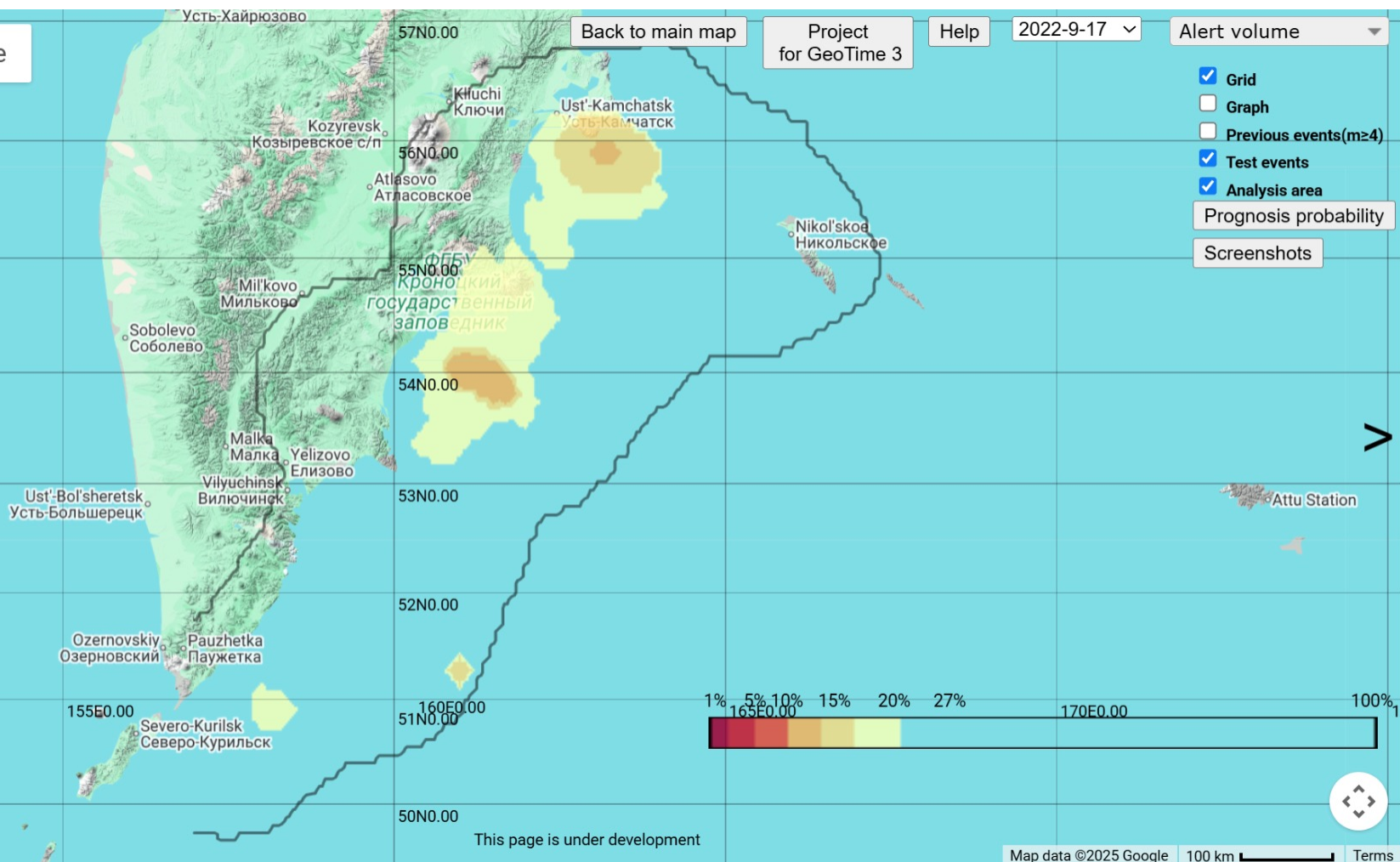
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Malka
Малка

Yelizovo
Елизово

Vilyuchinsk
Вилучинск

Pauzhetka
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Severo-Kurilsk
Северо-Курильск

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Ozernovskiy
Озерновский

Attu Station

155E0.00 160E0.00 165E0.00 170E0.00

50N0.00 51N0.00 52N0.00 53N0.00 54N0.00 55N0.00 56N0.00 57N0.00

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1% 5% 10% 15% 20% 27%

165E0.00

170E0.00

51N0.00

50N0.00

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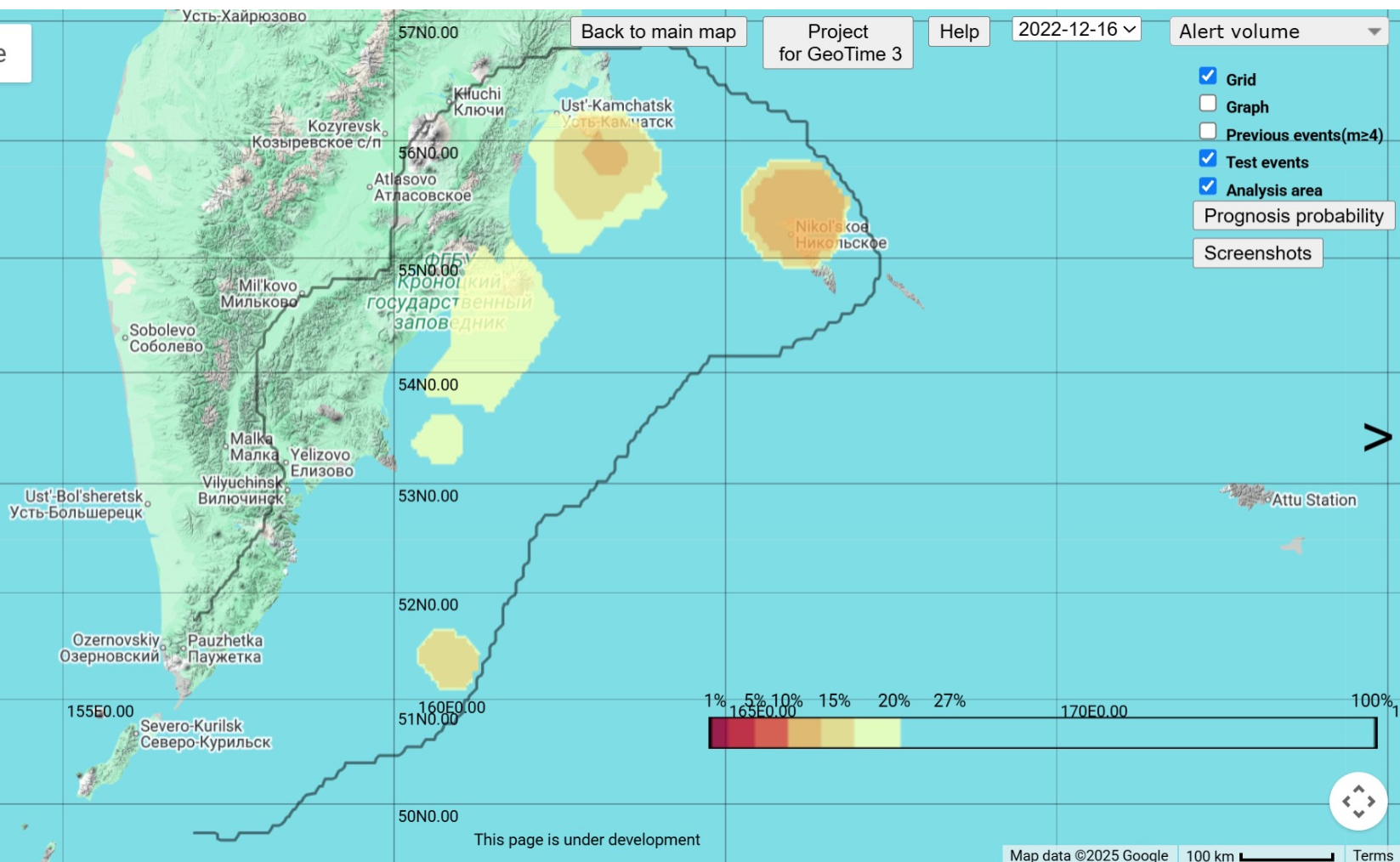
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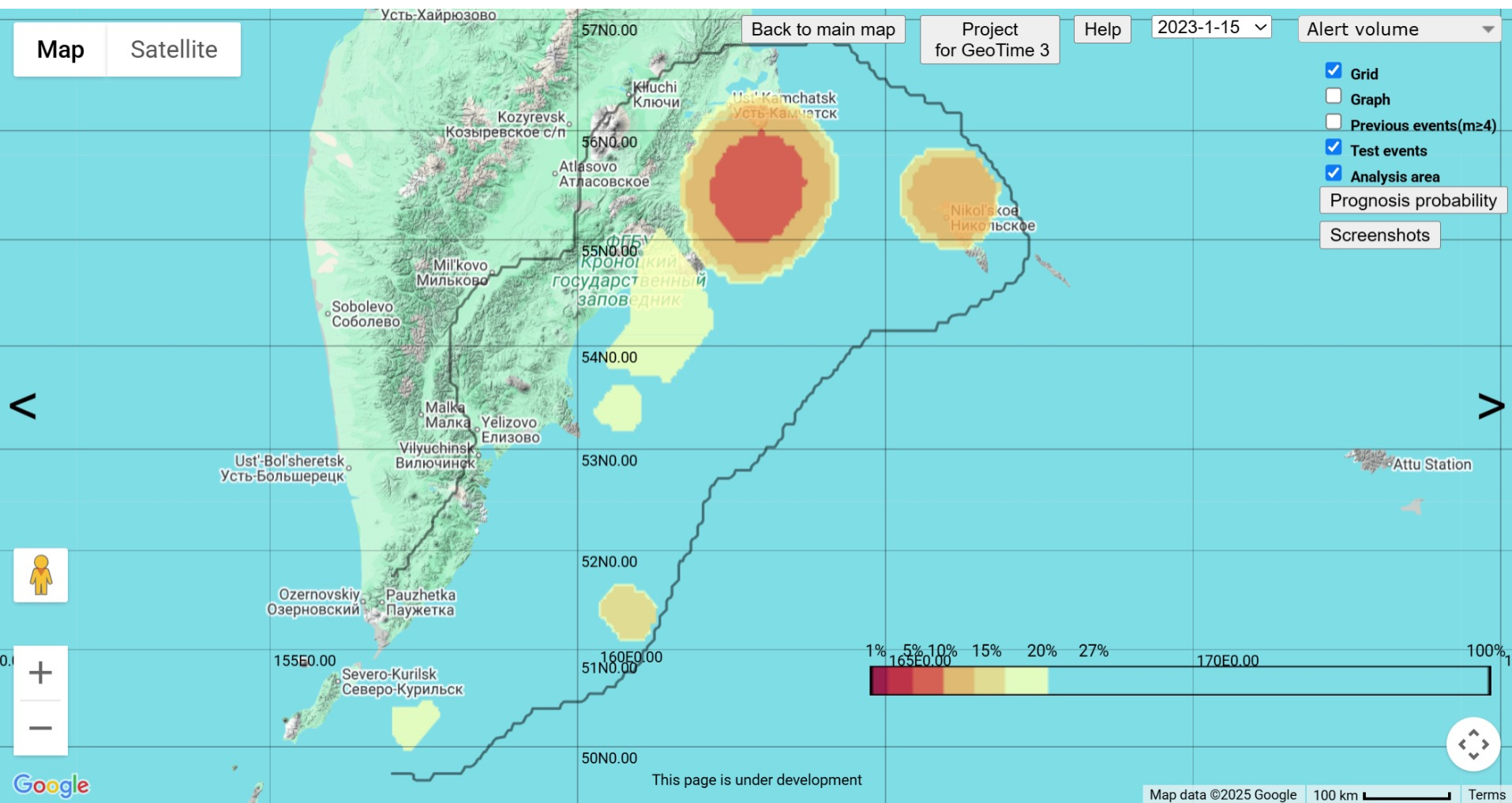
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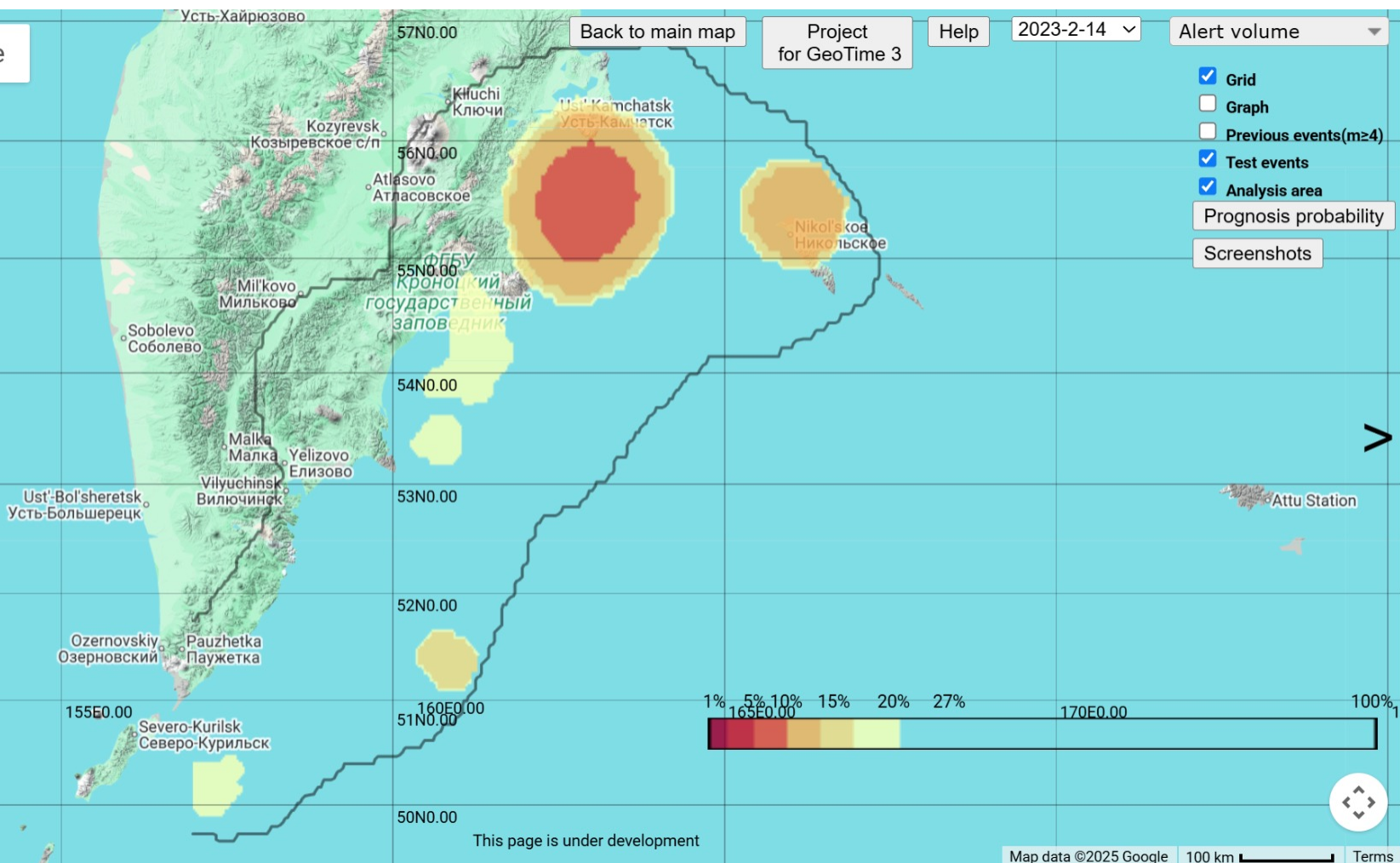
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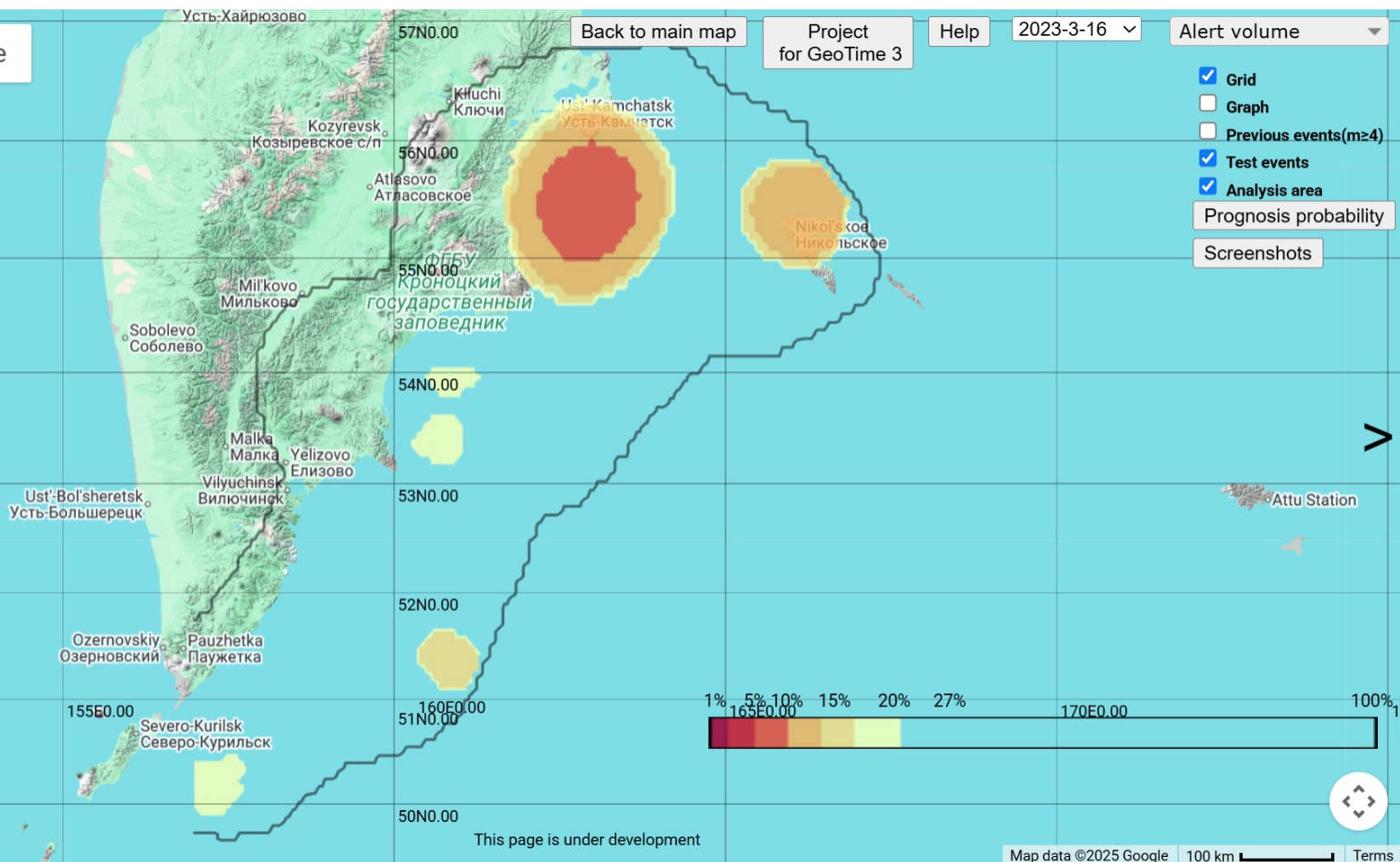
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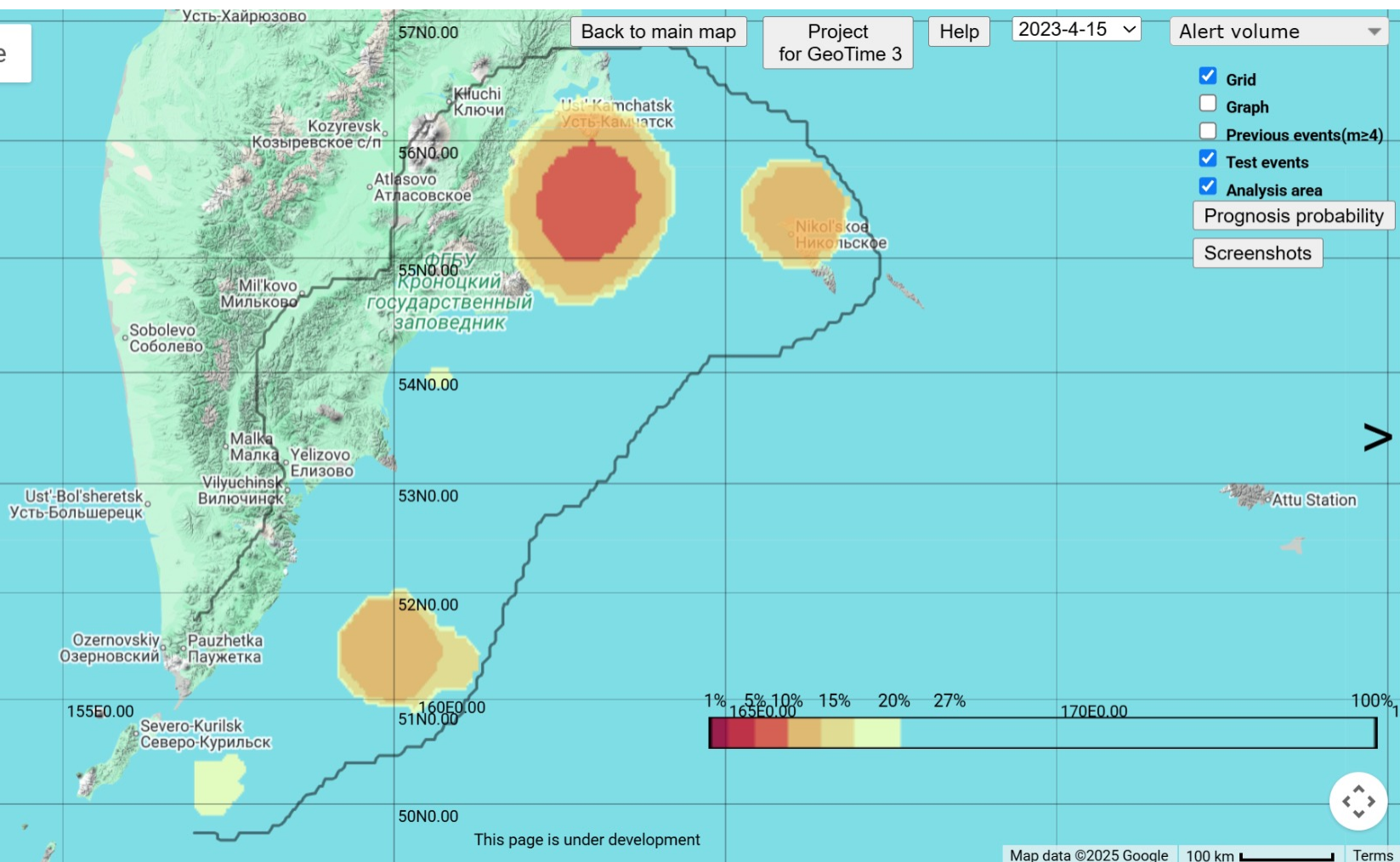
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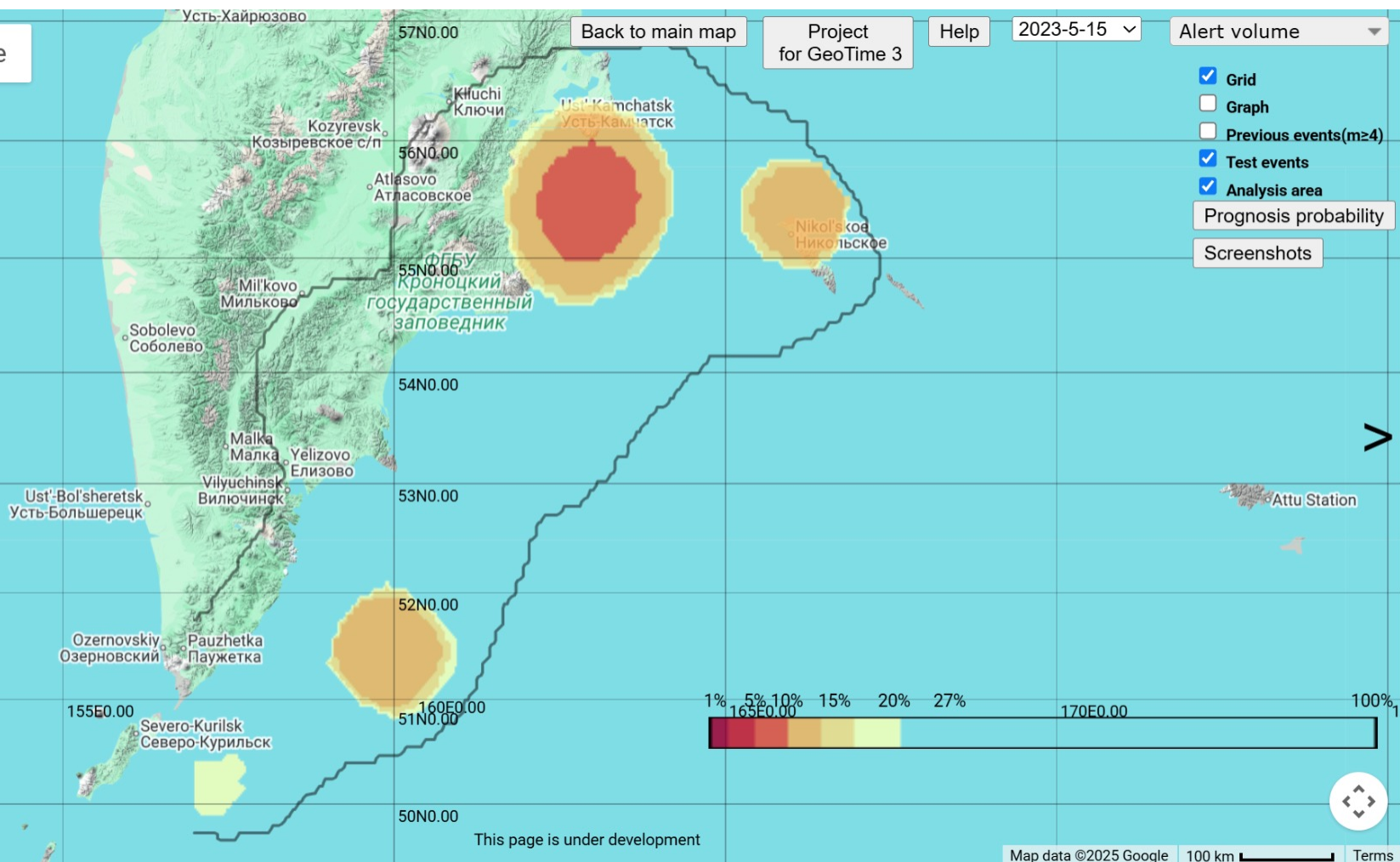
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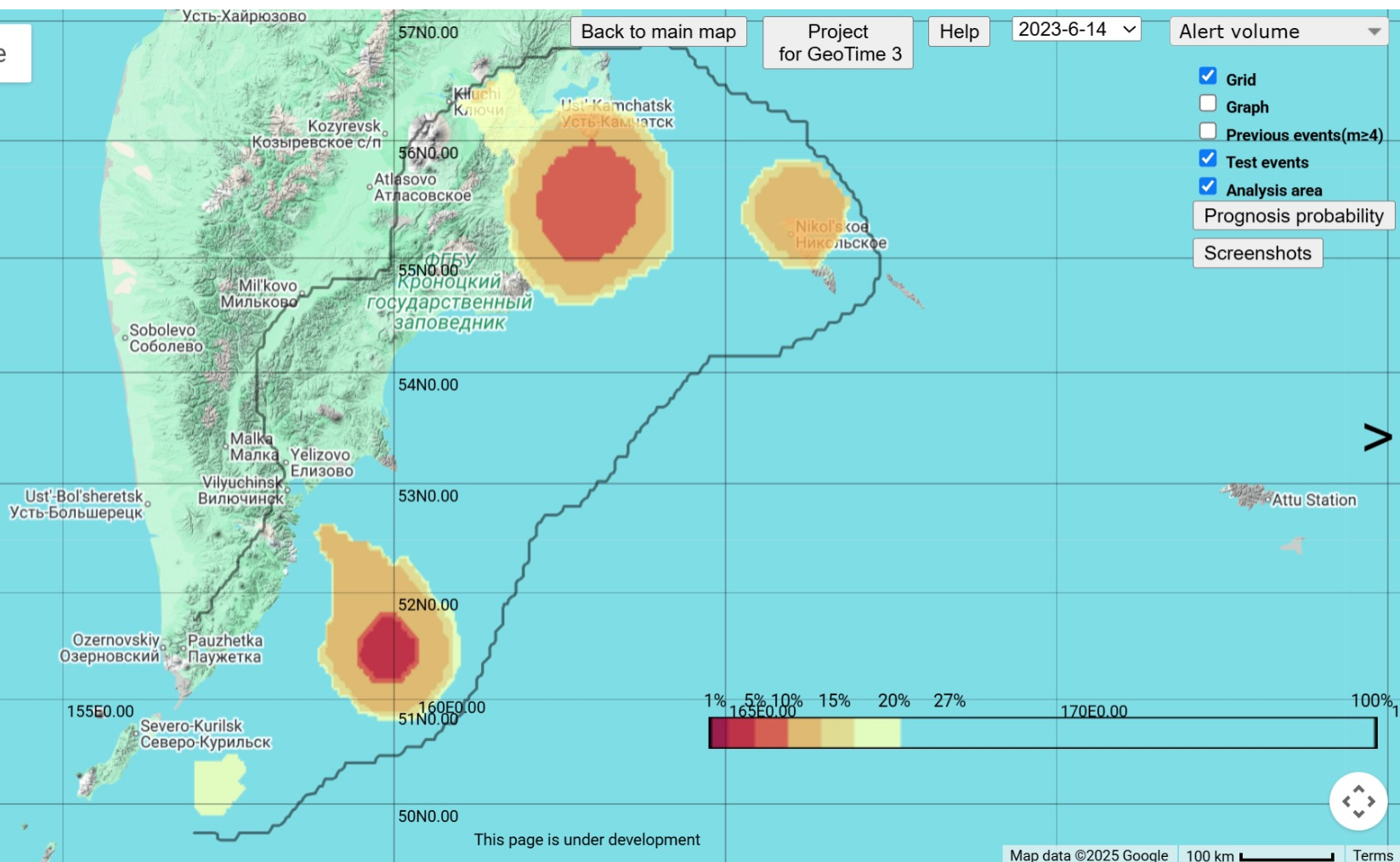
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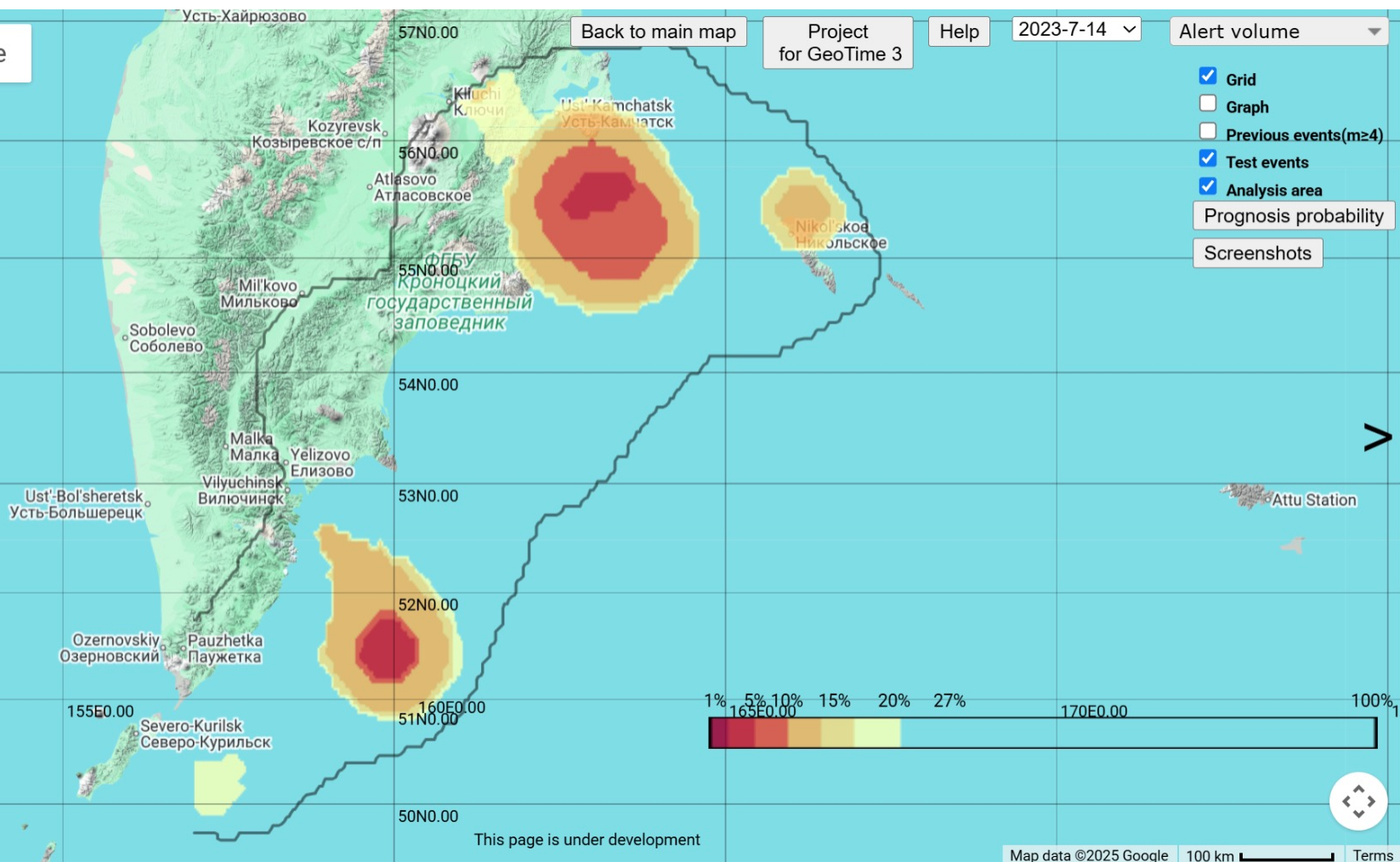
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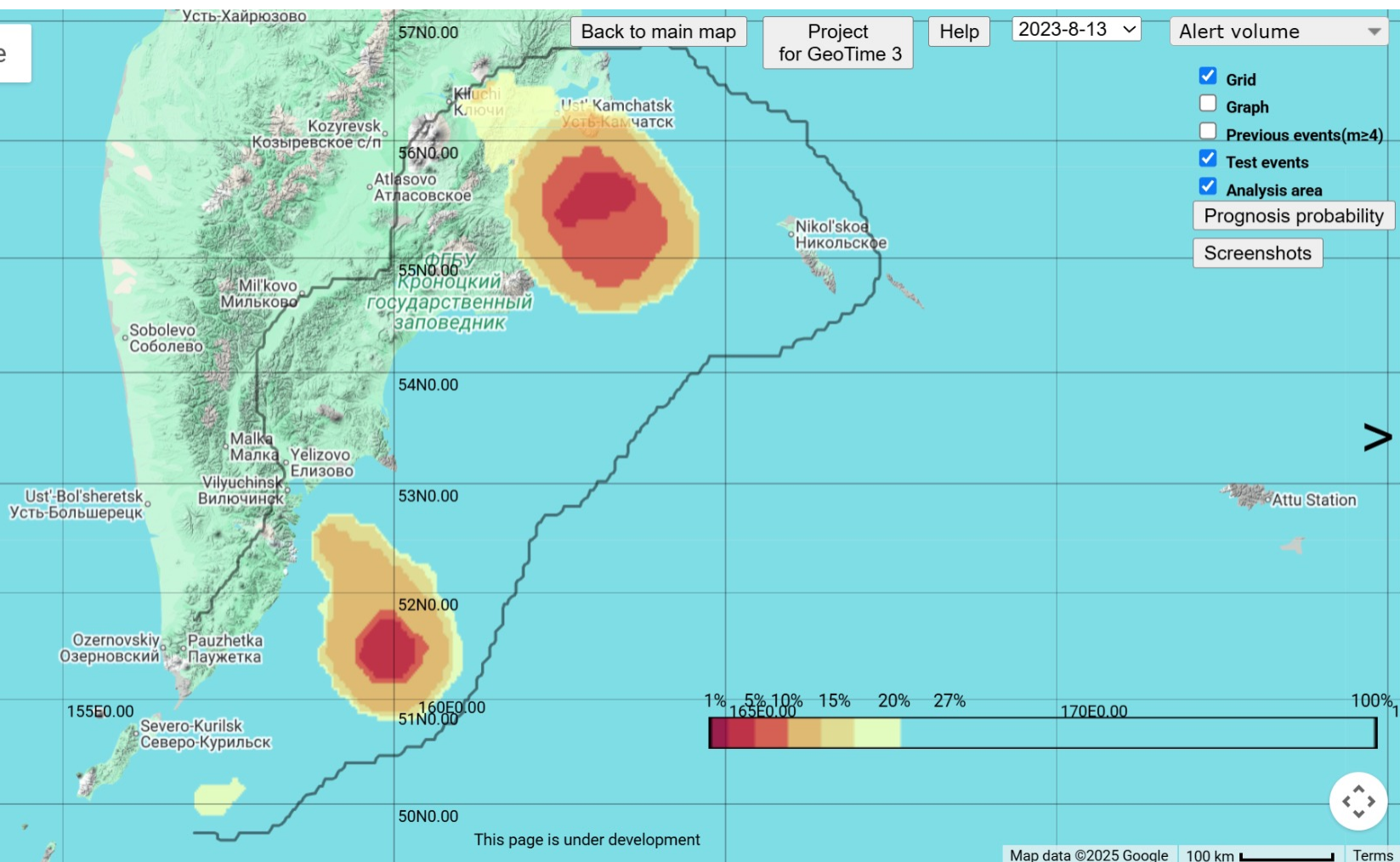
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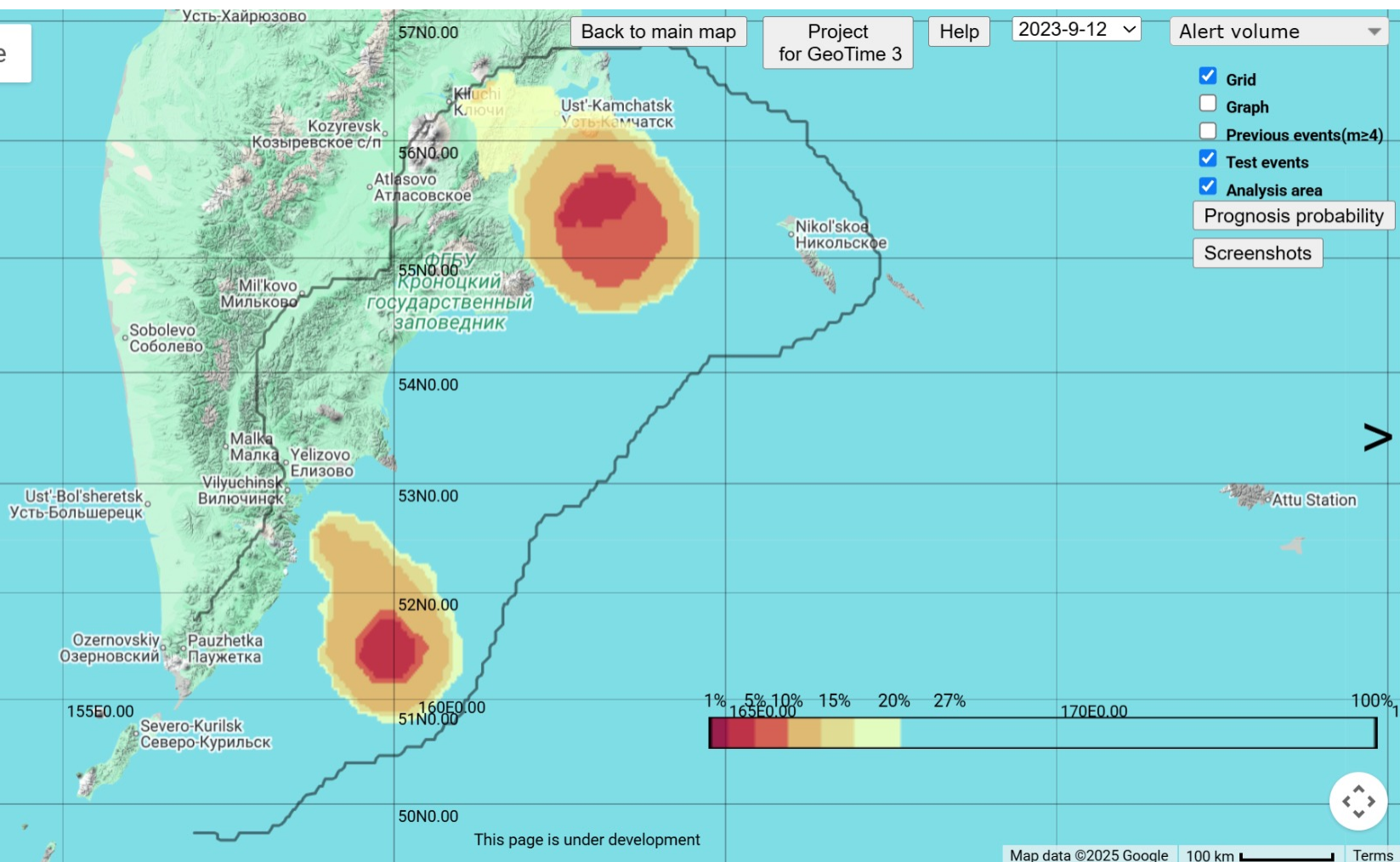
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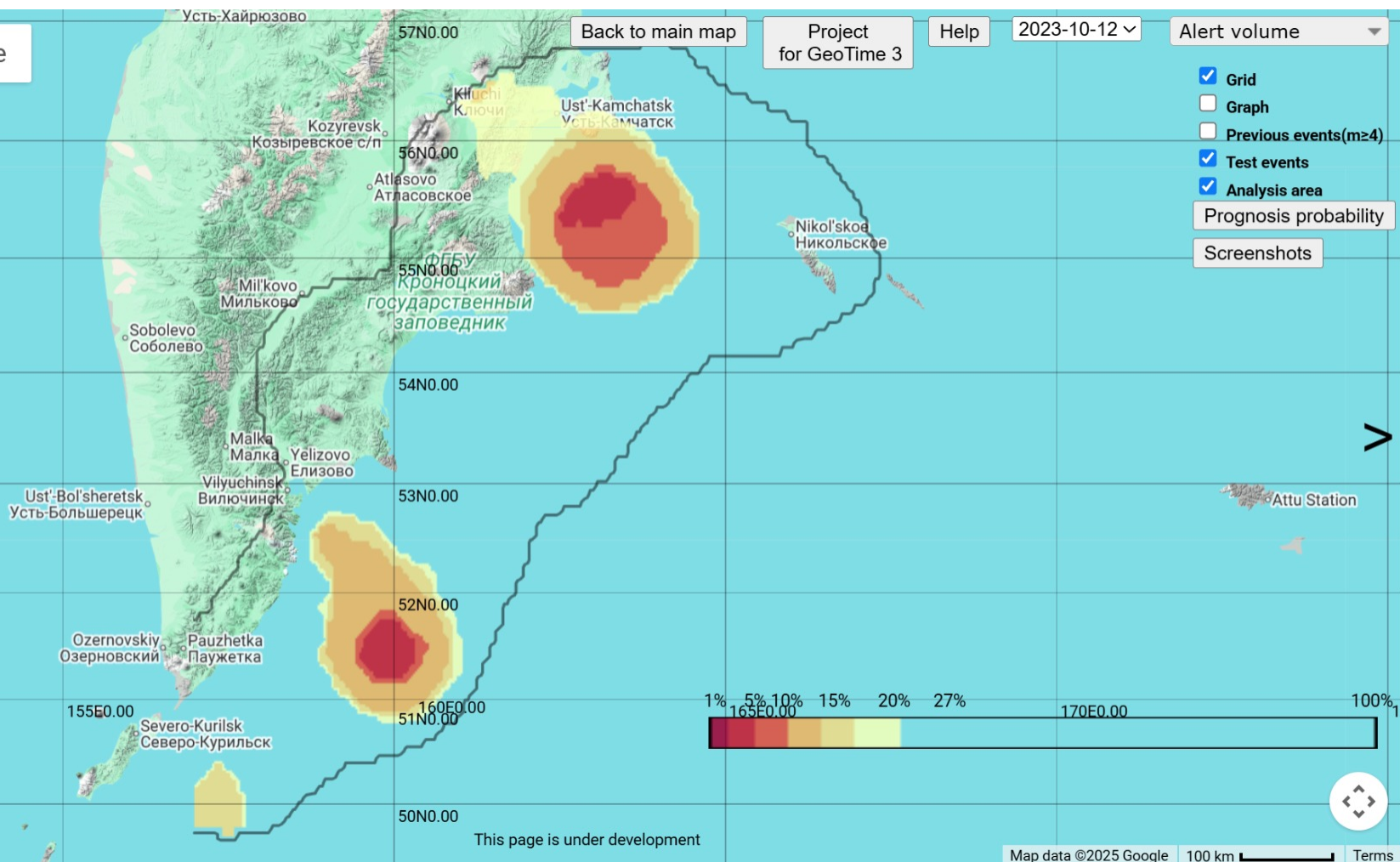
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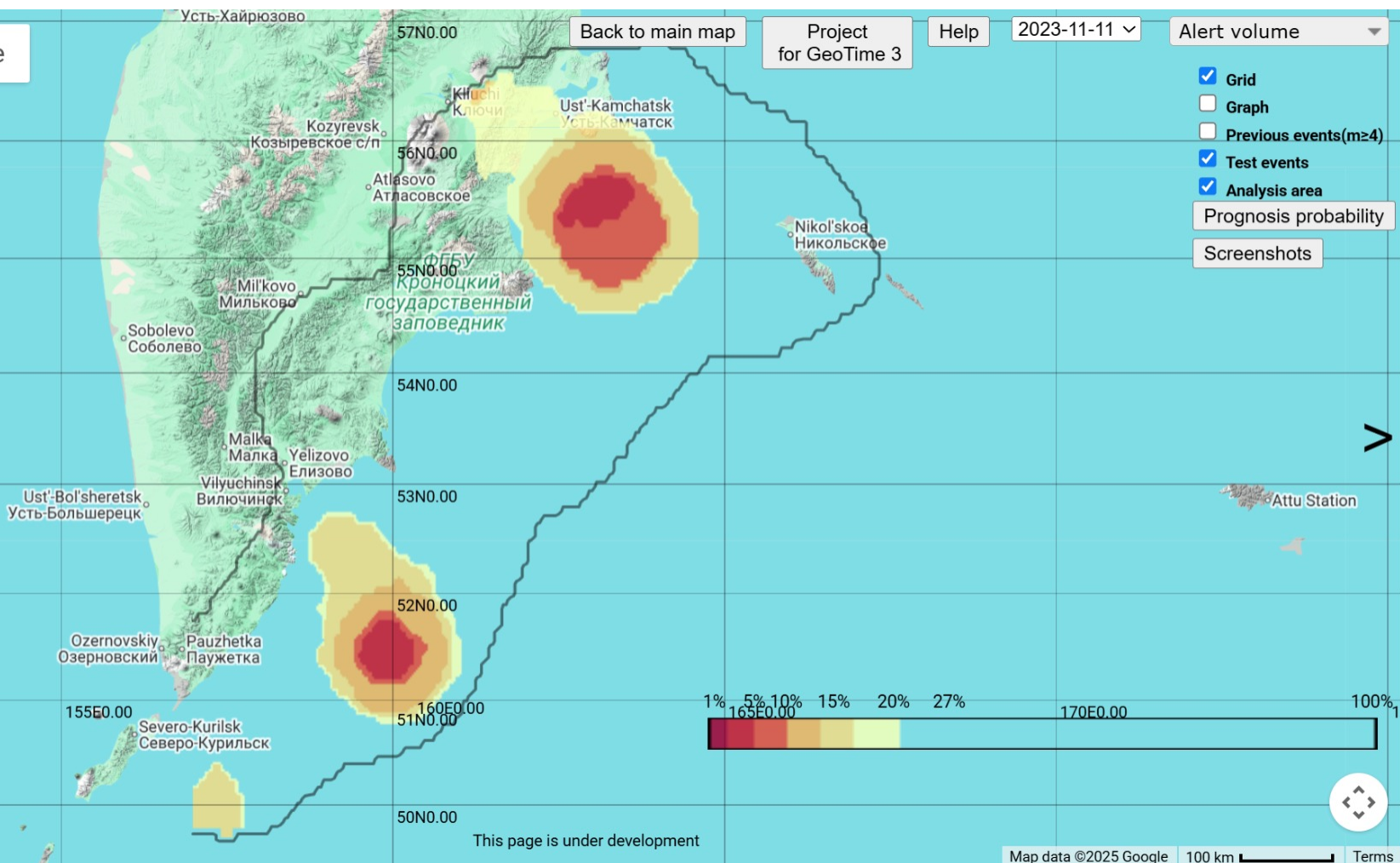
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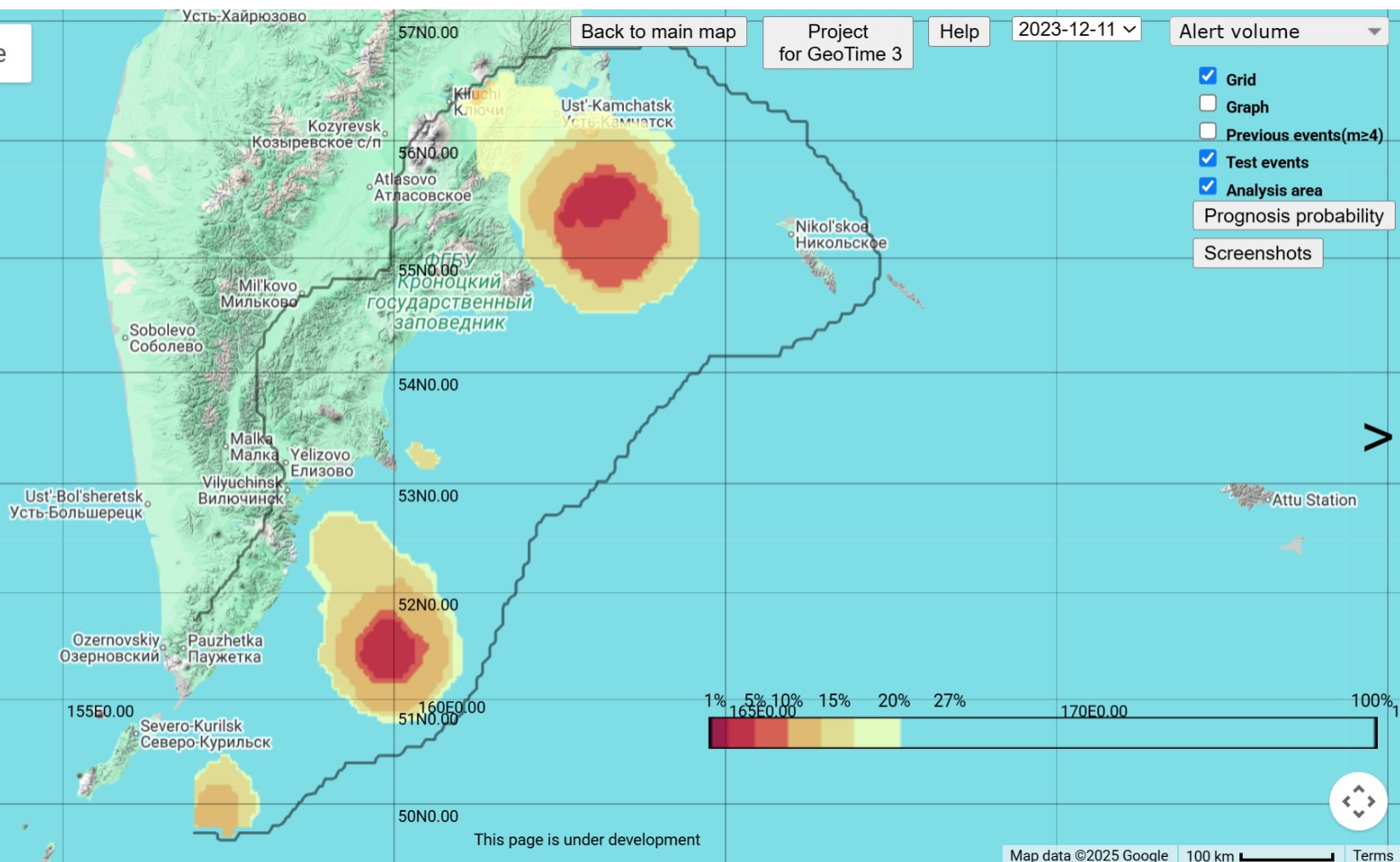
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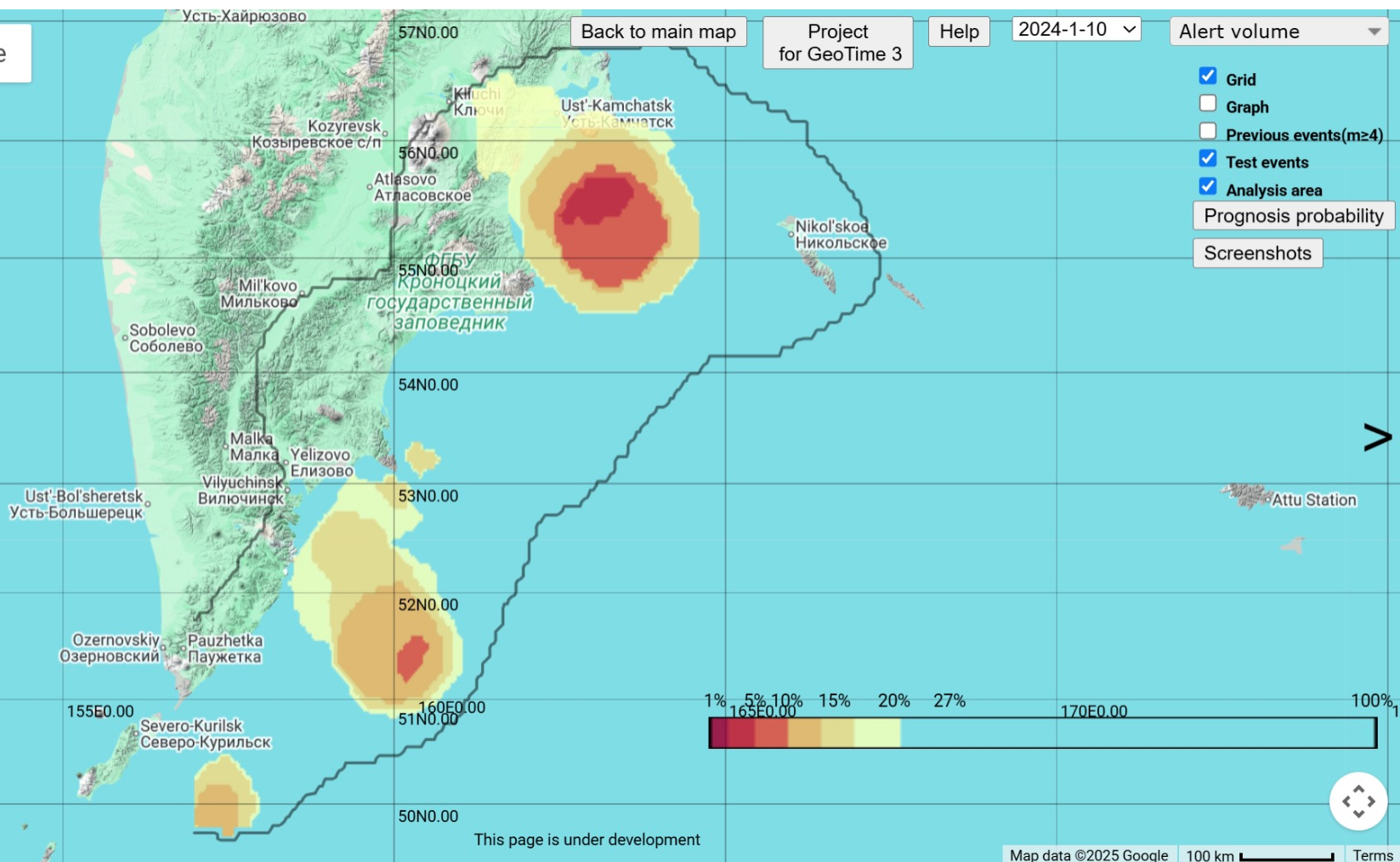
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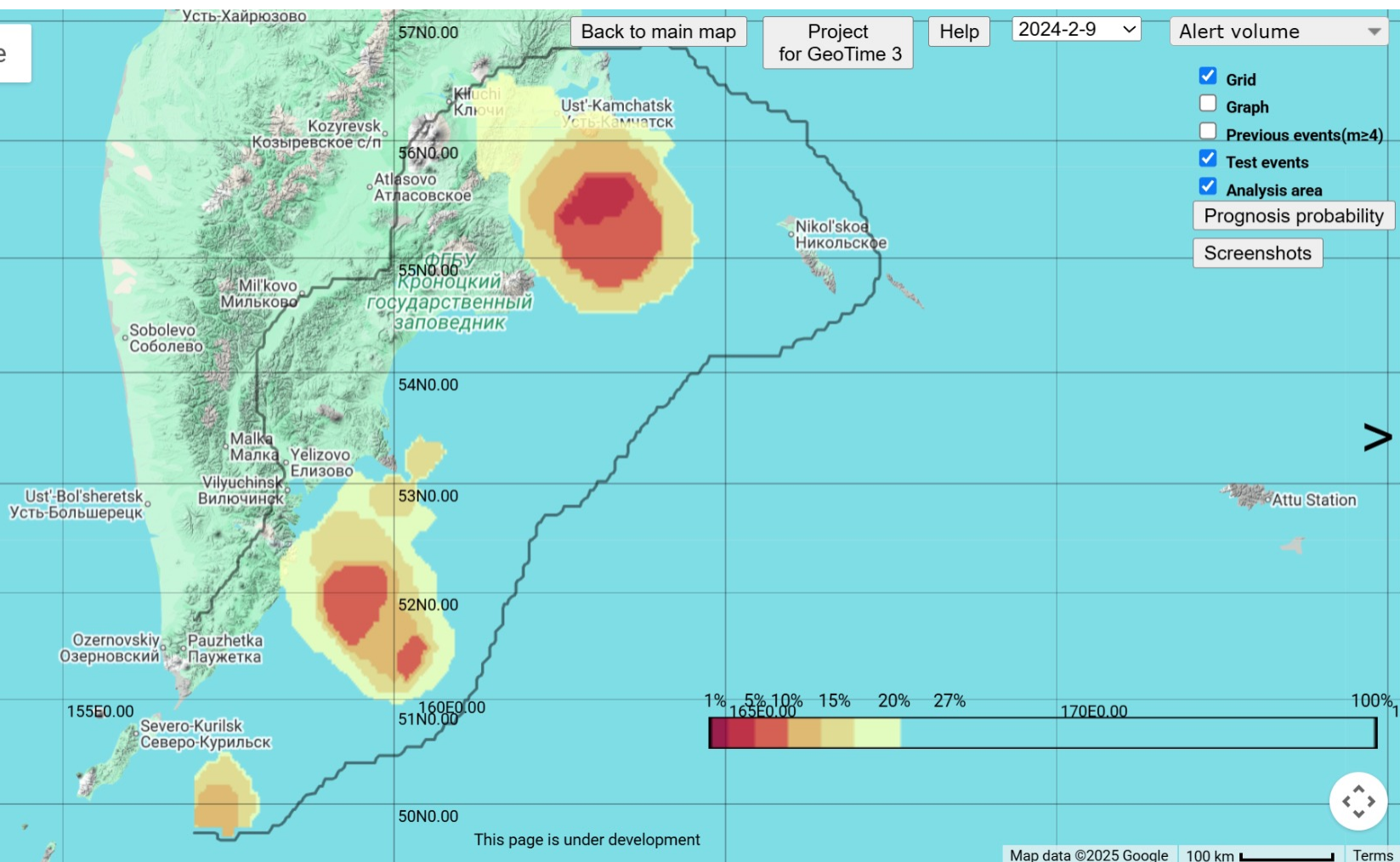
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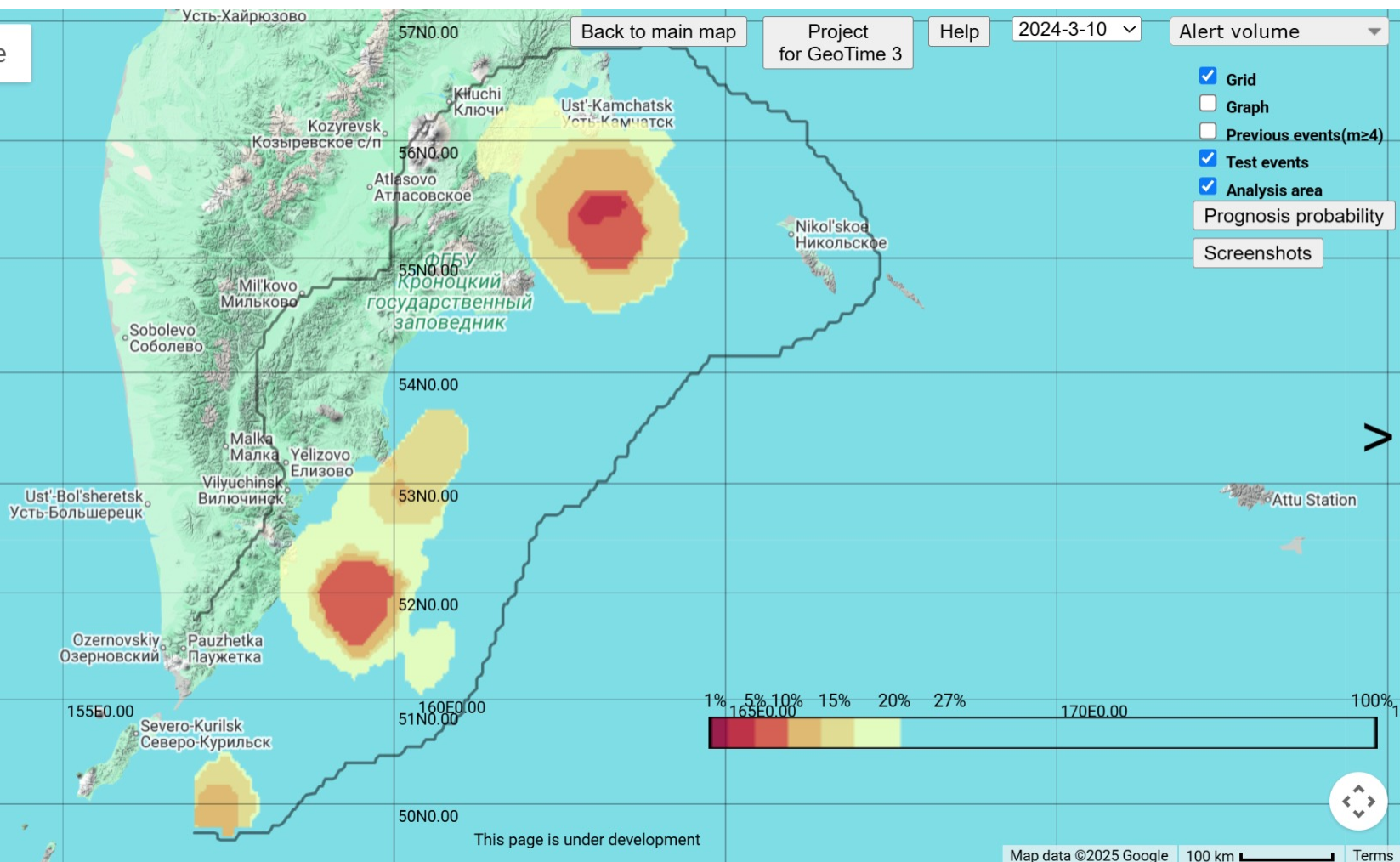
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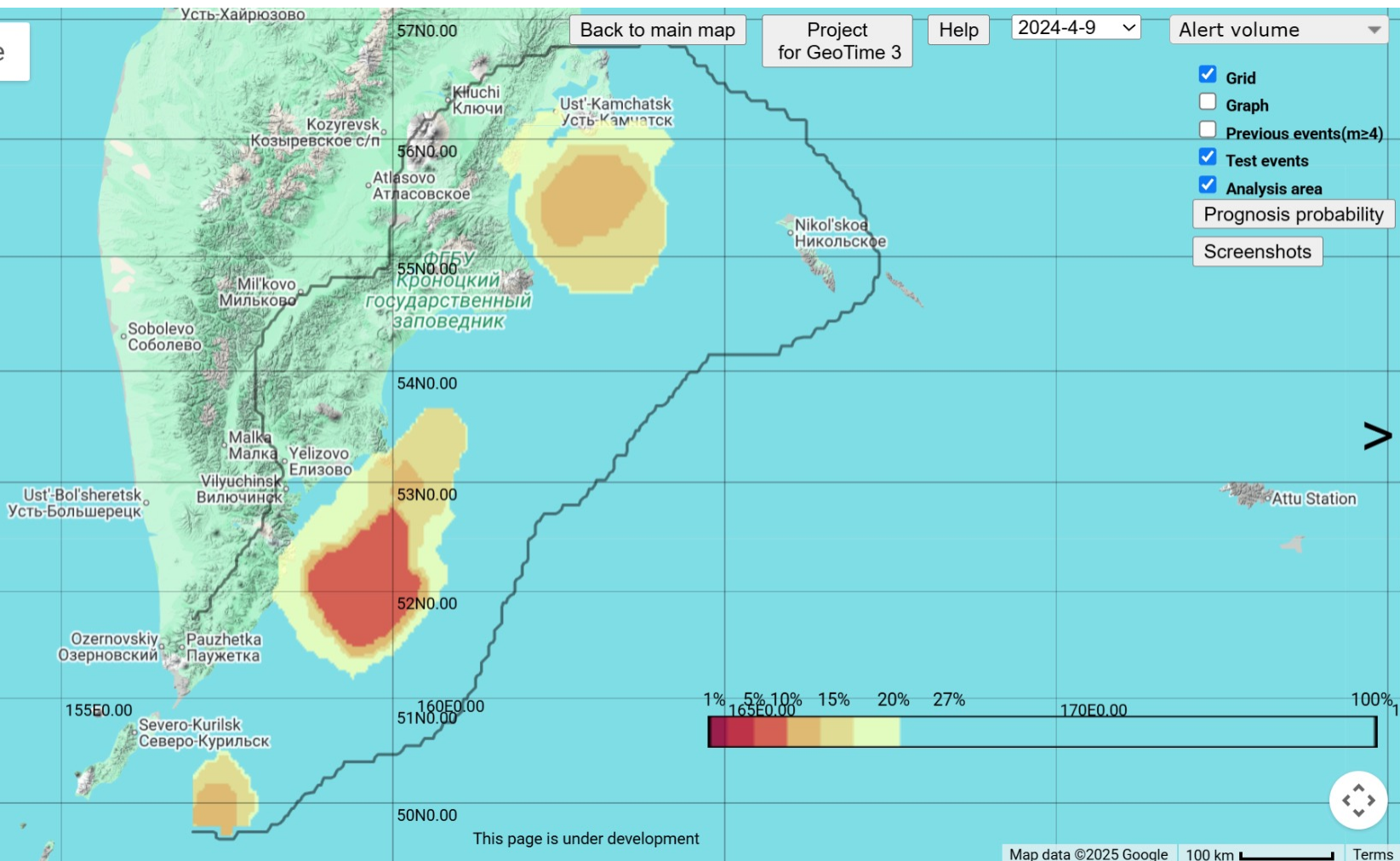
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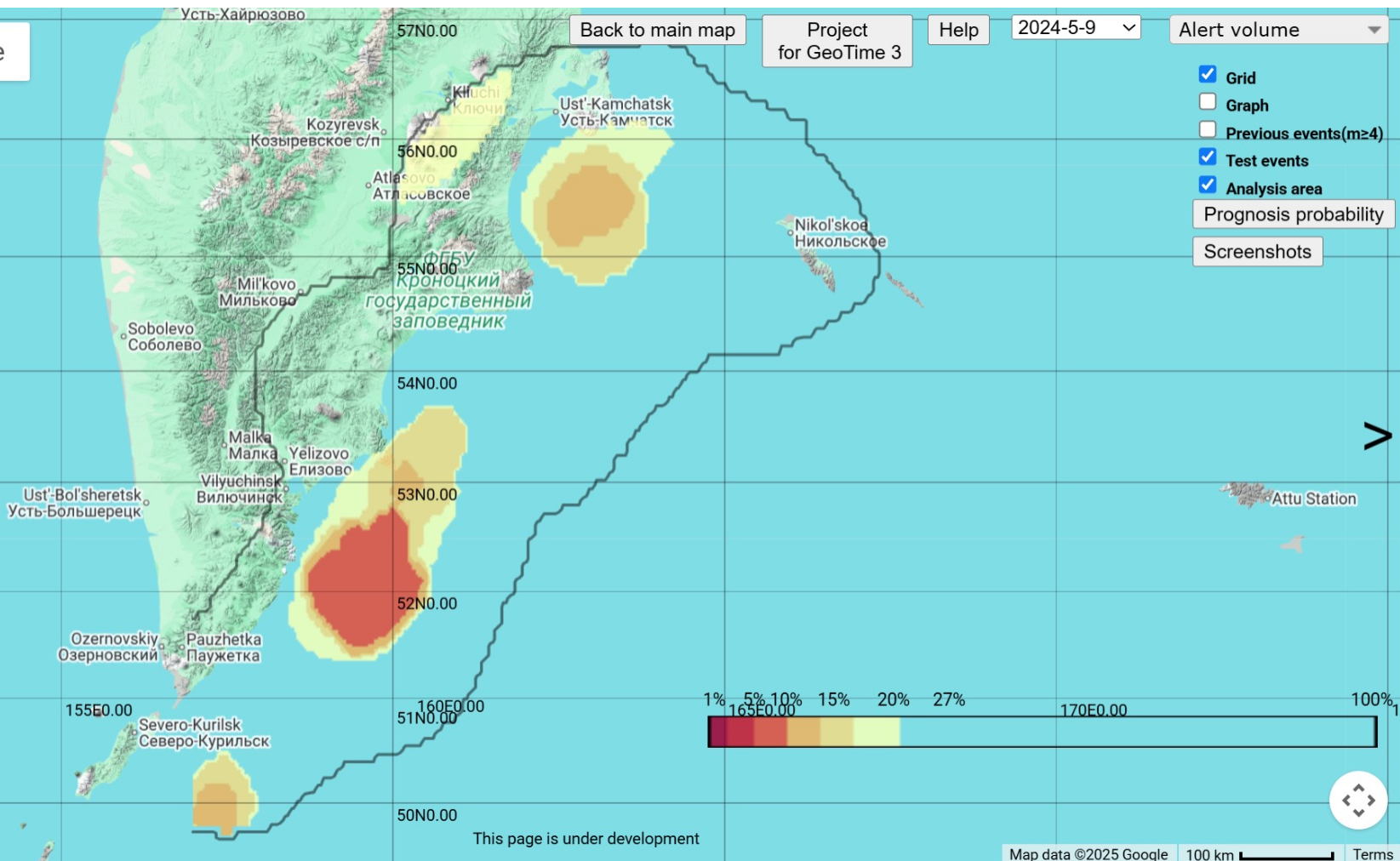
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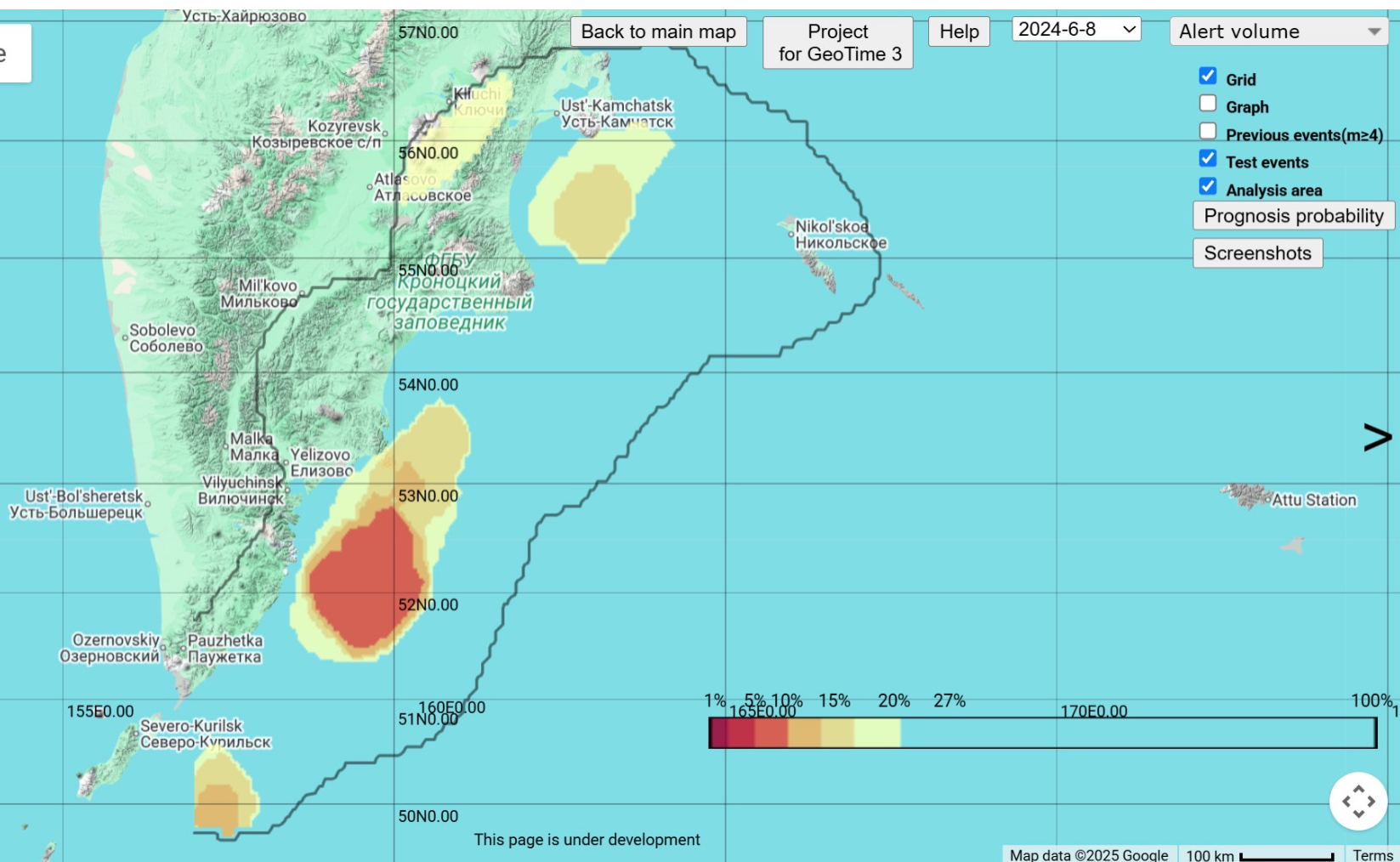
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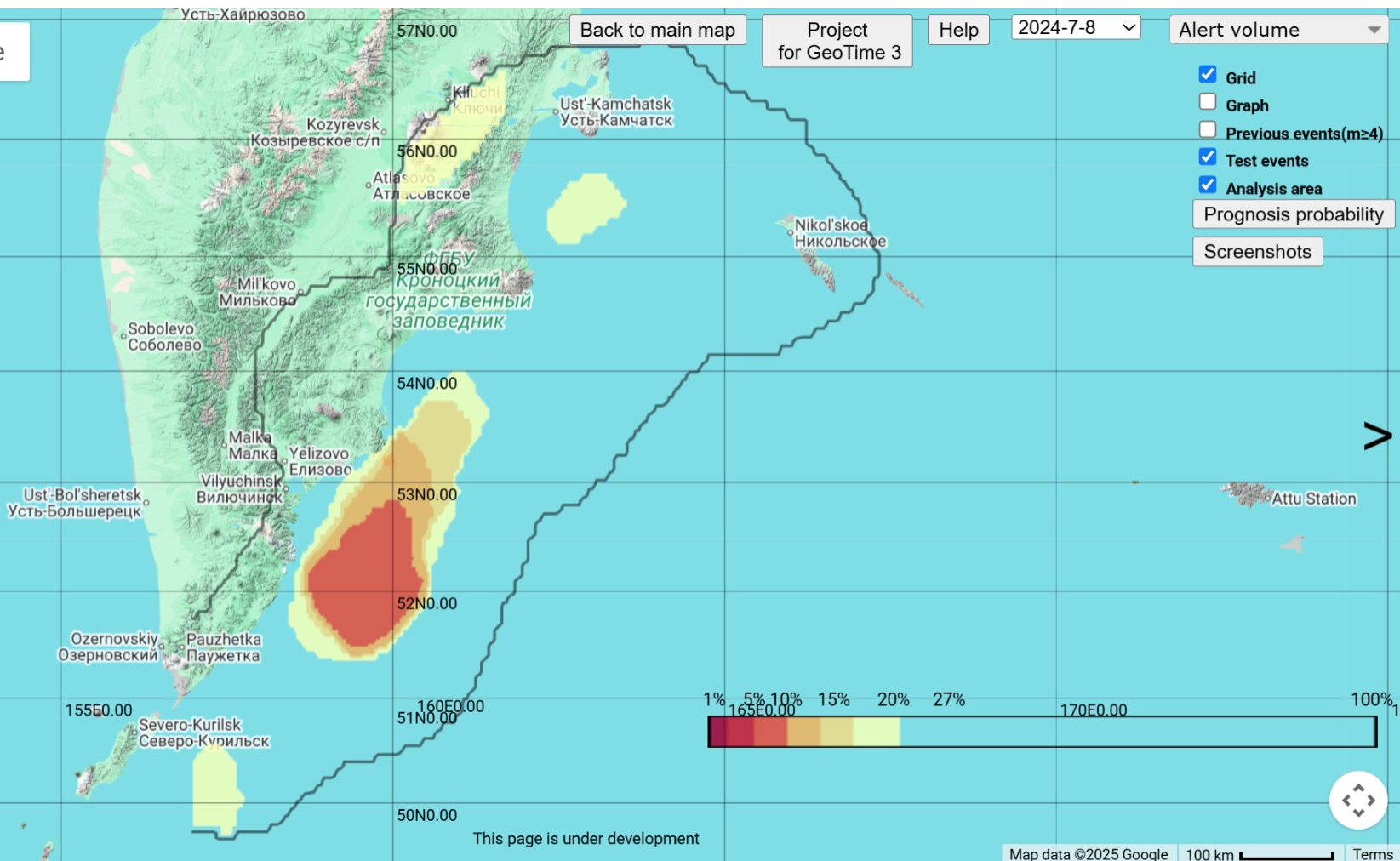
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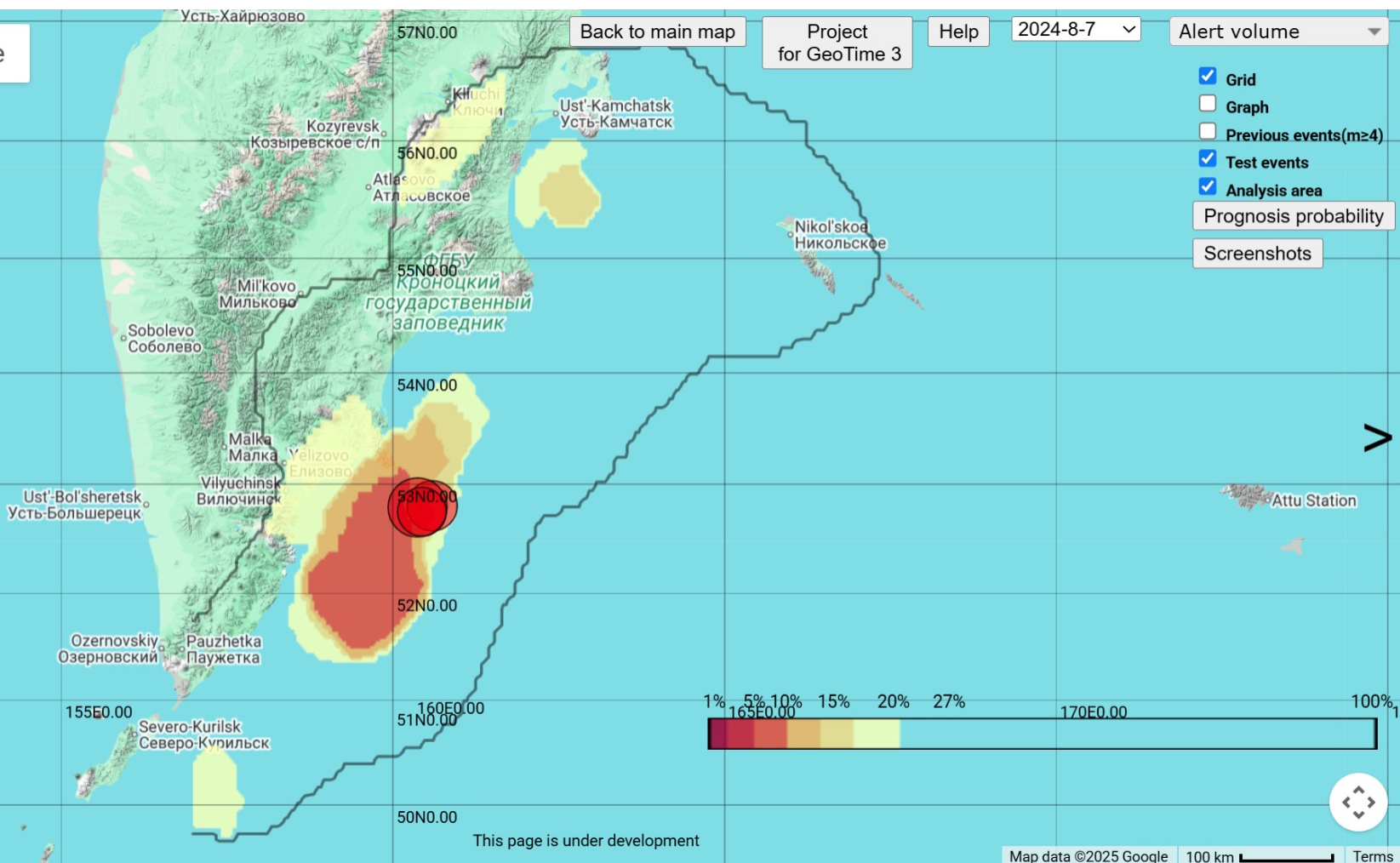
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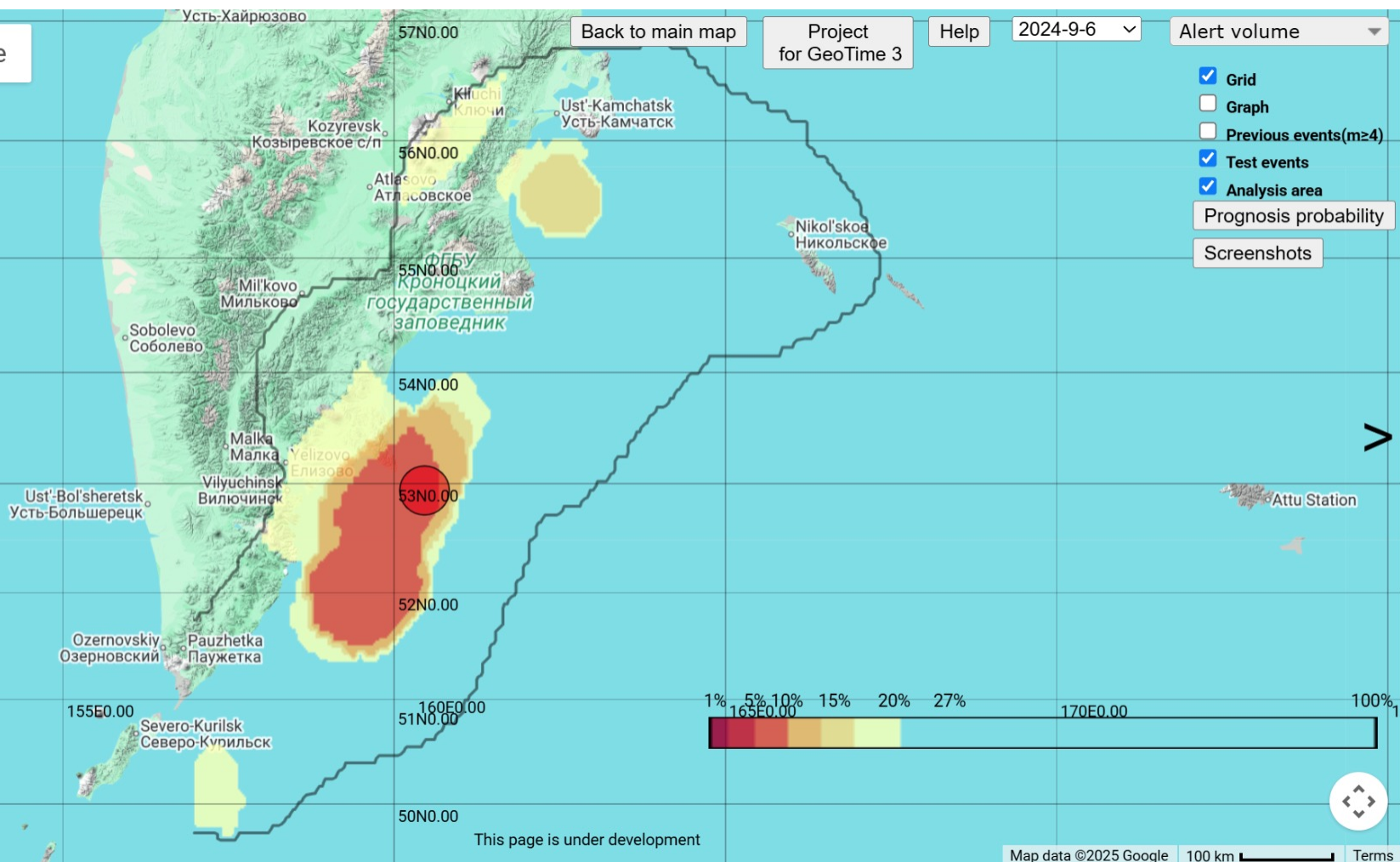
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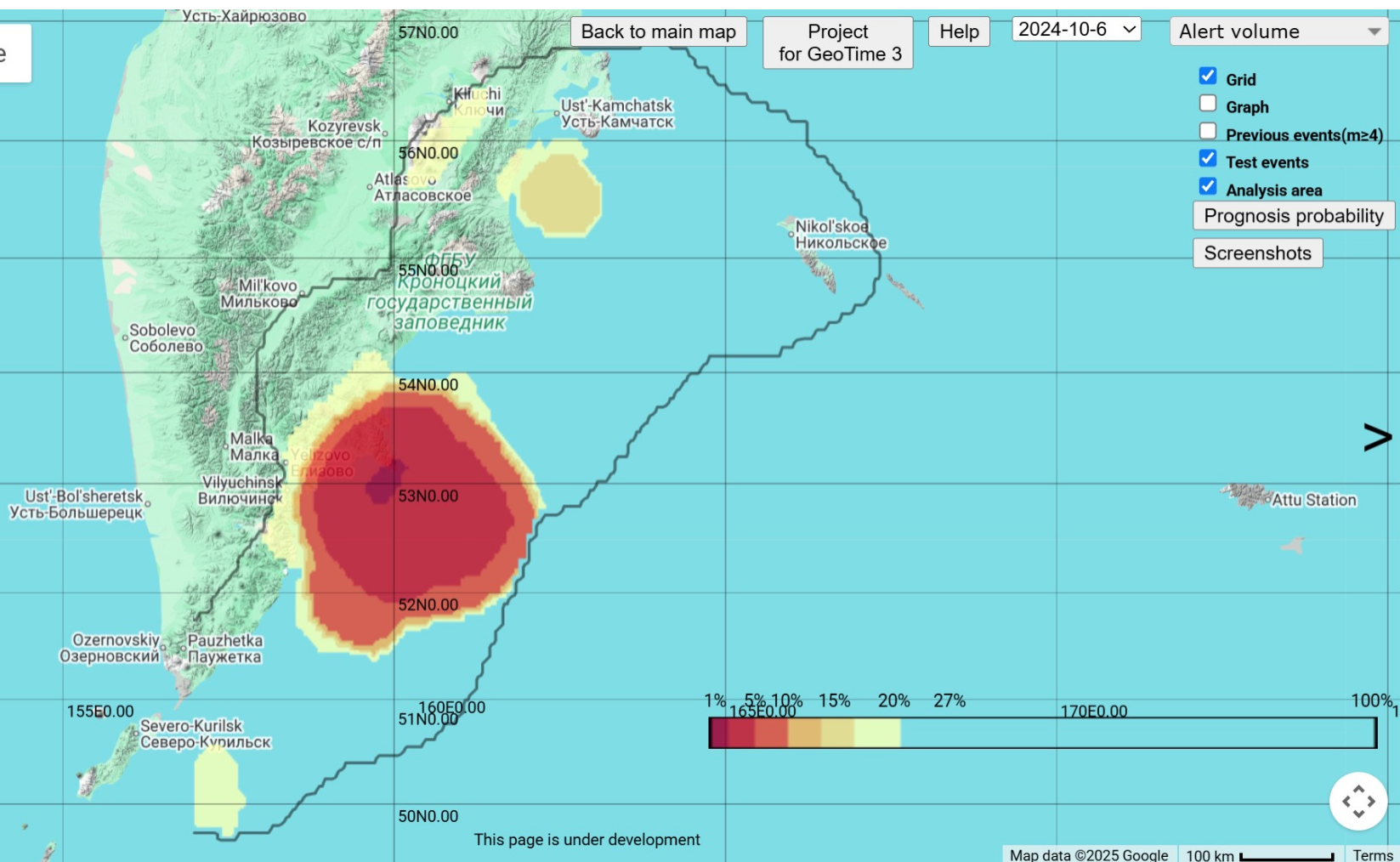
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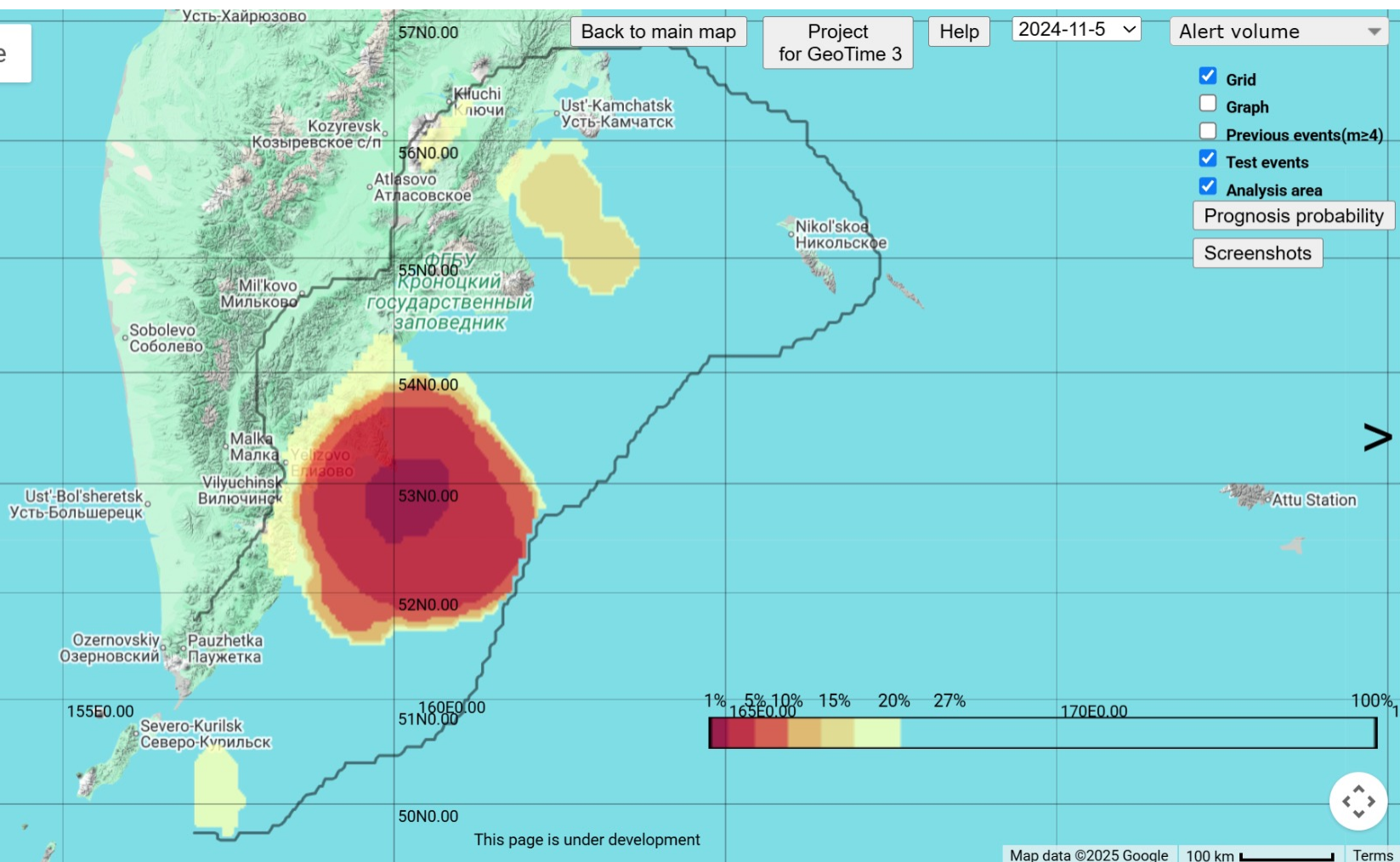
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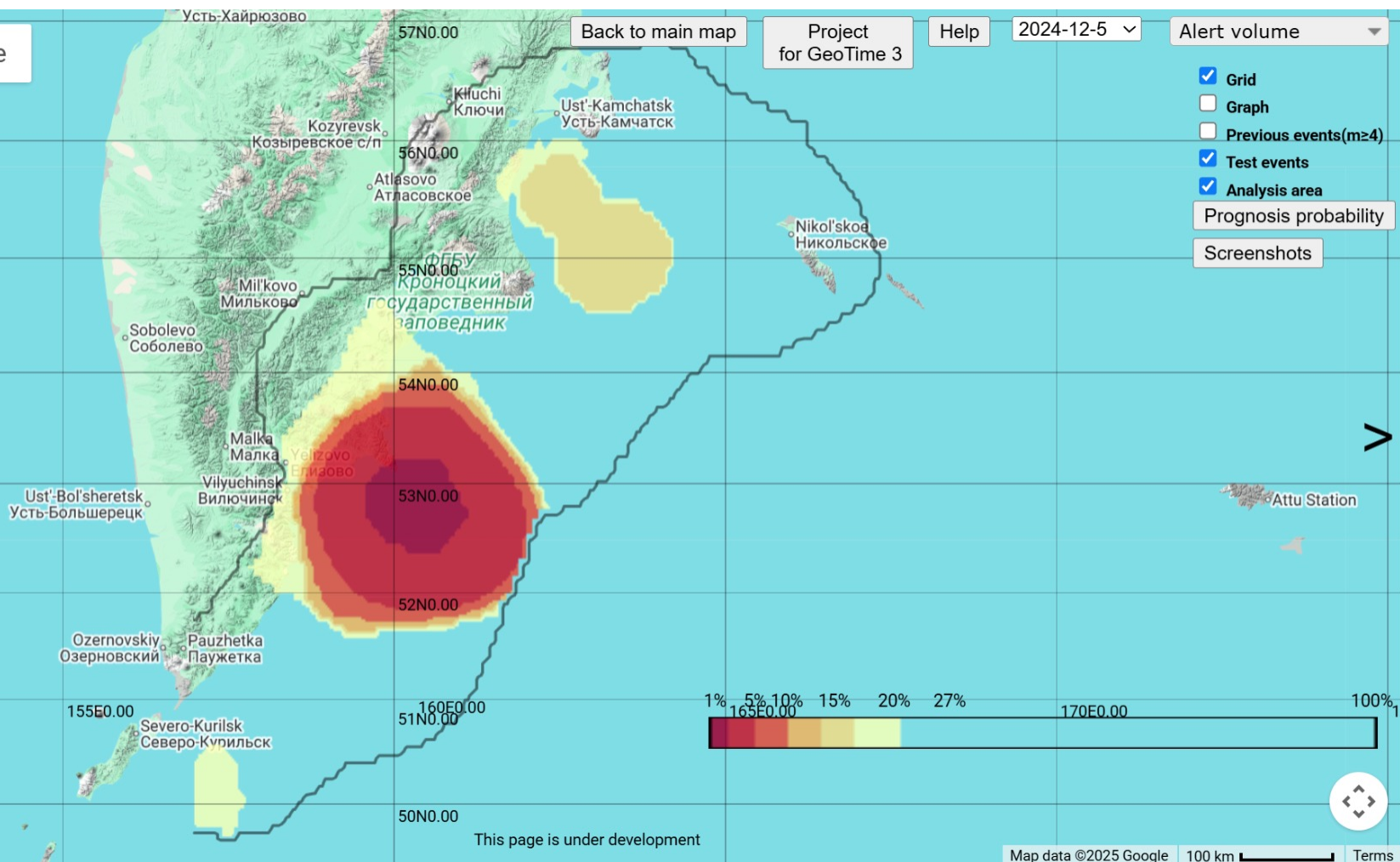
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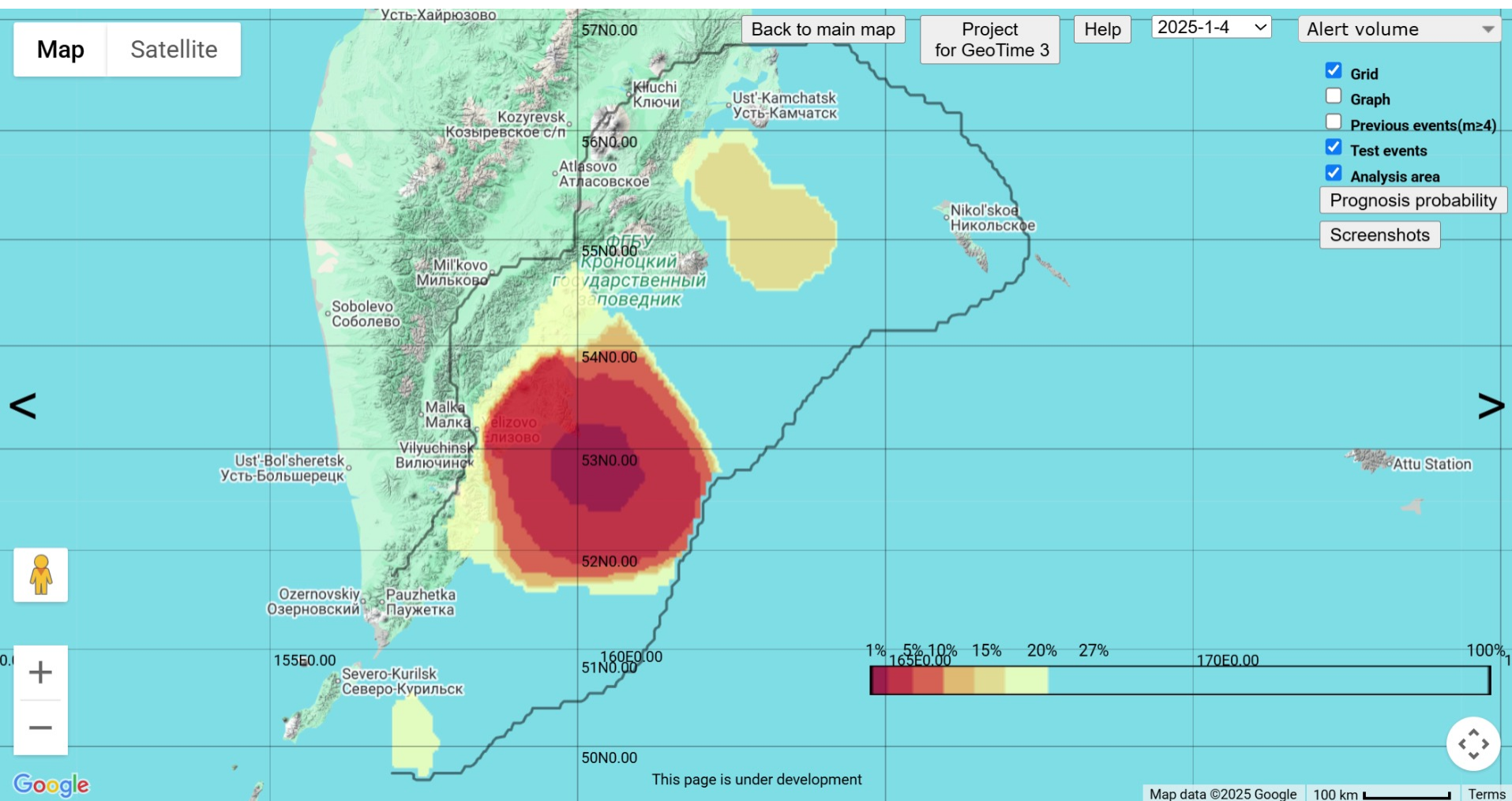
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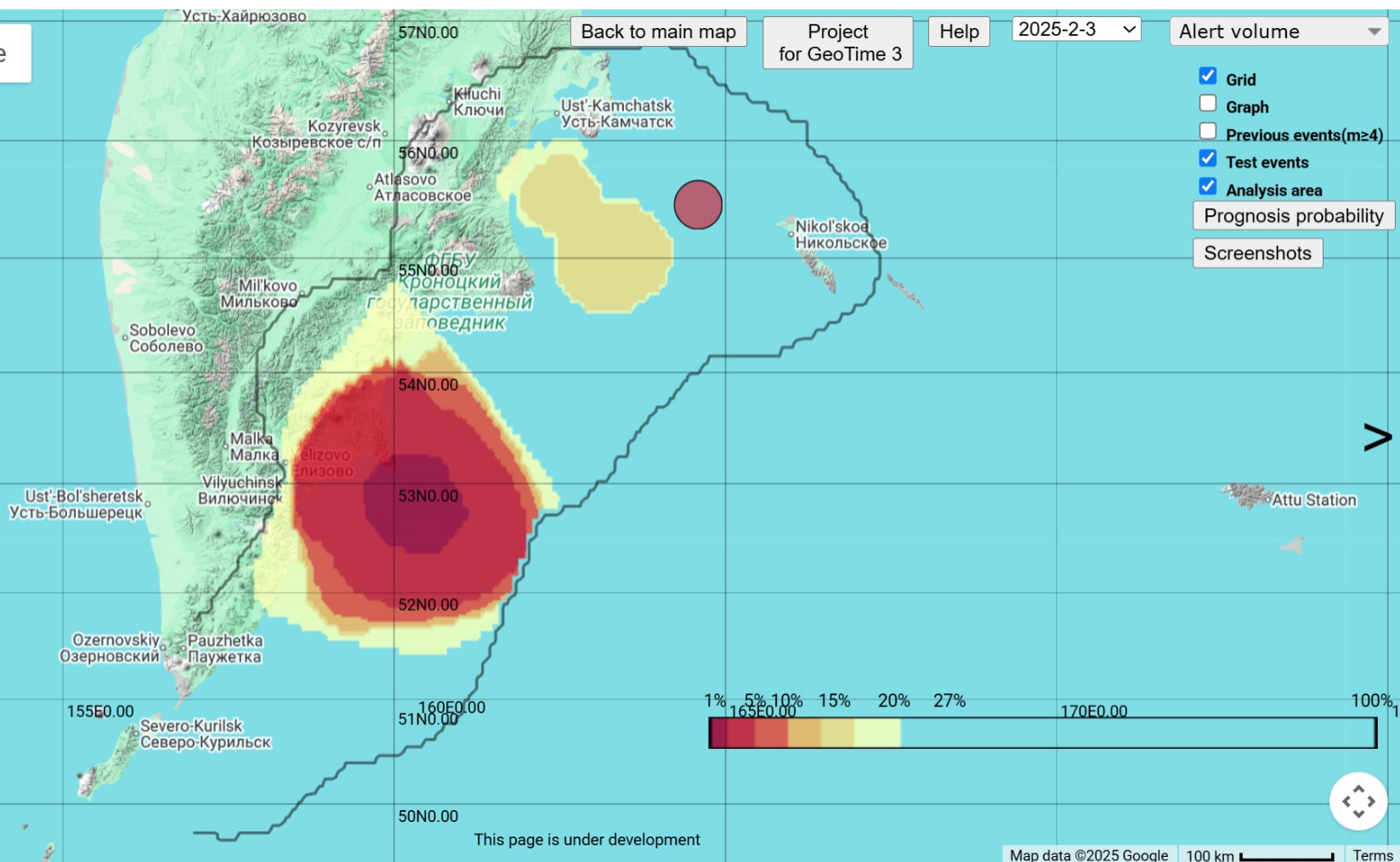
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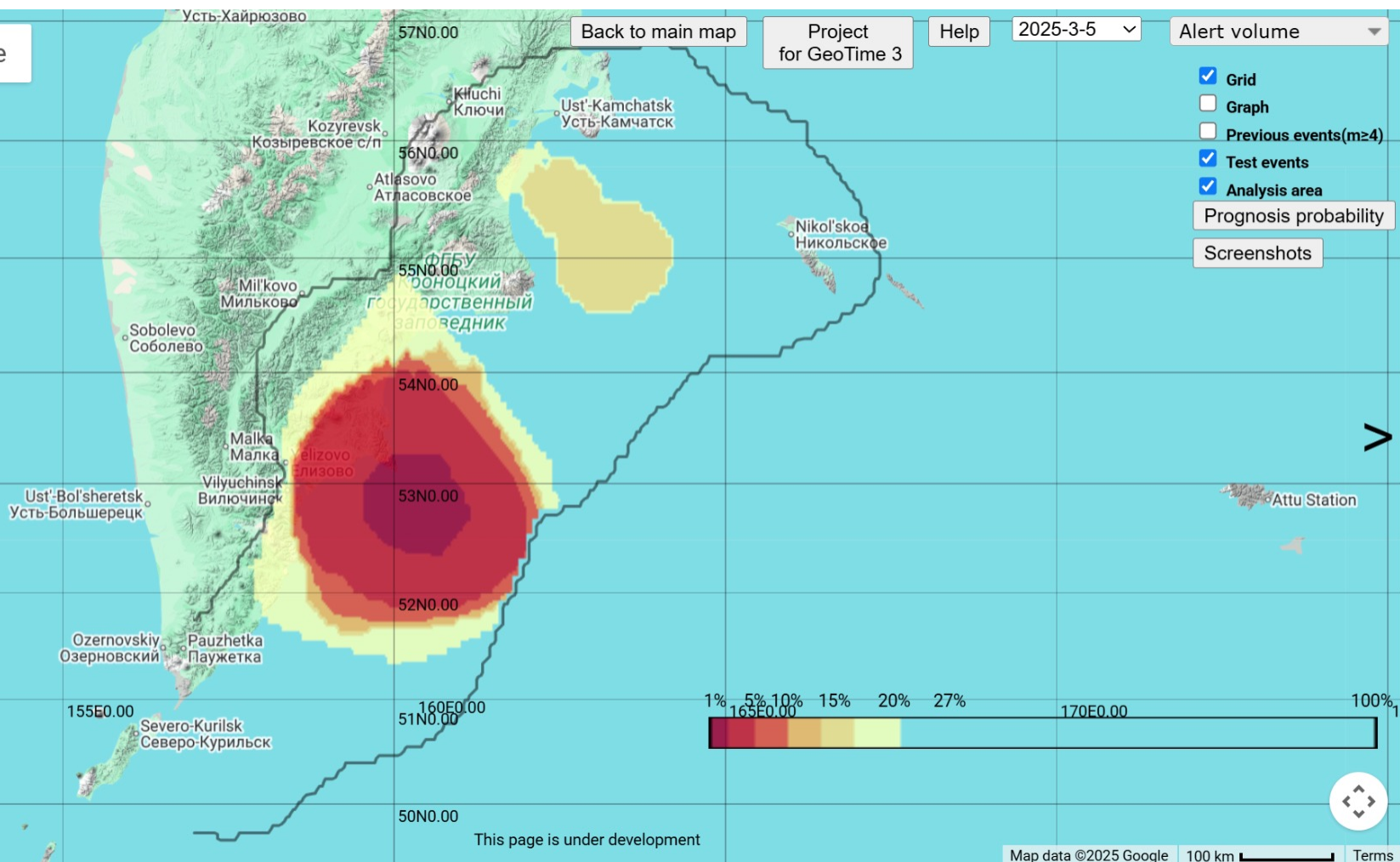
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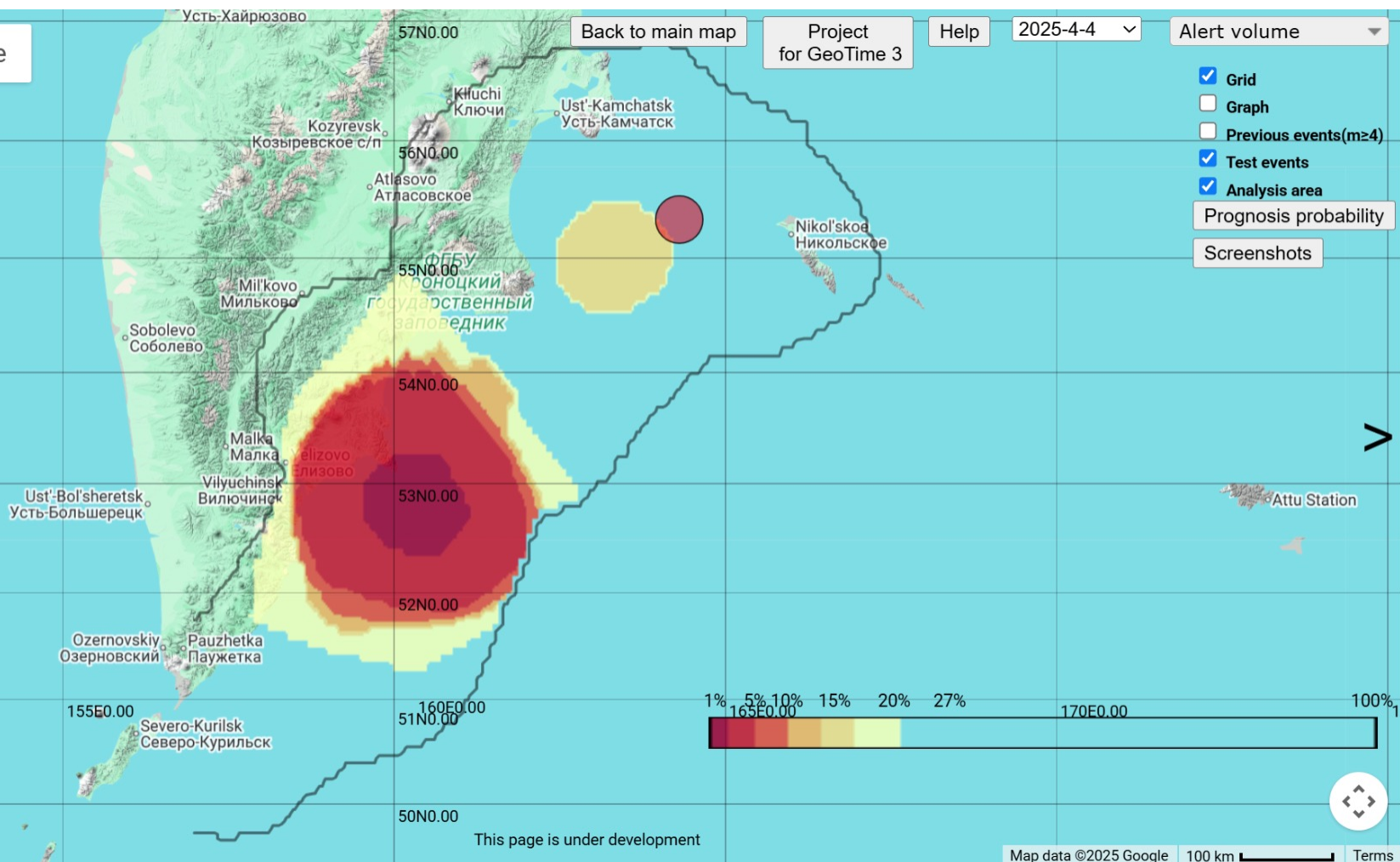
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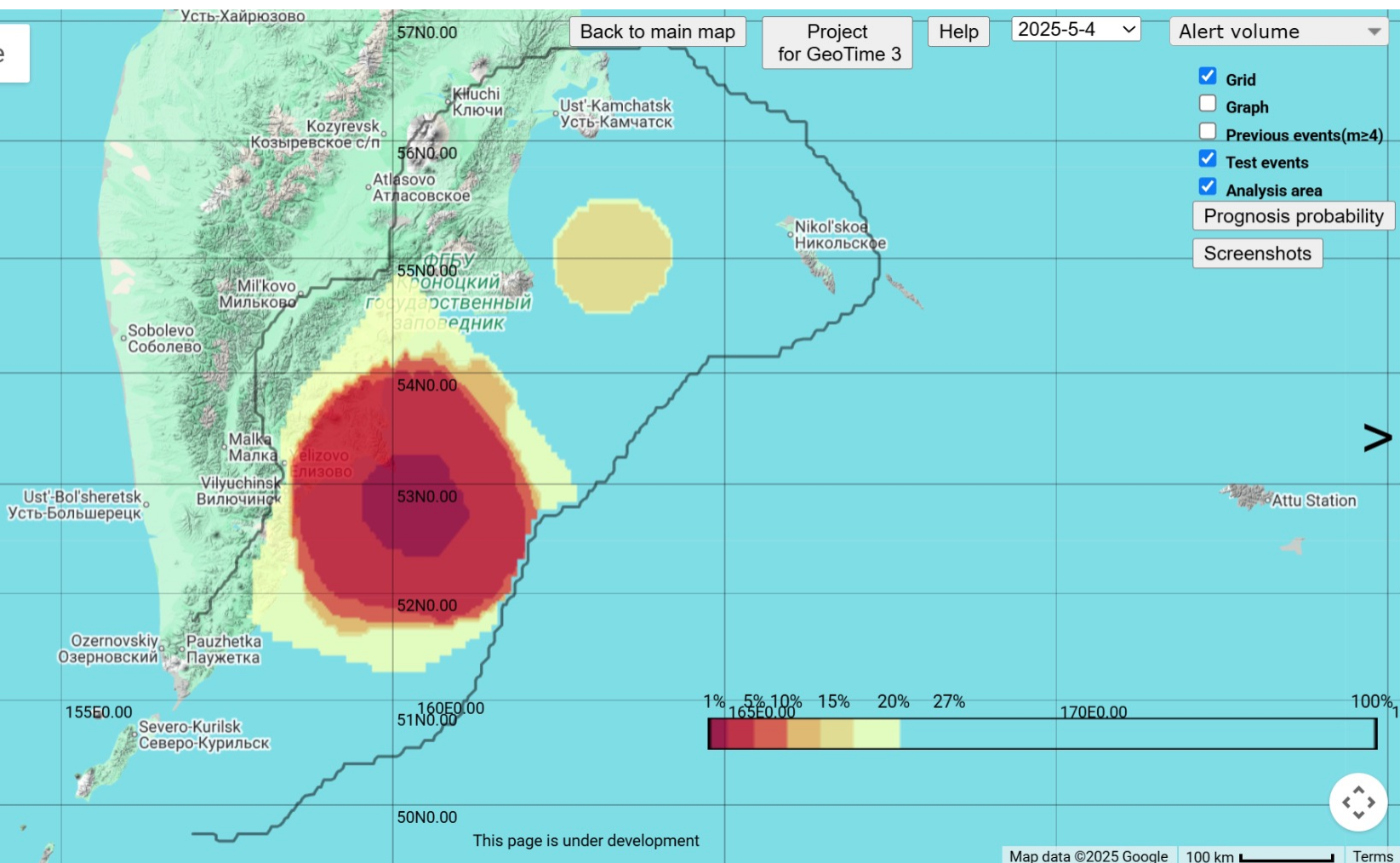
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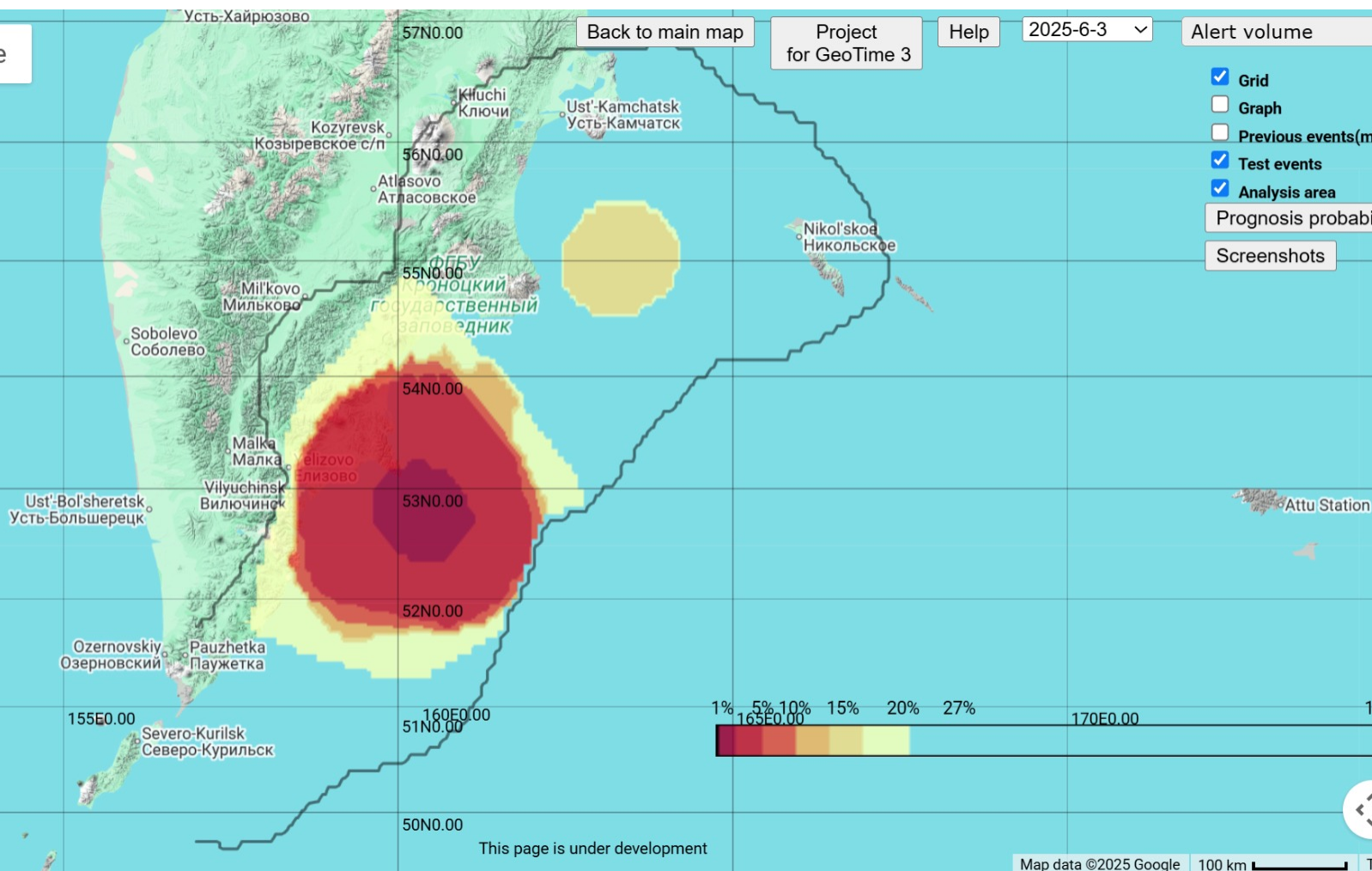
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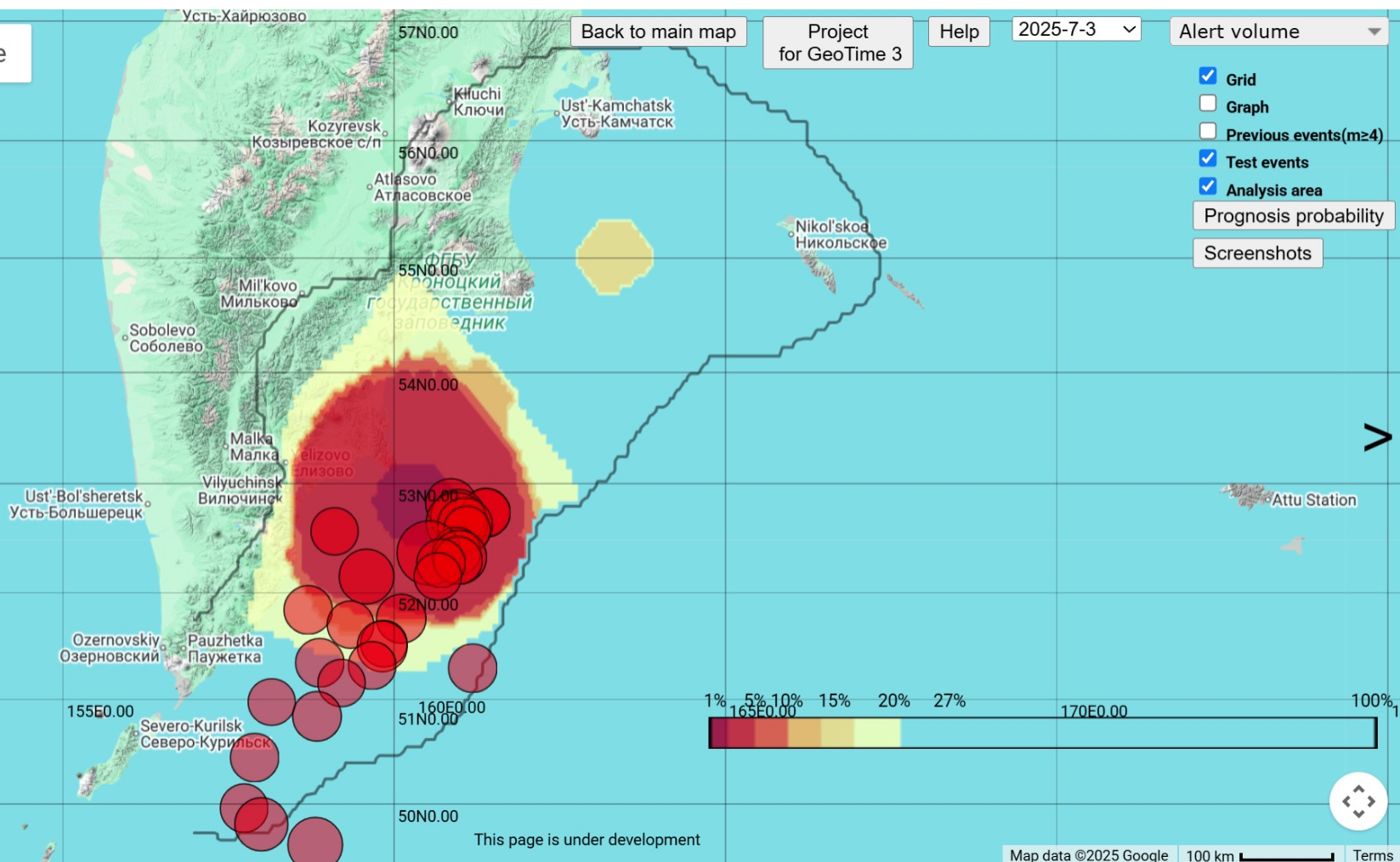
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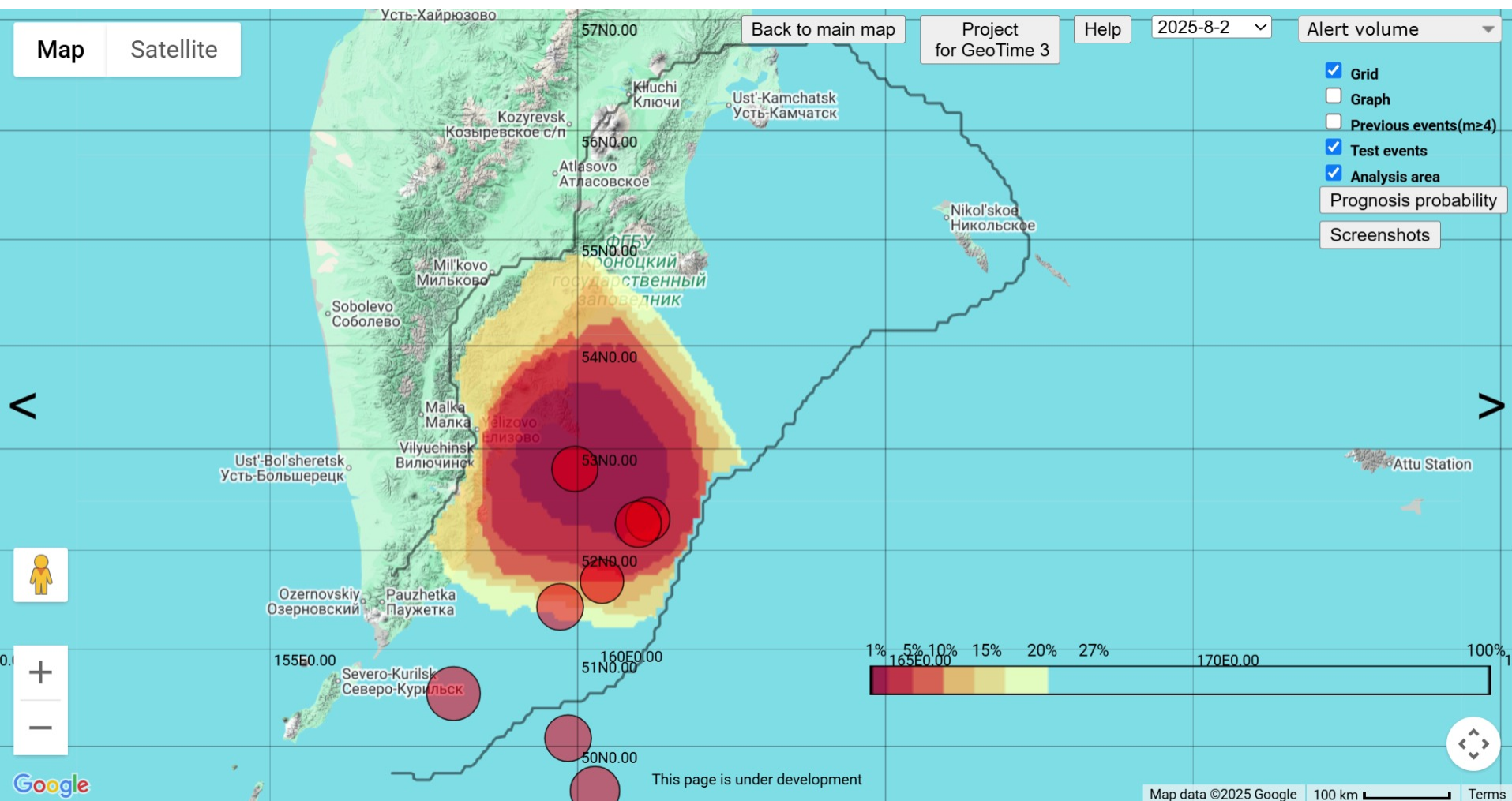
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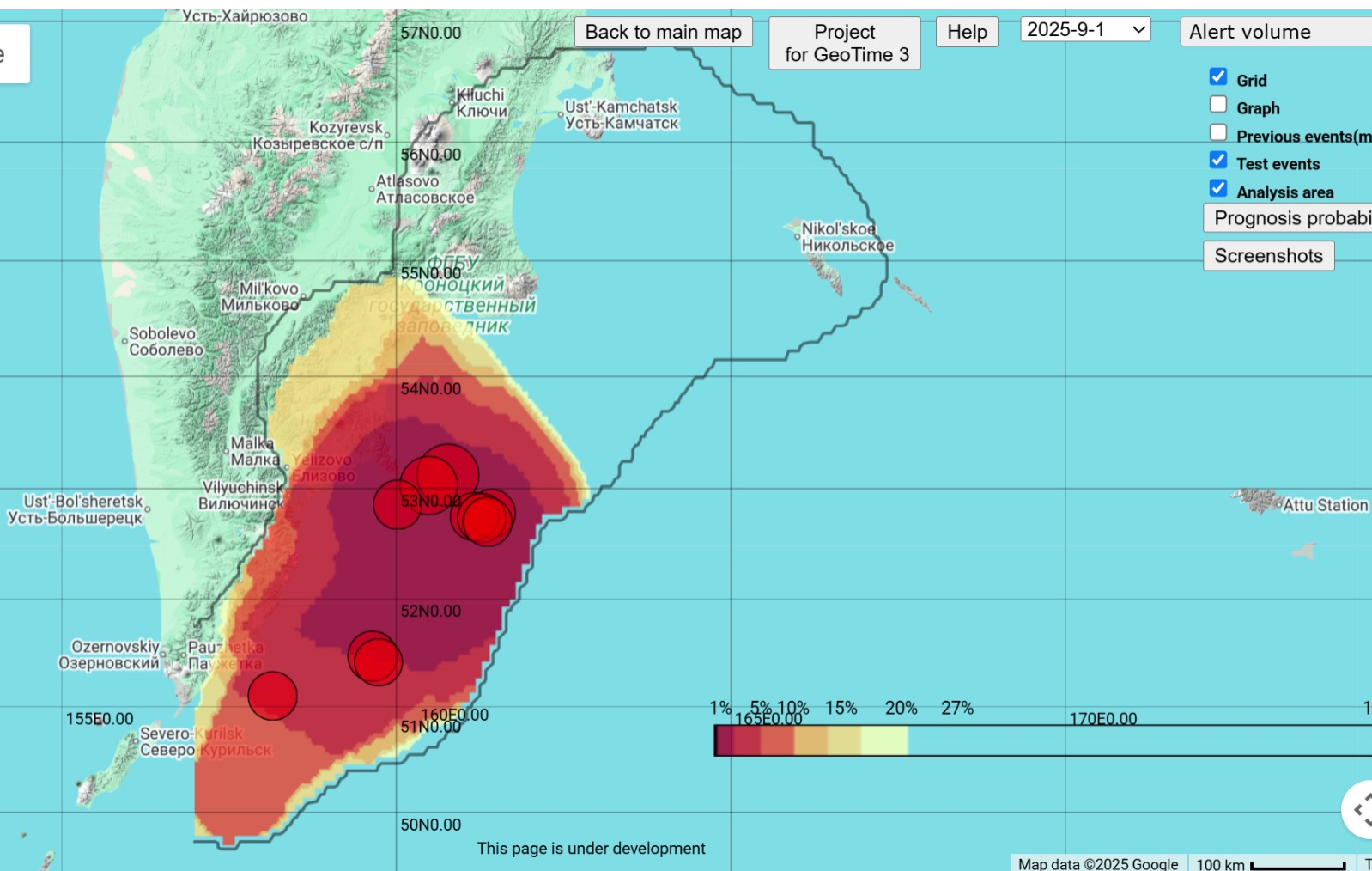
Project
for GeoTime 3

Help

2025-9-1

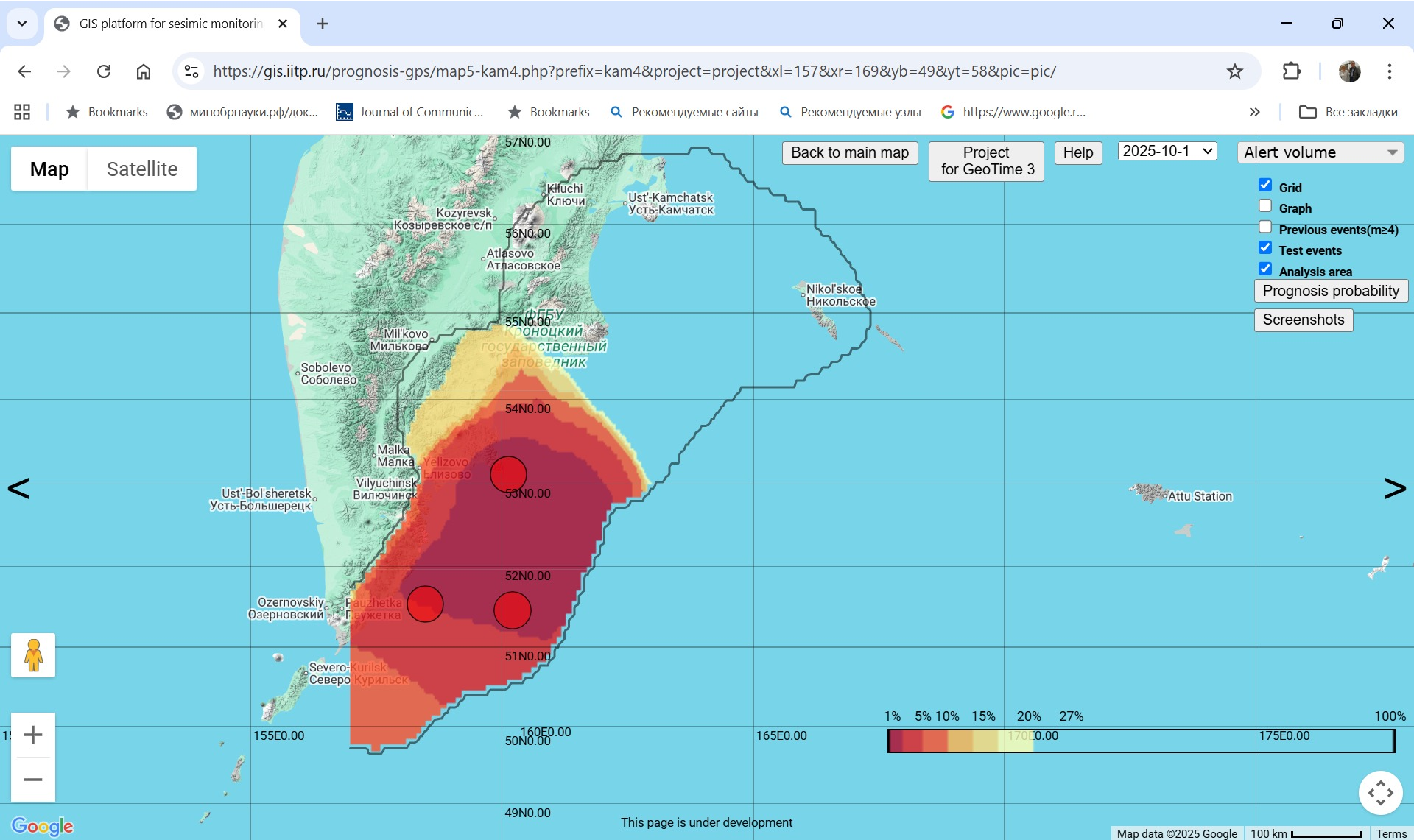
Alert volume

- ☒ Grid
- ☐ Graph
- ☐ Previous events($m \geq 4$)
- ☒ Test events
- ☒ Analysis area
- Prognosis probability
- Screenshots

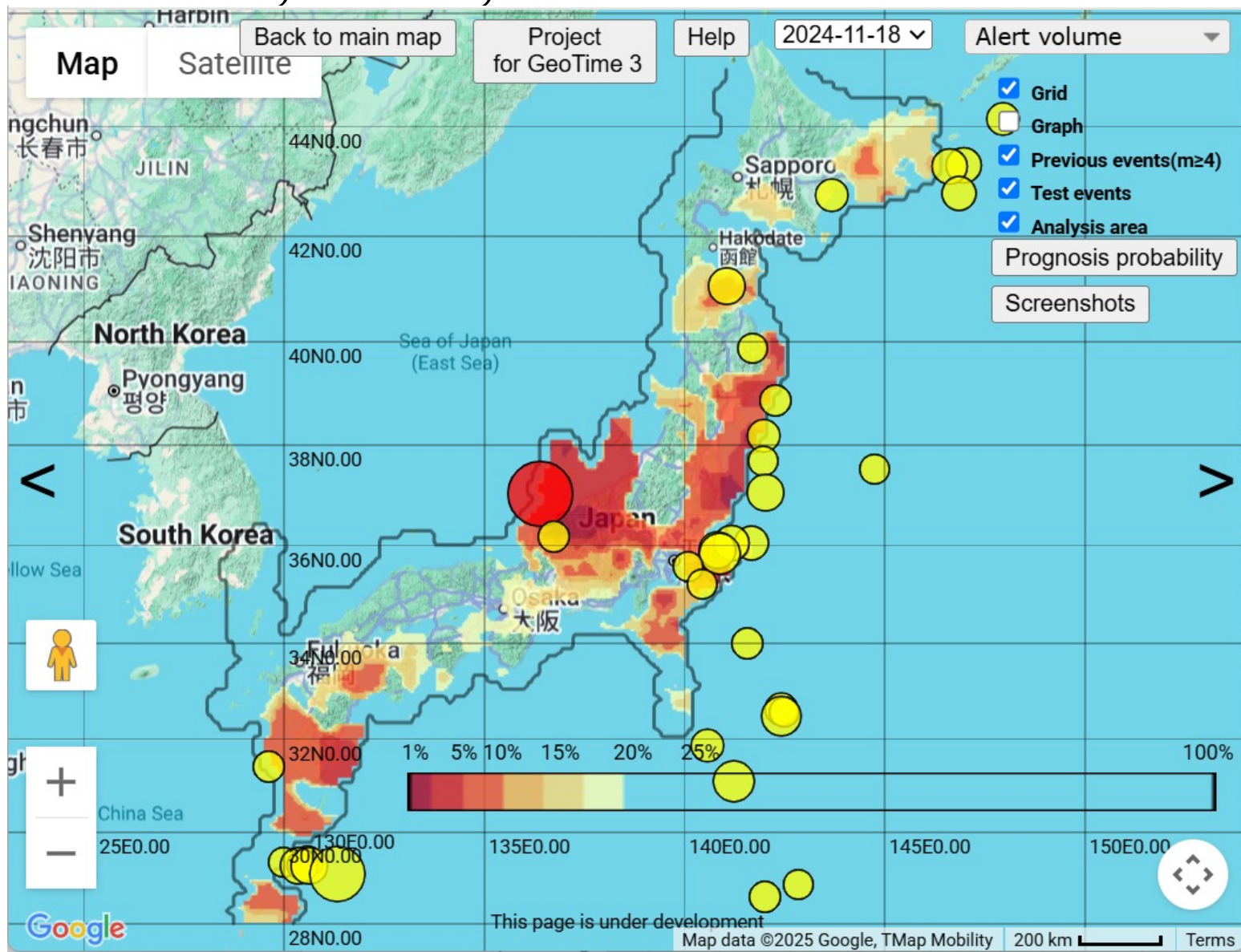


This page is under development

Map data ©2025 Google 100 km Terms



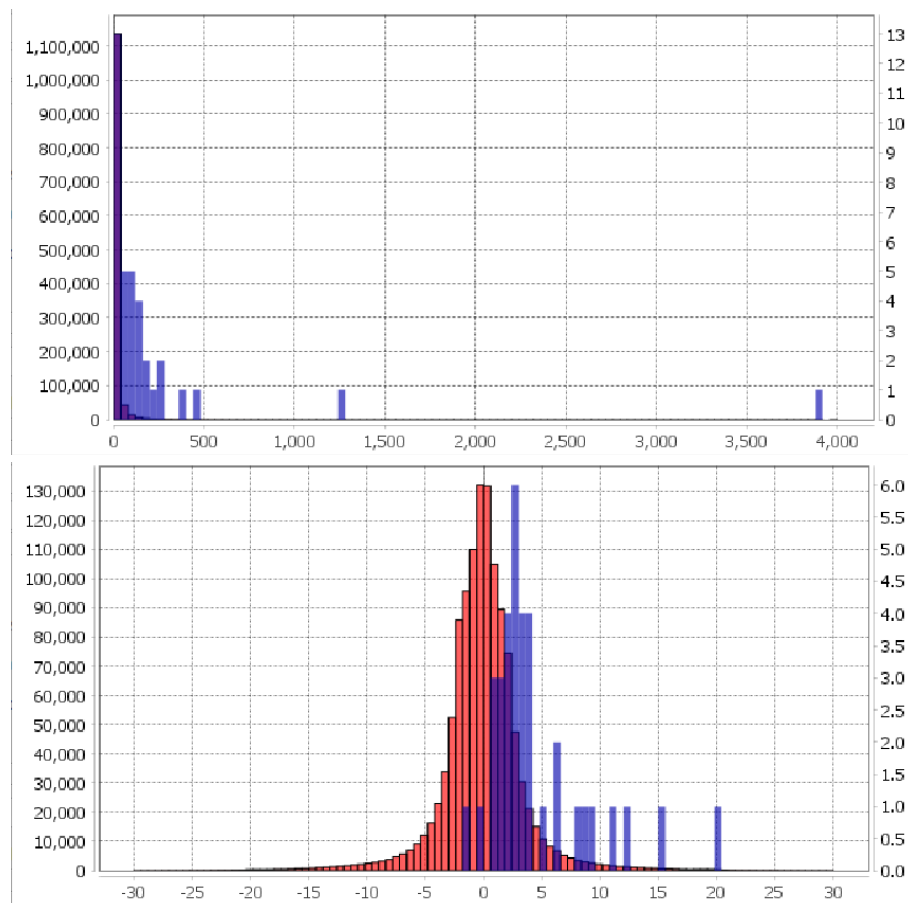
Одноэтапный прогноз землетрясений островной части Японии, $m \geq 6.0$, $H \leq 60$ км.



Значения полей на всех узлах
сетки зоны анализа. Значения
полей на узлах наиболее
информативных предвестников
землетрясений.

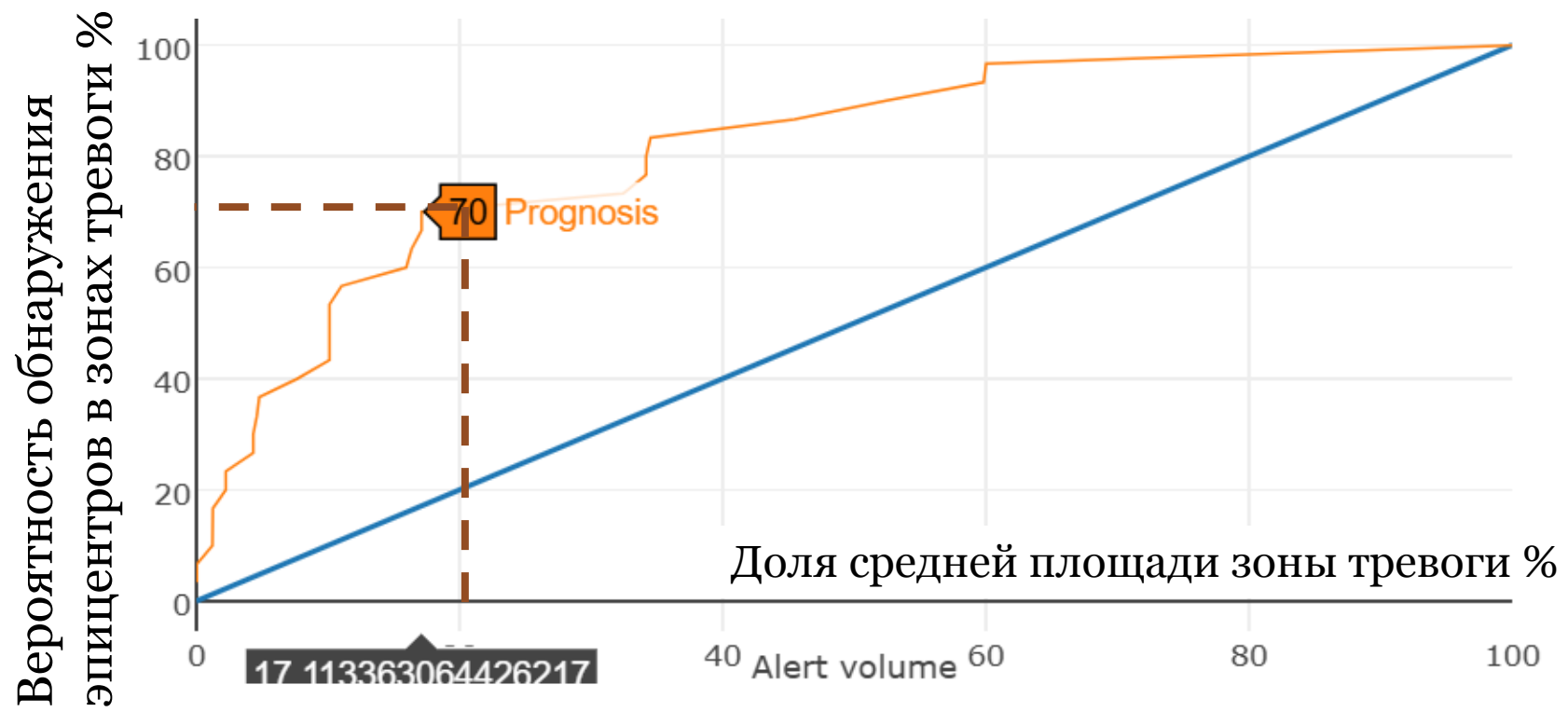
Поля

- Поле произведений плотности эпицентров землетрясений на их среднюю магнитуду, **$R=30$ км, $T=60$ суток.**
- Поле t-статистики Стьюдента от поля дивергенции скорости смещения поверхности земли по данным GPS, **$T_1=730$ суток, $T_2=90$ суток.**



<https://gis.iitp.ru/prognosis-gps/> (Одноэтапный прогноз)

Обучение от **27.01.2012**.
Тестирование **25.01.2018**.



4 Выводы

1. Поля произведений средней магнитуды землетрясений на плотность их эпицентров являются эффективными для прогноза землетрясений
2. Поля, учитывающие глубину гипоцентров землетрясений, значительно улучшают качество прогноза.

СПАСИБО ЗА ВНИМАНИЕ

4 Моделирование

Цель

Анализ прогностических возможностей полей произведения средней магнитуды землетрясений на плотность их эпицентров.

- Значений этих полей в узлах координатной сетки являются функцией от концентрационного критерия С.Н. Журкова $Z = l_{\text{ср}} / L_{\text{ср}}$:

- ✓ $l_{\text{ср}}$ - средний линейный размер очага является функцией от средней магнитуды землетрясений.
- ✓ $L_{\text{ср}}$ - среднее расстояние между очагами является обратной величиной от плотности эпицентров землетрясений.

- Методы вычисления полей: локально-ядерное сглаживание, адаптивное весовое сглаживания (AWS) и t-статистики Стьюдента.

Локально-ядерные оценки полей

- Произведение средней магнитуды на плотность эпицентров в точке (x, y, t) , где R, T – параметры полей, n – номер эпицентра:

$$s(x, y, t) = C \sum_n (m_n - m_{\min}) \exp\left(-\frac{r_n^2}{R}\right) \exp\left(-\frac{t_n^2}{T}\right), \quad t_n \leq t$$

- Плотность эпицентров :

$$s(x, y, t) = C \sum_n \exp\left(-\frac{r_n^2}{R}\right) \exp\left(-\frac{t_n^2}{T}\right),$$

- Средняя магнитуда:

$$s(x, y, t) = C \frac{\sum_n (m_n - m_{\min}) \exp\left(-\frac{r_n^2}{R}\right) \exp\left(-\frac{t_n^2}{T}\right)}{\sum_n \exp\left(-\frac{r_n^2}{R}\right) \exp\left(-\frac{t_n^2}{T}\right)}$$

**Калифорния, одноэтапный прогноз,
 $m \geq 5.3$, test 2018-01-22 - 2025-10-12, $U=83\%$, $W=40\%$.**

Поля:

- + MEAN-DEN $m \geq 2.5$ $R=130$ $T=365$ $EPS=r/R=t/T=2$
- + Student of shear with T 360 and 360 days
- + MEAN-DEN $m \geq 2.5$ $R=60$ $T=100$ $EPS=r/R=t/T=2$