

## Correlation Between the Coulomb Stress and Occurrence of the Large Induced Seismicity at Basel, Switzerland in 2006

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### Keywords

*Microseismicity, magnitude, HDR, EGS, stimulation, Basel, Coulomb stress*

### ABSTRACT

One of the critical problems in the development and operation of enhanced geothermal systems and hydrothermal reservoirs is the occurrence of felt earthquakes. Having previously shown that increases in pore pressure did not trigger the widely felt induced events observed at Basel, Switzerland, in 2006, we considered the possible triggering role of stress redistribution caused by preceding seismic events. We calculated static stress redistribution on the fault planes of the large events that were induced by preceding events, using the Coulomb 3 software package to model stress redistribution on a single fracture in a uniform crust. We found that average Coulomb stress decreased on many of the fault planes of the large events, bringing stability to the fractures. Although portions of the fault plane of the largest event showed positive changes in Coulomb stress, our modeling did not show a significant increase in Coulomb stress on this fault plane around the time of that event. We conclude that static stress redistribution did not trigger these large induced events. We also did not find any evidence that the magnitude of the events was correlated with static stress redistribution. Instead, stress redistribution in the fracture network, changes in the friction coefficient, or some undiscovered phenomenon may be the trigger mechanism.

### Introduction

Induced seismic events with large magnitude (“large events” hereafter) are recognized as a critical problem in subsurface development of hot dry rock/hot fractured rock/engineered geothermal system (HDR/HFR/EGS) projects, production of geothermal fluid from hydrothermal reservoirs, carbon capture and storage, and enhanced oil recovery operation of hydrocarbon reservoirs (Majer et al., 2007; Roger and Charles, 1982; Suckale, 2009). In EGS projects at Cooper Basin (Australia), Soultz

(France), and Basel (Switzerland), large events have been observed during and after stimulations (Asanuma et al., 2005; Baria et al., 2005). The large events at Basel caused damage to buildings and infrastructure in part of the city of Basel. Such events may cause public concerns that geothermal development increases the risk of catastrophic induced earthquakes.

Geothermal Explorers Ltd. (GEL), the operating company for Geopower Basel AG, started development of a cogeneration system for electrical power generation and heating energy (3 MWe and 20 MWt) at Basel in 1996. GEL drilled a deep borehole (Basel-1) into granitic basement to a depth of 5000 m true vertical distance (TVD) and conducted the first hydraulic stimulation in December 2006. A total of 11,500 m<sup>3</sup> of fresh water was injected into the open-hole section of the borehole from 4603 m to 5000 m over a stimulation period of six days (Häring et al., 2008). Seismic events with moment magnitude (M<sub>w</sub>) larger than 2.0 occurred in the deep and middle parts of the seismic cloud during and just after the hydraulic stimulation. Three more large events occurred in the shallow and middle part of the seismic cloud one and two months after the bleeding-off. Because of these large events, the Basel project was suspended for risk analysis, then discontinued in 2009.

We have defined the seismic events with M<sub>w</sub> > 2.0 at Basel as “large events” in this study and investigated the mechanism of the large events. We previously investigated the possibility that pore pressure is a trigger mechanism of large events (Mukuhira et al., 2009). Mukuhira (2009) observed that the critical pore pressure for shear slip of large events was relatively low and that large events tended to occur during the last stage of hydraulic stimulation or the bleeding-off phase, when the reservoir pressure was expected to be much higher than the inferred critical pore pressure. Although, many smaller events, for which the critical pore pressure was similar to that of the large events, have been induced in the hypocentral region of subsequent large events. These observations suggest that an increase in pore pressure was not the trigger mechanism of the large events. We interpreted the negative correlation between the critical pore pressure and the magnitude of the seismic events to mean that the large events occurred on a fracture plane where the stress state was close to sub-critical to failure (Mukuhira et al., 2009).

Estimates of source parameters from seismograms have revealed the characteristics of shear slip on the seismically active fractures (Mukuhira et al., 2010). The finding that large events follow a scaling law consistent with constant stress drop suggests that shear slip of large events is not a peculiar physical phenomenon, such as shear slip with high stress drop. We concluded that the controlling factor for the magnitude of seismic events at Basel was the size of the rupture area and the displacement of the slip, as commonly interpreted in global seismology (Mukuhira et al., 2010).

In a subsequent study (Mukuhira et al., 2011), we established the presence of four representative sets of fracture planes, which consist of two pairs of rock-mechanically conjugate fracture planes oriented according to the stress state. We observed that many of the large events occurred on two of the four representative fracture planes, suggesting that there was “unbalanced seismic activity” in the fracture system at Basel in which one of the conjugate pairs of fractures released most of the seismic energy, although seismic activity was low.

If increased pore pressure is not the trigger of the shear slip of the large events, possible triggers derived from the Coulomb failure criterion are redistribution of stress or changes in friction coefficient. Destabilization of fracture planes caused by stress redistribution due to preceding events might explain the occurrence of large events in later stages of stimulations. Therefore, we investigated the effect of stress redistribution using the open-source software package Coulomb 3, developed by seismologists.

## Stimulation and Geophysical Data

The hydraulic stimulation at Basel was conducted by pumping 11,500 m<sup>3</sup> of water into borehole (Basel-1) over six days. The entire open-hole section, which includes some pre-existing natural permeable zones, was pressurized. The maximum wellhead pressure reached around 30 MPa at a flow rate of 50 L/s (Schanz et al., 2007).

The distribution of hypocenters showed a subvertical planar seismic cloud oriented approximately NNW–SSE, coinciding with the direction of maximum horizontal stress in the Basel region. Source mechanisms for the 28 largest events were found to be of strike-slip type by the Swiss Seismological Service (SED) (Deichmann et al., 2007; Deichmann and Ernst, 2009). Asanuma et al., (2008) concluded that the hydraulic injection stimulated several subvertical fractures (or thin fracture networks) with NNW–SSE strikes and a horizontal extent of 200–400 m, and that this fracture system can be modeled by a mesh-like fracture model (Hill, 1977).

## Estimation of Stress Change on the Fault Planes of Seismic Events

### a) Methodology

Shear slip on an existing fault (source fault) causes deformation in its vicinity, changing the stress state on another fault plane (receiver fault). Stress redistribution is mainly determined by the distance between the source and receiver faults, the geometry of the two faults, and the displacement of the shear slip on the source fault. We used Coulomb 3 (Lin and Stein, 2004; Toda et al., 2005), which computes the Coulomb stress change on a specified fault

plane in isotropic media. Static stress change on fault planes is defined as the Coulomb stress change:

$$\Delta CFF = \Delta\tau + \mu\Delta\sigma \quad (1)$$

where  $\Delta CFF$  is the Coulomb stress change,  $\tau$  is the shear stress,  $\mu$  is the coefficient of friction, and  $\sigma$  is the effective normal stress.

Here a positive  $\Delta CFF$  means that the stress state on the receiver fault plane becomes closer to failure. Geologic deformation or Coulomb stress change is calculated as elastic deformation in a uniform and isotropic elastic medium (Okada, 1992). The software does not consider dynamic stress changes. It should be noted that source and receiver faults are isolated, and networks of receiver faults cannot be handled with this software. The inputs to Coulomb 3 are the hypocentral locations, fault plane solutions (azimuth, inclination, and slip direction), event magnitudes, and the fault area of the source fault. Average displacement on the source fault is calculated from the magnitude and fault area. The same parameters, except for the magnitudes, are used as input data for the receiver fault. This software has been widely used to investigate the correlation between occurrence of earthquakes or aftershocks and static stress changes in global seismology (Toda et al., 2011).

In this study, we used Coulomb 3 to model the static stress redistribution in the fracture system at Basel, where the target zone is much smaller than that for natural earthquakes and where fractures are intersecting. These constraints suggest that Coulomb 3 does not have the capability to fully simulate the static stress changes of the fracture network in geothermal reservoirs.

### b) Input Data

#### Fault Plane Solutions

Fault plane solutions for the 28 largest events were estimated by SED using the data from the SED seismic network. Local magnitudes of these events were determined to range from  $M_L$  1.7 to 3.4 (Deichmann and Ernst, 2009), 9 events of them corresponding large events in our definition of  $M_w > 2.0$ . Using these fault plane solutions we identified one fault plane as the ruptured fracture in a conjugate pair of nodal planes, selecting the plane with lower critical pore pressure for shear slip (Mukuhira et al., 2009).

We also estimated the orientation of the fault planes for the smaller events, for which SED did not estimate fault plane solutions, from the orientation of the multiplet seismic structure, assuming that all multiplet events within a cluster have their origin in shear slip on a single fracture plane (Asanuma et al., 2008). The direction of the slip vector was calculated from information on the stress state (Mukuhira et al., 2009).

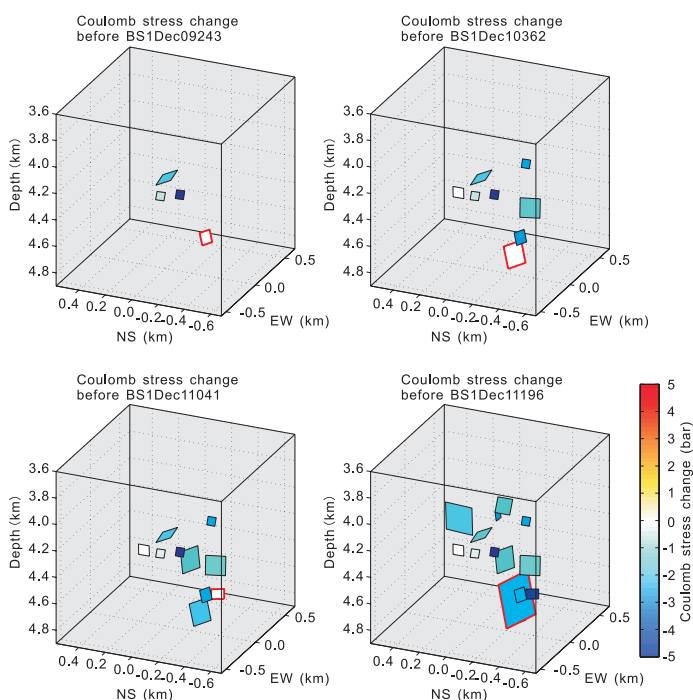
#### Source Parameters

The hypocentral locations used in this study were determined by Asanuma et al. (2008) using the double difference relocation method. We assumed that the hypocenters are in the center of the fault area. Necessary source parameters for Coulomb 3, such as moment magnitudes, average displacements, and source radius of circular fault areas, were estimated in our previous study (Mukuhira et al., 2010). Rectangular fault areas are used in Coulomb 3 so we redefined the shape of the fault areas as squares encompassing the same area.

### c) Analysis Results

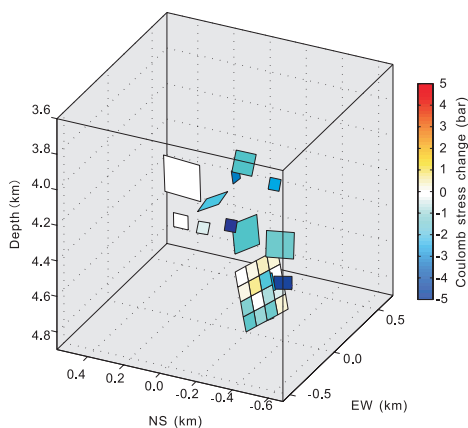
#### Coulomb Stress Change on the Fault Plane

Four large events occurred, during and just after the stimulation in the deep part of the seismic cloud where seismic activity was the highest (Mukuhira et al., 2008). Three of them, including the largest, had fault plane solutions of azimuth N111°E, and the rest occurred on a N-S striking fault plane (Mukuhira et al., 2011). Fig. 1 shows the average Coulomb stress changes on the fault planes of these four events (outlined in red). We computed Coulomb stress changes caused by the preceding seismic events with SED fault plane solutions. Negative Coulomb stress changes as great as 3.0 bar (0.3 MPa) were modeled on the fault planes of the four large events.



**Figure 1.** Average Coulomb stress change on the fault planes of the four large events at Basel in 2006 (red rectangles) and other significant events ( $1.7 < M_L < 3.4$ ) for which fault plane solutions are available.

We investigated the fault planes of the largest events by dividing the fault planes into 16 patches and calculating their Coulomb stress changes (Fig. 2). The results showed that the



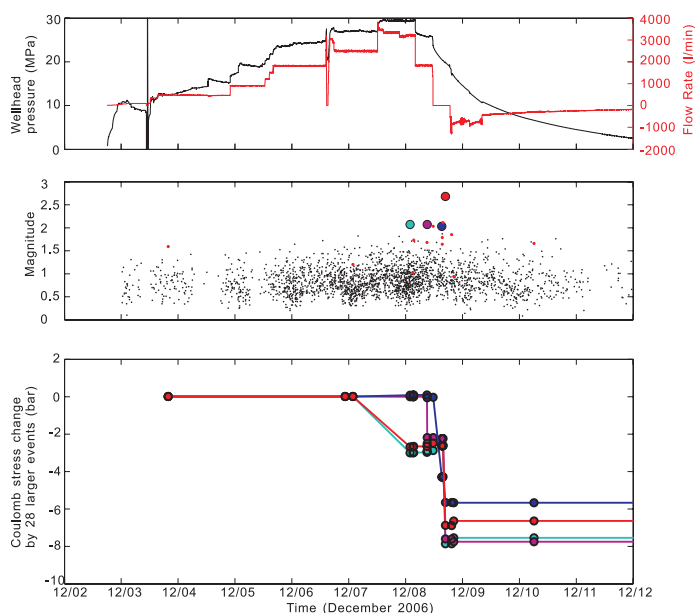
**Figure 2.** Detailed Coulomb stress changes on the fault plane (divided into 16 patches) where the largest induced event occurred. Results were similar for the other three large events.

Coulomb stress changes were heterogeneously distributed and that positive Coulomb stress changes up to 1 bar appeared on some of the patches.

#### Time-Series Analysis of Coulomb Stress Changes

Time variations of the average Coulomb stress change on the receiver fault planes of the four large events are shown in Fig. 3 along with the hydraulic records and history of magnitude of all seismic events. The source faults we used here are from the preceding seismic events for which fault plane solutions were estimated, and Coulomb stress was calculated at the times of these events.

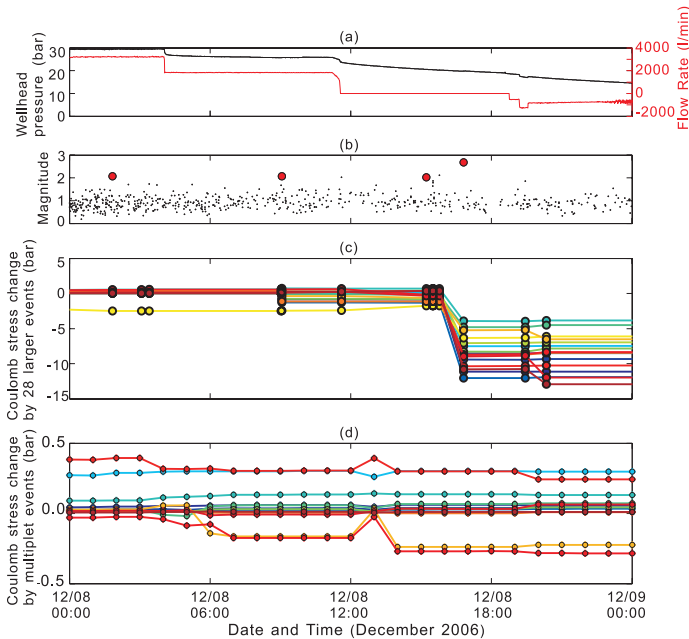
Coulomb stress on the fault planes of the first and fourth (largest) large events began to decrease one day before the first event and remained low afterward. However, Coulomb stress on these fault planes did not change more than 0.1 bar at the occurrence time of the second and third events. The Coulomb stress on the fault plane of the fourth event did not change significantly before the fourth event, although the Coulomb stress increased slightly on the fault planes of the second and third events. The Coulomb stresses on all four fault planes decreased as much as 6 bars during the fourth event. To summarize, no large event was preceded by a significant increase in average Coulomb stress on its causative fault.



**Figure 3.** Pumping records (top), magnitude history of seismic events (middle), and time series of average Coulomb stress changes on the fault planes on which four large events occurred (bottom). The colored circles in the middle plot show the times and magnitude of the four large events. The colored circles in the bottom plot show the times of occurrence of the 28 events for which fault plane solutions are available, and the colored lines show Coulomb stress changes on the fault planes of the four large events.

Fig. 4 shows details of the 24 hours around the final stage of the stimulation, including the change of Coulomb stress on the 16 patches of the fault plane of the largest event resulting from 13 events with fault plane solutions (Fig. 4(c)) and resulting from the smaller (multiplet) events (Fig. 4(d)). We calculated the

Coulomb stress change due to multiplet events every hour. Some of the patches had slight positive Coulomb stress changes after the significant events (Fig. 4(c)). The Coulomb stress on all 16 patches drastically decreased with the occurrence of the largest event, showing that the fracture was stabilized by releasing shear stress on the fracture as a seismic wave. The multiplet events loaded positive Coulomb stress changes on some of the patches, but the changes were smaller than 0.5 bar (0.05 MPa).

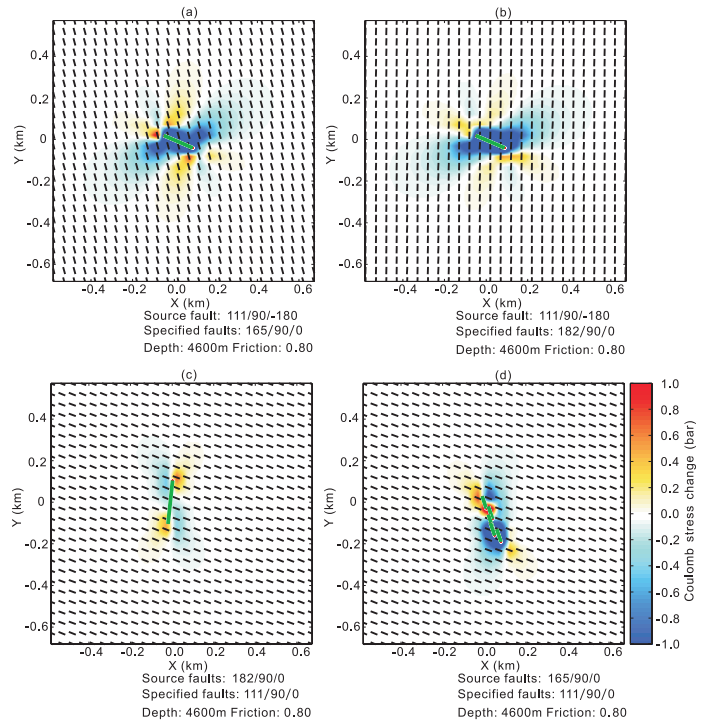


**Figure 4.** Time series of Coulomb stress change on the fault plane of the largest induced event, divided into 16 patches (see Fig. 2). (a) Hydraulic records at the last stage of stimulation and beginning of bleeding-off. (b) Magnitudes of seismic events in time, with the four large events shown by red dots. (c) Coulomb stress changes on the fault plane of the largest event, as loaded by significant events for which fault plane solutions were available. (d) Coulomb stress changes caused by smaller multiplet events, calculated every hour. Colors of the circles and lines in (c) and (d) correspond to Coulomb stress changes on each of the 16 patches.

### Coulomb Stress Changes on Four Significant Fracture Planes

Our previous study found that there are four representative subvertical fracture planes in the fracture system at Basel and that the seismic activity on these planes is unbalanced in terms of magnitude, released seismic energy, and number of seismic events (Mukuhira et al., 2011). We carried out a simulation to investigate stress interactions among these fault planes. The results of the simulation are shown in Fig. 5.

Fig. 5(a) shows the distribution of the Coulomb stress change on a receiver fault plane oriented N165°E for a source fault striking N111°E and an event of Mw = 2.0. The stress state on most receiver faults became more stable, although Coulomb stress increased in places near the ends of the source fault. We also modeled the stress interaction between two sets of fracture planes striking N111°E and N182°E caused by a Mw = 2 event on the first set (Fig. 5(b)) and the second set (Fig. 5(c)). At Basel many of the smaller events occurred on subvertical fractures striking N165°E. We modeled that situation in Fig. 5(d) using a set of five source



**Figure 5.** Stress interaction caused by seismic events on representative fracture planes from Basel. Black line segments indicate the estimated receiver faults distributed in each grid, and the green line indicates the source fault. All fracture planes are assumed to be vertical. (a) Source fault: N111°E (fault of the largest event), Mw = 2.0; receiver fault: N165°E (the most representative fracture planes in the reservoir). (b) Source fault: N111°E, Mw = 2.0; receiver fault: N182°E (where many large events occurred). (c) Source fault: N182°E, Mw = 2.0; receiver fault: N111°E. (d) Source fault: five segments N165°E, Mw = 1.0; receiver fault: N111°E.

faults striking N165°E, with a Mw = 1.0 event occurring on each fault, and receiver faults striking N111°E. It showed that some receiver faults intersecting the source fault had nearly 1.0 bar of positive Coulomb stress change.

### Discussion

Our modeling did not produce a significant increase in the Coulomb stress immediately before the occurrence of any large event. This result suggests that a Coulomb stress change was not the trigger of the large events at Basel under the assumptions embodied in Coulomb 3.

The Coulomb stress changes caused by the smaller events were much smaller than those caused by larger events even though many of these smaller events occurred around the hypocenter of the largest event (Fig. 4). Less than 0.1 bar decrease in Coulomb stress occurred on most of the 16 patches of the receiver fault (the fault plane of the largest events) owing to the preceding smaller events. This small stress change is of the same order as that induced by the tidal force. It is thus reasonable to conclude that Coulomb stress changes from the smaller events are negligible as a trigger mechanism for shear slip. Moreover, the Coulomb stress change caused by the preceding events was smaller than 5 bar (0.5 MPa), which is much smaller than the critical pore pressure for shear slip (5–30 MPa) (Mukuhira et al., 2009). One of the reasons for

this is that static stress change can propagate only in the near field of the source fault. Thus we conclude that the stress distribution caused by these seismic events was too small to trigger shear slip on existing fractures.

The average Coulomb stress on the fault planes of the large events generally decreased before the events occurred, as shown in Fig. 1, although small positive Coulomb stress changes were seen on parts of each fault plane, as shown for example in Fig. 2. These observations show that Coulomb stress changes did not destabilize large areas on the faults and cannot be considered a controlling factor for the magnitude of seismic events.

Our simulation of stress redistribution in the four representative fracture planes shown in Fig. 5 showed that areas of increased Coulomb stress tend to occur around the ends of the source fault. This suggests that the Coulomb stress at the intersection of fracture planes likely increases and that there is an increased probability of shear slip in this area than there is in independent fractures, although this kind of phenomenon cannot be simulated completely with Coulomb 3. Progress in simulation methods to model stress redistribution on fracture networks would improve understanding of the rock-mechanical interaction of seismic events in EGS reservoirs.

## Conclusions

We investigated static stress redistribution induced by the shear slip of preceding seismic events and evaluated the Coulomb stress changes on the fault planes of the large induced events at Basel using Coulomb 3. Our results showed that less than 1 bar of positive Coulomb stress change occurred on some parts of the fault planes. However, no significant change in the time series of Coulomb stress occurred before the large events, and the absolute value of the Coulomb stress change was much smaller than typical changes in pore pressure. Moreover, we found that static stress changes did not propagate to the far field even on the source faults of the largest events. We conclude that Coulomb stress change is not the trigger mechanism of the shear slip associated with the large events under the assumptions in Coulomb 3.

From our previous studies, we expected that stress redistribution would be the controlling factor for the magnitude of seismic events. In the present study we did not observe positive Coulomb stress changes over large areas capable of inducing large unstable failure and significant stress concentration on dominant fracture systems in the field. Thus it is reasonable to propose that stress redistribution is, in fact, not the controlling factor for the magnitude of seismic events.

We note that the insights in this study are based on an analysis which assumes the rock volume to be isotropic and elastically homogeneous. Coulomb 3 cannot fully simulate the behavior of static stress change in the presence of networked fracture systems, although it has enabled us to investigate the relation of stress redistribution and occurrence of large events to some extent. According to the Coulomb failure criterion, the coefficient of friction still remains as a critical parameter. There are also other undefined factors controlling the magnitude of seismic events. Further studies to establish a geomechanical model including stress redistribution in fracture networks and the friction factor will make it possible to better understand these phenomena.

## Acknowledgments

This study was conducted with the open-source Coulomb 3 software. We thank Geopower Basel AG for providing the microseismic data set and approving the publication of these results. This study was supported by the Japan Ministry of Education, Culture, Sports, Science and Technology and the Japan Society for the Promotion of Science.

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