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Structural control of geothermal reservoirs in extensional tectonic settings: An example from the Upper Rhine Graben

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ABSTRACT

In extensional tectonic settings major structural elements such as graben boundary faults are typically oriented subparallel to the maximum horizontal stress component S_{Hmax}. They are often structurally accompanied by transfer zones that trend subparallel to the extension direction. In the Upper Rhine Graben, such transfer faults are typically characterized by strike-slip or oblique-slip kinematics. A major re-orientation of the regional stress field by up to 90° of the Upper Rhine Graben in the Early Miocene led to the present-day normal and strike-slip faulting regimes in the North and South of the Upper Rhine Graben, respectively, and a transition zone in-between. Consequently, conditions for fault frictional failure changed significantly. Moreover, it has been observed during tracer and stimulation experiments that such transfer faults may be of major importance for the hydraulic field of geothermal reservoirs under the present stress condition, especially, when located between production and injection well.

In this context we have investigated slip and dilation tendencies (T_S and T_D) of major structural elements at reservoir scale for two representative geothermal sites, Bruchsal (Germany) and Riehen (Switzerland), located close to the Eastern Main Boundary Fault of the Upper Rhine Graben. We have evaluated the quality and uncertainty range of both tendencies with respect to potential variation in S_{Hmax} orientation. Despite significant differences in orientation of the structures and the stress regimes, the resulting variation of T_S and T_D reveal major similarities concerning the reactivation potential of both, the graben-parallel structures and the transfer faults. The conditions of criticality for tensile failure and non-criticality for shear failure suggest that transfer faults are most likely naturally permeable structures with low stimulation potential. This is in agreement with the absence of both immediate tracer recovery and seismicity in the studied geothermal sites.

1. Introduction

Most of the geothermal systems world-wide are controlled by their tectonic setting and related structural features. Extensional tectonic settings and related structures comprising normal and transtensional faults and fractures dominate in intra- and back-arc basins, extending zones of orogenic belts, spreading ridges, and continental rifts (Angelier et al., 1997; Curewitz and Karson, 1997; Bellani et al., 2004). Faults and fractures that are favorably oriented and critically stressed for frictional failure commonly control both fluid flow and reactivation potential (Barton et al., 1995; Sibson, 1996; Ito and Zoback, 2000).

Extensional terrains and, in particular, continental rifts are commonly characterized by closely spaced and complex en-echelon normal faults that represent main structural boundaries as described for the West Anatolian or Basin and Range provinces (Faulds et al., 2010, 2011). These normal faults can be linked either by accommodation zones or transfer faults. Complex interplay of such extensional faults, including stress concentrations at and along fault tips and fault intersections, favors localization of geothermal anomalies (e.g. Curewitz and Karson, 1997; Baillieux et al., 2013). Intersections of graben-parallel normal faults with transversely oriented oblique-slip faults are common structural features of some of the most productive geothermal fields world-

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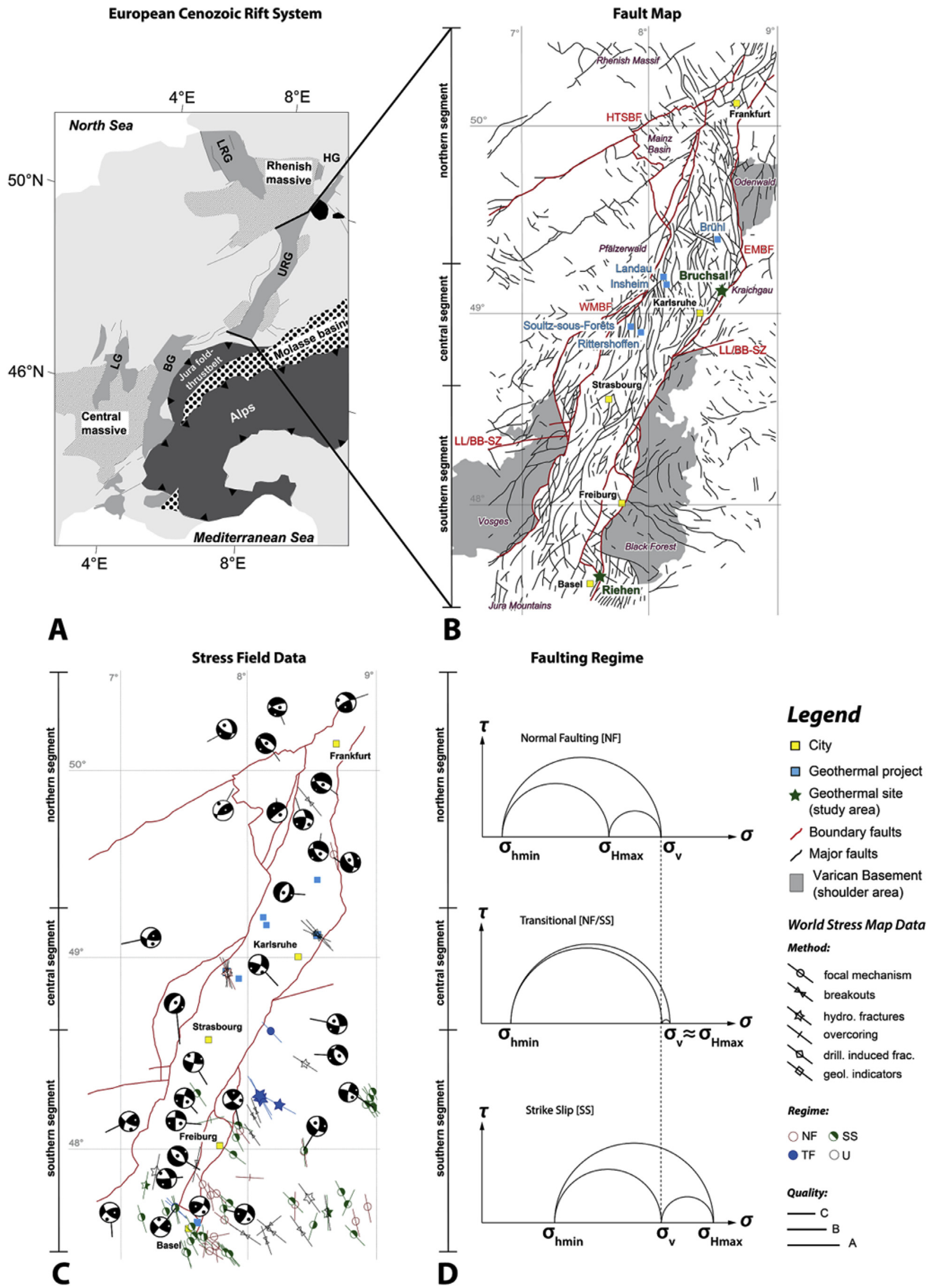
European Cenozoic Rift System
North Sea
4°E
8°E
50°N
46°N
LRG
Rhenish massive
HG
URG
LG
BG
Jura fold-thrustbelt
Molasse basin
Alps
Central massive
Mediterranean Sea
A
Fault Map
7°
8°
9°
50°
49°
48°
northern segment
central segment
southern segment
Rhenish Massif
Frankfurt
HTSBF
Mainz Basin
Odenwald
Brühl
EMBF
Pfälzerwald
Landau
Insheim
Bruchsal
Kraichgau
WMBF
Karlsruhe
Soultz-sous-Forêts
Rittershoffen
LL/BB-SZ
Strasbourg
Freiburg
Vosges
Black Forest
Basel
Riehen
Jura Mountains
B
Stress Field Data
Frankfurt
Karlsruhe
Strasbourg
Freiburg
Basel
C
Faulting Regime
Normal Faulting [NF]
σ_{hmin} σ_{Hmax} σ_v
Transitional [NF/SS]
σ_{hmin} $\sigma_v \approx \sigma_{Hmax}$
Strike Slip [SS]
σ_{hmin} σ_v σ_{Hmax}
τ
σ
D
Legend
City
Geothermal project
Geothermal site (study area)
Boundary faults
Major faults
Varican Basement (shoulder area)
World Stress Map Data
Method:
focal mechanism
breakouts
hydro. fractures
overcoring
drill. induced frac.
geol. indicators
Regime:
NF
SS
TF
U
Quality:
C
B
A