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Effective crustal permeability controls fault evolution: An integrated structural, mineralogical and isotopic study in granitic gneiss, Monte Rosa, northern Italy

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ABSTRACT

Two dextral faults within granitic gneiss in the Monte Rosa nappe, northern Italy reveal key differences in their evolution controlled by evolving permeability and water/rock reactions. The comparison reveals that identical host rock lithologies develop radically different mineralogies within the fault zones, resulting in fundamentally different deformation histories. Oxygen and hydrogen isotope analyses coupled to microstructural characterisation show that infiltration of meteoric water occurred into both fault zones. The smaller Virgin Fault shows evidence of periodic closed system behaviour, which promoted the growth of hydrothermal K-feldspar, whilst the more open system behaviour of the adjacent Ciao Ciao Fault generated a weaker muscovite-rich fault core, which promoted a step change in fault evolution. Effective crustal permeability is a vital control on fault evolution and, coupled to the temperature (i.e. depth) at which key mineral transformations occur, is probably a more significant factor than host rock strength in controlling fault development. The study suggests that whether a fault in granitic basement grows into a large structure may be largely controlled by the initial hydrological properties of the host rocks. Small faults exposed at the surface may therefore be evolutionary "dead-ends" that typically do not represent the early stages in the development of larger faults.

Fault zones are long-lived zones of weakness in the Earth's crust; how they form and evolve is crucial to studies of earthquake mechanics and subsurface fluid flow (Martel, 1990; Cavailhes et al., 2013). In faults within basement rocks, the damage zone generally has high permeability compared to both the host rock and the fault core (Caine et al., 1996; Evans et al., 1997), however the permeability of the fault core and damage zone will vary as successive deformation events create new fractures or re-open existing fractures (Caine et al., 1996; Zhang and Tullis, 1998). Fracturing and cataclasis cause grain size reduction and generate weaker rocks that can be deformed more easily by granular flow/cataclasis (Tullis and Yund, 1985). Hence as deformation proceeds, mechanisms may switch from discrete fracturing to cataclasis (Fitzgerald and Stünitz, 1993). Fracturing creates higher permeability and the presence of fluids in a fault zone may control the mineralogy via fluid–rock reactions (Chester et al., 1993; Wintsch et al., 1995), which in turn influences the deformation mechanisms and fault rock strength (Janecke and Evans, 1988; Wibberley, 1999; Di Toro and Pennacchioni, 2005; Faulkner et al., 2008; Boulton et al., 2009). Depending on the nature of the reactions; porosity can be created or destroyed, permeability increased or decreased and these characteristics, in turn, can affect seismic processes (Wintsch et al., 1995; Janssen et al., 1998; Kirkpatrick and Shipton, 2009; Mittempergher et al., 2009).

This paper describes the relationships between mineralogy, fluid influx and deformation history on two adjacent but contrasting Alpine faults in granitic gneiss from the Monte Rosa nappe, northern Italy using a combination of field and petrographic evidence, fluid inclusion and stable isotope analysis. We develop a model for fault development that links the evolving hydraulic properties of the fault to the mineral reactions controlling rock strength.

1. Geological setting

The field area, Passo Moro, is within the Monte Rosa nappe of the Western Alps, northern Italy. The area consists of granitic gneiss, amphibolite and an approximately 150 m thick metasedimentary layer primarily composed of quartz-rich pelites (Fig. 1A). Both the granitic gneiss and pelites have a foliation defined by muscovite and biotite dipping at ca. 35° to the WNW. The largest amphibolite sheet can be traced for 300–400 m. Several other thin amphibolites are below the resolution of the map. The Macugnaga augen gneiss was originally emplaced as a

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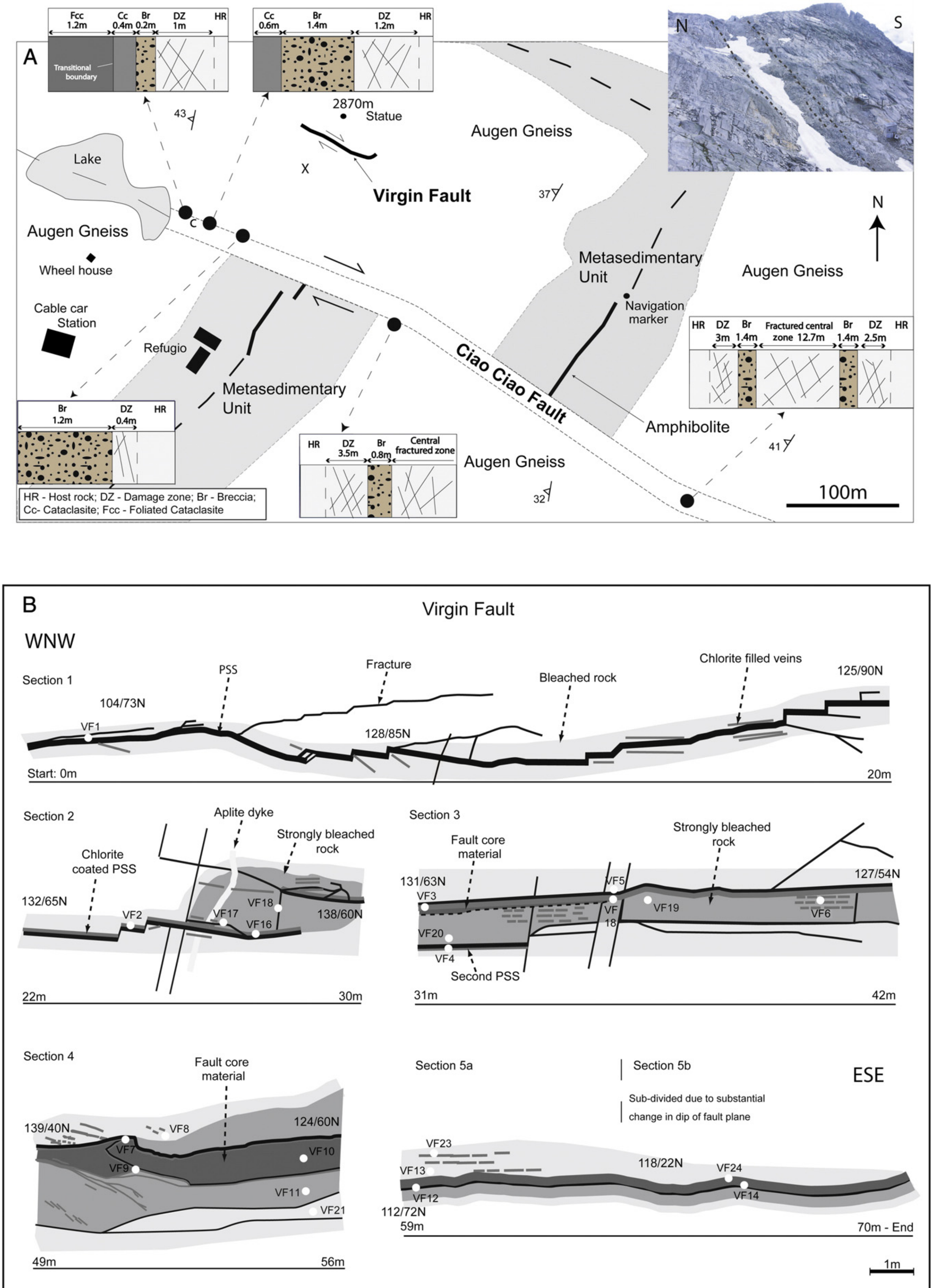
A
Fcc 1.2m
Cc 0.4m
Br 0.2m
DZ 1m
HR
Transitional boundary
Cc 0.6m
Br 1.4m
DZ 1.2m
HR
N
S
2870m
Statue
Augen Gneiss
Lake
X
Virgin Fault
37
43
Augen Gneiss
c
Wheel house
Cable car Station
Refugio
Metasedimentary Unit
Navigation marker
Augen Gneiss
N
HR DZ 3m Br 1.4m Fractured central zone 12.7m Br 1.4m DZ 2.5m HR
Ciao Ciao Fault
Metasedimentary Unit
Amphibolite
Br 1.2m
DZ 0.4m
HR
HR DZ 3.5m Br 0.8m Central fractured zone
Augen Gneiss
41
32
100m
HR - Host rock; DZ - Damage zone; Br - Breccia; Cc- Cataclasite; Fcc - Foliated Cataclasite
B
Virgin Fault
WNW
Section 1
PSS
Fracture
Bleached rock
Chlorite filled veins
125/90N
104/73N
VF1
128/85N
Start: 0m
20m
Section 2
Aplite dyke
Strongly bleached rock
Chlorite coated PSS
132/65N
VF2
VF17
VF18
VF16
138/60N
22m
30m
Section 3
Fault core material
Strongly bleached rock
131/63N
VF3
VF5
VF 18
VF19
127/54N
VF6
VF20
VF4
Second PSS
31m
42m
Section 4
Fault core material
139/40N
VF8
124/60N
VF7
VF9
VF10
VF11
VF21
49m
56m
Section 5a
Section 5b
ESE
Sub-divided due to substantial change in dip of fault plane
VF23
VF13
118/22N
VF24
VF12
VF14
112/72N
59m
70m - End
1m