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The structural and seismological evolution of dilational step-overs in regional transtension zones

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We propose a theoretical model, supported by field data from the Northumberland Basin (UK) to describe the patterns of fault/fracture meshes formed within dilational step-overs developed along faults accommodating wrench-dominated transtension and to explain seimsicity observed at these sites. The geometry and kinematics of the faulting in the dilational step-overs are related to the angle of divergence (a), and differ from patterns traditionally predicted in dilation zones associated with boundary faults accommodating strike-slip displacements (where a = 0°). We examine a dilational step-over zone associated with regional dextral strike-slip zones, developed during Late Carboniferous wrench-dominated transtension in the Northumberland Basin (UK). For low values of oblique divergence (a $<$ 30°) and low strain, the fault/fracture mesh comprises interlinked tensile fractures and wrench-dominated planes. Doleritic dyke intrusion was favoured at this stage by local structural permeability increase. At higher values of strain, a switch occurs from wrench- to extension-dominated transtension leading to the oblique-extensional reactivation and/or disruption of the early formed structures. Suction pump behaviours have been widely documented within the transtensional dilational step-over. These structural processes lead to the development of a geometrically complex and kinematically heterogeneous fault pattern, which likely inhibits and/or perturbs the development of a through-going fault linking and facilitating the slip transfer between the two overlapping fault segments. In this context, dilational step-over zones formed during transtensional deformation, represent long-lived sites of localised oblique extension and subsidence. We test our theoretical/field

based results against seismological data from the Dead Sea Transform (DST, Gulf of Aqaba, NE Africa), a seismically active transtensional plate boundary where deformation occurs in a few tens of kilometers wide zone characterized by NNE-aligned left-stepping strike-slip faults parallel to the plate boundary. A number of pull-apart basins are developed between the overlapping segments. The seismic activity along the DST is characterized by strike-slip events (e.g. 1995, Mb = 6.2) nucleating along NNE faults and N-S oblique extensional earthquakes localized at pull-apart bounding faults (e.g. 1993, Mb = 5.8). Seismicity prior to 1995 was located at the two major fault step-overs and was followed by the 1995 earthquake which ruptured 45-50 km along a DST segment, propagating NNE during a sinistral strike-slip event. The mainshock was followed by an intense aftershock sequence characterised by left-lateral strike-slip largest aftershocks ($Mw>5$) on the major bounding faults and small aftershocks ($Mw<5$) localised mainly at step-overs between major faults. Aftershocks ($Mw<5$) display a pronounced heterogeneous kinematics with both strike- and oblique-slip extensional focal mechanisms. We interpret the geometry and kinematics of the aftershock sequence as being consistent with our theoretical models and field-based observations of wrench- (low strain) and extension-dominated (high strain) deformation patterns at 3-D transtensional dilational step-overs. Our interpretation represents an alternative to a heterogeneous seismic sequence induced by an almost complete stress drop as suggested by previous authors. The lack of wrench through-going faults and the localised extensional seismicity (1993) within the major dilational step-overs is thus in accord with the theoretical and field based findings.