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**Slip heterogeneity on a corrugated fault**

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Abstract

Slip heterogeneity reflects the fundamental physics of earthquake rupture and has been attributed to strong fault patches termed asperities or barriers. We propose that variations in fault surface orientation due to slip-parallel corrugations may act as geometric asperities and barriers, generating variations in incremental (i.e. due to a single earthquake) slip across a fault surface. We evaluate this hypothesis using observations from the Arkitsa normal fault exposure in central Greece.

A scan of the Arkitsa Fault surface with 1-m spatial resolution and mm-scale precision reveals corrugations made up of 1-5 m wide synforms, antiforms, and nearly planar fault sections with long axes that extend in the slip direction across the entire exposed surface. The surface is thus more than an order of magnitude smoother in the direction of slip than in the perpendicular direction. Slip-perpendicular profiles exhibit nearly self-similar scaling across the range of observed wavelengths (~2-50 m), whereas slip-parallel profiles are significantly smoother at shorter wavelengths (<~5 m).

Millimeter-scale striations, indicators of incremental slip direction, have heterogeneous orientations across the corrugated surface. Using spherical statistics we demonstrate a statistically significant correlation between striation orientation and the local orientation of the fault surface. These results are consistent with the hypothesis that corrugations have acted as asperities and/or barriers and thus play a fundamental role in earthquake mechanics.

We propose that slip heterogeneity associated with corrugations may play an important role in the evolution of fault surface morphology both by smoothing fault surfaces in the slip perpendicular direction and by generating wall rock flow.
perturbations that may act to enhance corrugation topography with slip. Slip
heterogeneity is likely to further impact fault zone mechanics by generating significant
variations in near fault stress. Patterns of wall rock fracturing and localization of
aftershocks in the hanging walls of normal fault earthquakes may reflect these stress
effects. Slip-parallel corrugations may be particularly important to the mechanics of
large-slip faults where faults are smoothed significantly in the slip direction.

Keywords
Faults, earthquakes, asperities, fault-surface roughness, kinematics, mechanics, Greece

1. Introduction
Slip during earthquakes, imaged by geophysical inverse studies (Mai & Beroza,
2002, and references therein) and direct observations of surface ruptures (Wesnousky,
2008, and references therein), is heterogeneously distributed across fault surfaces. This
heterogeneity reflects the fundamental physics of earthquake rupture and has been
attributed to asperities and barriers, strong fault patches that respectively accumulate high
pre-slip stress leading to large coseismic slip magnitude or resist coseismic slip and
generate high post-seismic stress (Aki, 1984; Kanamori & Stewart, 1978). Asperities and
barriers are inferred to play a fundamental role in earthquake nucleation and termination
(e.g. Schwartz & Coppersmith, 1984; Wesnousky, 2006), the evolution of near fault
stress including the occurrence of foreshocks and aftershocks (e.g. Das & Scholz, 1981;
Dodge et al., 1996; King et al., 1994; Oppenheimer et al., 1988; Woessner et al., 2006),
and generation of high-frequency seismic radiation (e.g. Madariaga, 1983; Spudich &
Frazer, 1984). At present, dynamic models of earthquake rupture are unable to uniquely resolve the underlying physical causes of slip heterogeneity (Guatteri & Spudich, 2000; Peyrat et al., 2004). Observations of exhumed fault zones, however, provide a means to directly observe fault zone geometry and architecture at the scale of earthquake slip and thus investigate likely causes of slip heterogeneity including rheological and geometric asperities or barriers.

Investigations of exposed fault zones reveal a consistent architecture in which a broad damage zone surrounds a narrow core that is generally cut by through-going shear surfaces that accommodate the majority of slip (Chester & Chester, 1998; Chester & Logan, 1986; Wilson et al., 2003). Fault surfaces are in turn characterized by a suite of structures elongated sub-parallel to the slip direction (e.g. Stewart & Hancock, 1991). Fault surfaces are thus naturally rougher in the direction perpendicular to slip than in the direction parallel to slip (Power et al., 1987; Renard et al., 2006). This effect is greater for large-slip faults (Sagy et al., 2007) and likely reflects processes of frictional wear (Power et al., 1988; Sagy et al., 2007). Fault surface roughness in the direction perpendicular to slip is approximately self-similar for wavelengths ranging from $10^{-5}$ to $10^5$ m (Lee & Bruhn, 1996; Power & Tullis, 1991; Sagy et al., 2007). In detail, however, scaling parameters appear to vary between specific wavelength ranges, a phenomenon that has been attributed to different physical processes acting at various length scales (e.g. Lee & Bruhn, 1996). Shorter wavelength features: slickenside lineations, tool-tracks, and gutters, generally termed striations, have widths (half wavelengths) << 1 m and lengths < 5 m. Striations are interpreted to form due to frictional wear associated with asperities (used here in the physical sense) on the fault surface, with individual structures typically
recording a single seismic event (Engelder, 1974). Longer wavelength features, generally
termed corrugations, have widths ranging from \(\sim 10^{-1} - 10^5\) m and lengths > \(10^1\) m.
Although the mechanism(s) leading to the formation of corrugations is less clear, they are
interpreted to form through processes of fault growth (Ferrill et al., 1999; Hancock &
Barka, 1987) and/or flow instabilities within fault zones (Sagy & Brodsky, 2009).
Variations in the composition and distribution of the various fault zone elements
(damage zone, fault core, and slip surface) are likely sources of rheological asperities or barriers (Biegel & Sammis, 2004; Sagy & Brodsky, 2009). Variations in the overall geometry of the fault zone, and of the slip surface in particular, are likely sources of geometric asperities or barriers. Kilometer-scale slip-parallel and perpendicular fault bends and discontinuities have been correlated with variation in near fault stresses (Saucier et al., 1992), earthquake rupture initiation and termination (King & Nabelek, 1985; Schwartz & Coppersmith, 1984; Wesnousky, 2006), and aftershock occurrence (King et al., 1994), as well as variations in long-term slip direction (Maerten, 2000; Roberts, 1996). Small-scale slip-parallel roughness has also been suggested as a major source of geometric asperities and barriers through variation in dynamic friction parameters (Power et al., 1987) as well as generation of variable near-fault stress (Chester & Chester, 2000; Sagy & Brodsky, 2009). The role of small-scale slip-perpendicular roughness in earthquake and fault mechanics has received considerably less attention than the roles of small-scale slip-parallel or large-scale fault surface roughness.
We propose that variations in fault surface orientation due to corrugations may lead to differences in resolved tractions on active fault surfaces. In this manner slip-perpendicular roughness due to slip-parallel corrugations may act as geometric asperities...
and barriers, generating variations in incremental (i.e. due to a single earthquake) slip
direction and magnitude across a fault surface. On exposed fault surfaces striations,
formed during incremental slip, may therefore record slip heterogeneity associated with
variations in surface orientation due to corrugations. In this study we evaluate this
hypothesis using observations of fault surface morphology and striation orientation from
the spectacular Arkitsa Fault exposure in central Greece. We find that striations
orientation varies systematically with changing fault normal direction across the
corrugated surface even though corrugations and striations have similar mean directions
(differing by less than 10° in azimuth). We conclude that corrugations are a likely source
of geometric asperities and barriers and may be of particular importance for large-slip
faults where slip surfaces are significantly smoother in the slip direction due to processes
of frictional wear.

2. Description of the Arkitsa fault surface

The study area is located near the eastern end of the Arkitsa fault (Figure 1), one
of a series of north-dipping normal fault segments that define the southern boundary of
the North Gulf of Evvia - Sperchios Basin graben of central Greece (Cowie et al., 2006;
Eliet & Gawthorpe, 1995; Goldsworthy & Jackson, 2001; Jackson & McKenzie, 1999;
Roberts & Ganas, 2000). This graben is one of several seismically active zones of
extension generally inferred to accommodate mechanical interaction of the North
Anatolian-Aegean Trough strike-slip fault system and the Hellenic subduction zone
(Flerit et al., 2004; Goldsworthy et al., 2002). Basin bounding faults of these grabens are
often well-exposed where they juxtapose Mesozoic carbonates in their footwalls with
Neogene sediments in their hanging walls. The Arkitsa exposure is the most extensive and pristine due to removal of hanging wall colluvium since ~1996 that has exposed a 50 m high fault surface along more than 500 m of strike length (Jackson & McKenzie, 1999). Slip on the Arkitsa fault, although poorly constrained, is likely to significantly exceed the 300-400 m topographic relief of the associated footwall block.

Jackson and McKenzie (1999) first described the Arkitsa exposures in detail, noting that the surface is corrugated at all scales and that although the surface varies in strike orientation by up to 40°, slip vector orientation varies by less than 10° in azimuth (based on 7 measurements). Kokkalas et al. (2007) scanned the surface with ~10^-1 m data spacing using a terrestrial laser scanner (TLS) and found that corrugation axes also show significantly less variability in orientation than fault surface normals, and that corrugation axis plunge is correlated with fault dip. In this study we integrate fault surface scanning at ~1 m scale with field measurement of ~2 mm wavelength slickenlines within a GIS and analyze the data using spherical statistics and curvature analysis to more thoroughly explore the relationship between fault surface orientation and fault slip direction recorded by both meter-scale corrugations and mm-scale striations.

To characterize the geometry of the Arkitsa fault surface we scanned the two eastern panels (a and b of Kokkalas et al. (2007)) of the surface (Figure 2a) with a robotic reflectorless total station (Topcon GPT-8203A). (The westernmost fault panel (c of Kokkalas et al. (2007)) was avoided due to the presence of an active garbage dump.) The reported precision of this system, ~3 mm in range and ~1 mm in horizontal distance at 50 m range, is equivalent to or slightly better than many TLS systems; however the data collection rate is significantly slower, up to 4 seconds per point. The surface was
scanned from six positions along the fault at distances of 20-75 m and individual scans were co-registered by surveying the relative locations of these stations using the total station in prism mode. The resulting point cloud (Figure 2b) was rotated into a strike perpendicular reference frame (x axis trend 288°, y axis vertical, z axis trend 18°) and interpolated using tension splines to generate a gridded fault surface with 1 m spacing. Digital photographs and control points were collected to generate orthophotos to assist with integration of field measurements as well as surface scan data editing and interpretation (Figure 2a). A shaded relief image of the gridded fault surface (Figure 2c) shows the characteristic corrugations plunging toward the northwest.

Curvature analysis of the scanned fault surface provides a means to quantify and visualize the geometry of the entire surface (Mynatt et al., 2007; Pearce et al., 2006). We calculated the absolute maximum curvature and geologic curvature of the gridded fault surface using the Matlab® code of Mynatt et al. (2007). For geologic curvature calculations, absolute curvature magnitudes less than a threshold value equivalent to a 50 m radius of curvature were set to zero when defining idealized forms (Mynatt et al., 2007). The resulting image (Figure 2d) shows that the corrugations are made up of relatively narrow (1-5 m) antiforms and synforms that are nearly continuous across the exposure in their axial direction. Nearly planar regions of similar width separate these curved portions of the fault surface. Maximum absolute curvatures for these synforms and antiforms range from -0.13 to 0.13 respectively (Figure 2e), equivalent to a minimum ~8 m radius of curvature. Cross fracturing and zones of hanging wall colluvium (Figure 2a) disrupt this overall pattern and are the major sources of curvature at a high angle to the corrugations. The cross fractures appear to have been active during slip, as evidenced...
by rounding, polishing, and scratching of corners formed at the intersections between
cross fractures and the fault surface.

To quantify the roughness of the fault surface we applied root mean square
(RMS) and power spectral density (PSD) methods (Brown, 1995; Power et al., 1988) to
58 m x 10 m windows oriented with their long dimensions perpendicular and parallel to
the corrugation axes. Windows were selected from areas with both significant (eastern
panel) and minimal (western panel) cross fracturing (Figure 2 a, c). Profiles from
corrugation perpendicular windows (Figure 3a) reveal broadly curving and nearly planar
portions of the fault surface that define the corrugations. RMS roughness in the direction
perpendicular to the corrugations is similar for both the highly cross-fractured eastern
window (0.589 ± 0.094 m) and the less-fractured western window (0.745 ± 0.011).

Corrugation parallel profiles (Figure 3b) generally exhibit lower-amplitude long-
wavelength curving with shorter wavelength “noise” due to cross fracturing and other
surface irregularities. RMS roughness results reveal that the western window, with little
cross fracturing, is more than an order of magnitude smoother (0.035 ± 0.014 m) in the
direction parallel to corrugations compared to the corrugation perpendicular direction
(0.745 ± 0.011 m). The eastern window, however, where cross fracturing is more
prevalent, has larger amplitude long wavelength curvature in the slip direction than the
western window and has an intermediate RMS roughness (0.246 ± 0.027 m).

Power spectral density plots, calculated using the multitaper method, provide a
means for visualizing the relative distribution of amplitude over wavelengths from ~2-50
m (Figure 3c). The relatively low number of samples in our windows prohibits precise
estimates of power spectra scaling parameters (Simonsen et al., 1998). Corrugation
perpendicular profiles show nearly self-similar scaling (linear slope of 3 on PSD plot) for
2-7 m wavelengths, but appear to exhibit a slightly steeper linear slope at wavelengths
greater than ~ 7 m. Corrugation parallel profiles from the western window are smoother
(have a lower PSD) across all wavelengths than the corrugation parallel profiles, while
profiles from the eastern cross-fractured window are smoother than the corrugation
parallel profiles at short wavelengths (< ~ 7 m), but approach the PSD values of the
corrugation-perpendicular profiles at longer wavelengths.

These results illustrate that the Arkitsa fault surface, similar to other fault surfaces
that have been analyzed in detail (Lee & Bruhn, 1996; Power et al., 1987; Renard et al.,
2006; Sagy et al., 2007), is characterized by corrugations elongated parallel to the slip
direction that exhibit nearly self-similar scaling in slip perpendicular profiles over the
range of observed wavelengths. The fault is thus significantly smoother in the direction
parallel to slip than in the direction perpendicular to slip. Curvature analysis reveals that
the Arkitsa fault surface is characterized by nearly planar surfaces separated by regions of
high curvature and that corrugation axes are nearly continuous across the entire exposed
surface rather than forming closed domes as observed for a suite of faults from the
Western United States by Sagy et al. (2007). The major source of long wavelength slip-
parallel roughness appears to be warping of the fault surface associated with cross
fracturing rather than terminations of individual corrugations.

3. Analysis of striation and corrugation orientations

We collected 321 measurements of fault surface orientation (dip and dip
direction) and striation rake using a field compass and protractor to evaluate the
heterogeneity of incremental slip (i.e. due to a single earthquake) across the corrugated fault surface. Measured features included mineralized, gouge-filled, and open mm-to-cm-scale slickenlines and grooves (Figure 4a). Individual measurement locations were marked on digital photographs to allow for spatial registration with the surface scan data using digital orthophotos (Figure 2a, b). Mean orientations and 2 sigma ellipses were calculated assuming a Kent (elliptical) distribution (Fisher et al., 1987) with propagation of an additional ±2° error for field compass measurements. A plot of poles to the fault surface (open circles in Figure 4b) shows a broad spread of data over 75° of trend and 29° of plunge with a mean dip direction of 23±5° and a mean dip of 63±3°. Poles to the two fault panels analyzed overlap by 25° in strike but only 6° in dip. The western panel is steeper and strikes more northerly (mean dip direction 31±5°, dip 68±3°) than the eastern panel (mean dip direction 12±5°, dip 57±2°). Striations are more tightly clustered (filled dots in Figure 4b, mean trend 341±4°, plunge 56±3°) with largely overlapping trends (mean trend 339±4° western, 344±8° eastern) and plunges (mean plunge 58±3° western, 54±4° eastern) between the two panels.

Tools for exploratory data analysis of scalar variables are unable to completely characterize the relationship between the vector quantities of striation orientation and local fault surface orientation. We have therefore taken two approaches to explore the relationship between these observations, one graphical and the other statistical. Our first approach was to rotate the data into a kinematically relevant reference frame with the y-axis parallel to the mean corrugation direction and the z-axis parallel to the mean fault normal direction (Figure 4d). The data were then reduced to scalar values through projection. Figure 4e shows a scatter plot of the angle (clockwise positive) between the
mean fault normal and the projection in the x-z plane of the individual fault surface normal vectors (*inclination from the mean fault plane*) vs. the angle (counterclockwise positive) between the mean striation direction and the projection in the x-y plane of the individual striation vectors (*variation from the mean striation direction*). This plot shows a weak, but significant correlation. This result is more clearly illustrated by plotting variation across a single large amplitude (~10 m peak to trough) corrugation (Figure 5). Figure 4f shows a scatter plot of the angle (counterclockwise positive) between the mean striation direction and the projection in the x-y plane of individual fault surface normal vectors (*direction of maximum inclination from the mean fault plane*) vs. the variation from the mean striation direction. If variation in striation direction were predominately due to hanging wall flow around footwall asperities one might expect positive (counterclockwise) variation in striation direction in the upper right (90-180°) and lower left (0-90°) quadrants and negative variation in the other two quadrants as flow both diverges around asperities and converges at the terminations of asperities. 200 of the 321 observations are consistent with this model. The clustering of values near ±90 for the direction of maximum inclination is a result of the continuity of the corrugations in the slip direction.

Although projections allow for visual inspection of possible associations between striation direction and fault orientation, they necessarily omit the third dimension of the problem. Our second approach was thus to apply spherical statistics to fully quantify the relationship between surface orientation and striation direction. We calculated the correlation coefficient, \( \rho_v \), between the two vector quantities and estimated the significance level, \( \rho_\beta \), using matrix permutation methods (Fisher et al., 1987). We tested...
against the alternative hypothesis of no correlation by calculating the statistic for 10,000 random pairings of fault normal and slip direction with orthogonality enforced through projection of the slip vector onto the fault plane. The field measurements have a correlation coefficient $\rho_v = 0.305$, significantly higher than the randomized data ($\rho_v = -0.050 - 0.132$ for 99% probability interval). Incremental slip, as recorded by mm-scale striations, thus varies systematically with changes in fault surface orientation associated with corrugations. The correlation between slip direction and fault orientation is also significant for each of the fault panels treated separately, indicating that the correlation is not driven solely by the relatively large changes in fault orientation and slip direction between panels.

We performed a similar statistical analysis to test if meter-scale corrugation axial orientation varies systematically with long-wavelength changes in fault surface orientation. We extracted corrugation orientations by calculating axes of zero curvature for selected regions of the fault surface. The data were filtered to select only axes from antiforms or synforms with a radius of curvature less than ~30 m (Figure 2e). The resulting corrugation axes (Figure 4d) have a mean trend of $329\pm2^\circ$ (mean trend of $328\pm2^\circ$ western panel, $333\pm5^\circ$ eastern panel) and a mean plunge of $55\pm1^\circ$ (mean plunge of $56\pm1^\circ$ western panel, $52\pm2^\circ$ eastern panel). To calculate the underlying fault surface orientation, we low-pass filtered the gridded surface scan data to preserve long wavelength (> 30 m) undulations while removing variation in orientation due to m-scale corrugations. The corrugation axes and filtered fault orientation data have a correlation coefficient $\rho_v = 0.107$ which is significant in comparison to a random corrugation axis model ($\rho_v = -0.040 – 0.106$ for 99% probability), however the data from each of the fault
panels analyzed individually do not show a significant correlation. These results
demonstrate that the orientation of meter-scale corrugation axes varies in relation to the
orientation of the fault surface at the fault panel scale (>~50 m).

We interpret correlations between striation and surface orientation as evidence
that incremental slip on the Arkitsa fault surface is perturbed by the presence of
corrugations. Although mean striation orientation (trend 341±4°, plunge 56±3°) across
the Arkitsa quarry exposure is nearly parallel to mean corrugation axis (trend 329±2°,
plunge 55±3°), variability in the orientation of striations is correlated with the orientation
of the fault surface. The orientation of m-scale corrugations in turn is correlated with the
orientation of the fault surface at long wavelengths (> ~50-m scale). Our graphical
analysis suggests that changes in striation orientation are a function of both the
magnitude and direction of changes in the fault surface orientation. We propose a likely
explanation for these relationships is that the variation in slip direction reflects changes in
resolved shear traction associated with a remote tectonic stress (Angelier, 1979; Bott,
1959; Wallace, 1951). To evaluate this hypothesis we determined an optimal remote
stress tensor using Fault and Stress Analysis software (Celerier, 2006). The rakes
predicted from this model have a root-mean-square error (RMSE) of 4.8° in comparison
to observed rake data, an improvement over the assumption of a constant slip direction
(RMSE 5.3°). The remaining error may be due to random variation and measurement
error, however, we suspect an additional source of error is the effect of near-fault stress
perturbations due to slip on the irregular surface (Pollard et al., 1993). A more complete
model would also account for stress interactions and wall-rock deformation across the
slipping corrugated fault.
4. Implications for the formation of corrugations

Striation orientations reveal that incremental slip across much of the Arkitsa fault surface includes a component of slip perpendicular to the corrugation axes. If this slip heterogeneity were common to other faults, then faults should become polished in both the slip parallel and slip perpendicular directions with increasing slip. Observations of a suite of faults by Sagy et al. (2007) support this contention, revealing significant slip-perpendicular smoothing at wavelengths < 1m for at least two of the six large slip faults that they measured. If corrugations form during fault propagation (Ferrill et al., 1999; Hancock & Barka, 1987) then faults would be expected to evolve toward smoother geometries in all directions with increasing slip magnitude. Slip heterogeneity would also likely decrease with increasing net slip as fault surfaces become smoother.

Heterogeneous slip across corrugated fault surfaces is also likely to generate zones of convergent and divergent flow in the surrounding wall rocks. This flow perturbation may lead to buckling or necking instabilities across the fault zone that generate or enhance corrugation topography. Sagy and Brodsky (2009) suggested that the closed “bumps” that they observed on the Flowers Pit fault surface may have formed in this manner. They noted that the bumps were associated with lenses of granular material, visible where the fault surface was breached due to erosion, and suggested that the bumps may be boudins or mullions (as described by Smith (1975)) formed due to necking or buckling of the fault core within the surrounding wall rocks. Flow instabilities associated with finite-thickness layers have growth rates that are strongly dependent on wavelength, leading to a dominant wavelength for a given layer thickness and viscosity.
contrast (Biot, 1961; Smith, 1975), a hypothesis that is testable from observations of exposed fault zones (Sagy & Brodsky, 2009). At least in the case of the Arkitsa fault we suggest, alternatively, that the slip-parallel corrugations may grow as mullions in the classic sense where cuspate-lobate folds form in response to shortening parallel to the contact between two layers of markedly different stiffness (Ramsay, 1967; Wilson, 1953). The Arkitsa fault surface presently separates relatively stiff footwall carbonates and carbonate breccias from poorly consolidated, soft Neogene sediments in the hanging wall. A similar juxtaposition is likely to have existed for a relatively long time as the depth to basement in the hanging wall Gulf of Evvia is ~ 4 km (Makris et al., 2001). Mullions formed from a single interface between stiff and soft material would not have a characteristic wavelength (Pollard & Fletcher, 2005), which is consistent with the common observation that slip-perpendicular roughness of fault surfaces exhibits nearly self-similar scaling rather than exhibiting a dominant wavelength (Lee & Bruhn, 1996; Power & Tullis, 1991; Power et al., 1988; Sagy et al., 2007). A testable prediction of the single interface model is that the cusps, or folds of short radius of curvature, should point toward the stiffer wall rocks. A visual inspection of surface profiles of the Arkitsa fault (Fig. 3a and b) suggests that long wavelength (10’s of meters) corrugations have relatively broad ridges and narrow troughs, consistent with this hypothesis, however an analysis of the entire scanned fault surface reveals that the mean curvature is nearly identical for ridges and troughs. Results for the Arkitsa Fault are thus inconclusive, however, we believe that this model warrants further testing with higher resolution data from a suite of large-slip faults.

The down-plunge continuity of the corrugations on the Arkitsa Fault surface is particularly striking. If corrugations form through linking of pre-existing structures (Ferrill et al., 1999), the continuity of corrugations may reflect the geometry of pre-existing fractures. For layered materials, fracture spacing and height are dependent on layer thickness (Bai & Pollard, 2000; Helgeson & Aydin, 1991; Narro & Suppe, 1991).

The continuity of the corrugations on the Arkitsa Fault surface may therefore reflect the large layer thickness of the footwall carbonates in which they are hosted. The extreme aspect ratios of the nearly planar fault segments (> 10:1), however, require initial structures that were highly elongated in the slip direction (nearly perpendicular to bedding) or incorporation of highly elongate segments of overlapping initial structures. Either of these situations is unlikely based on the observations of fault scaling and spacing in layered media cited above. Alternatively, the continuity of corrugations may be explained as an effect of polishing associated with large slip magnitude. The magnitude of slip on the Arkitsa fault is equal to or greater than the largest slip faults observed by Sagy et al. (2007). Slip-parallel culminations and saddles that define the “bumps” of Sagy et al. (2007) may have been removed by continued slip on the fault surface. A third explanation for the continuity of corrugations is suggested by results of three-dimensional buckling experiments (Kaus & Schmalholz, 2006) where a component of extension in the intermediate direction (parallel to eventual fold hinges) generates greater fold continuity. If corrugations grow due to flow instabilities then their continuity may reflect the three-dimensional (3D) strain state of the volume surrounding the fault. The continuity of corrugations in the slip direction may thus reflect the homogeneity of the faulted material, the magnitude of slip, or the 3D strain state of faulting. Each of
these hypotheses should be testable through additional observations of fault surface
morphology and fault zone geometry.

5. Relevance to fault and earthquake mechanics

Our analysis of the Arkitsa fault illustrates that corrugations are associated with
heterogeneity in incremental slip direction and that these slip-parallel features thus act as
geometric asperities or barriers. We propose that variations in resolved tractions on the
fault surface are the most likely cause of the observed slip heterogeneity. The resulting
variation in slip direction may, however, have additional significant effects on fault
mechanics. Previous work has shown that slip perpendicular roughness can reduce
normal stresses to near zero in close proximity to a fault surface (Chester & Chester,
2000; Saucer et al., 1992). Variation in slip direction across a corrugated fault surface
may similarly reduce near-fault normal stresses due to divergence of slip across
corrugation axes. De Boer (1992) noted that open joints were more abundant in concave
footwall corrugations, consistent with a localized reduction in least-compressive stress.
Fault corrugations may therefore generate heterogeneity in footwall and hanging wall
damage zones and thus alter the distribution of permeability within the fault zone (Caine
et al., 1996). Fault zone permeability may in turn effect fault strength through temporal
and spatial variations in fluid pressure (Sibson, 1990). In the case of normal faults the
majority of strain associated with slip heterogeneity due to corrugations is likely
accommodated by hanging wall rocks due to the relative compliance of hanging wall
basin sediments as well as geometric weakening associated with dipping fault surfaces
(Grasemann et al., 2005). Slip and stress heterogeneity associated with fault surface

Corrugations may thus provide an explanation for the localization of aftershocks in the hanging wall of normal fault earthquake ruptures (e.g. Chiaraluce et al., 2003; Resor et al., 2005), even where the fault surface is apparently planar at ~km-scale.

Corrugations may play an especially important role in the mechanics of mature faults. Fault surfaces evolve toward simpler geometry with increasing slip (Ben-Zion & Sammis, 2003, and references therein). This effect has been documented both for km-scale steps in surface traces of strike-slip faults (Stirling et al., 1996; Wesnousky, 1988) and in roughness of exposed fault surfaces (Sagy et al., 2007). Short-wavelength (≤ 1 m) smoothing has been attributed to abrasional wear associated with fault slip (Sagy et al., 2007). Faults are smoothed most significantly in the slip parallel direction, and to a lesser degree in the slip perpendicular direction. Slip heterogeneity associated with corrugations provides an explanation for the observed smoothing of slip-perpendicular roughness with accumulated slip, as the incremental slip is not perfectly parallel to large-scale roughness. The perseverance of significant slip-perpendicular roughness in the form of fault corrugations on mature fault surfaces, however, may still generate slip and stress heterogeneities fundamental to earthquake and fault mechanics.

Observations from creeping faults appear to corroborate the importance of slip-parallel geometry on fault and earthquake mechanics. Streaks of microearthquakes have been observed along a number of creeping fault segments (Rubin et al., 1999; Schaff et al., 2002; Waldhauser et al., 1999; Waldhauser et al., 2004). The observation that these streaks parallel the slip direction independent of local geology suggests a geometric rather than rheological control (Rubin et al., 1999). Rubin et al. (1999) suggest that fault
corrugations of a scale that is unresolvable in the relocated seismic data (10’s of meters) are a likely candidate for the generation of these streaks.

6. Conclusions

The Arkitsa fault surface, similar to other large-slip faults, is characterized by slip-parallel corrugations that exhibit nearly self-similar scaling across the range of observed wavelengths (~2-50 m). Millimeter-scale striations on this corrugated surface record heterogeneous slip directions likely associated with slip during a single seismic event. This slip heterogeneity is correlated with the local orientation of the fault surface. Slip-parallel corrugations thus act as asperities or barriers to incremental fault slip. We attribute this effect to variations in resolved tractions across the corrugated surface.

We propose that slip heterogeneity may play an important role in the evolution of fault surface morphology through two, possibly competing, mechanisms. 1) Heterogeneous slip, including a small component perpendicular to the mean direction, may act to smooth fault surfaces through frictional wear in mean-slip-perpendicular as well as mean-slip-parallel directions. 2) Where faults separate materials of significantly different stiffness, zones of convergent and divergent slip across corrugations may generate flow instabilities in the surrounding wall rocks that help to enhance corrugation topography. Slip heterogeneity may further impact fault and earthquake mechanics by generating significant variations in near fault stresses that impact fault strength, damage zone formation, and hydrology. These mechanical effects of corrugations may be particularly important for large-slip faults that are nearly smooth in the slip-parallel direction.
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Figure Captions

Figure 1. Tectonic and structural setting. (a) Seismotectonic map of the Aegean

(Modified after Resor et al., 2005). Major plate bounding faults are shown in black with
sense of slip indicated by arrows for transform boundaries and teeth on overriding plate for subduction or collisional boundaries. Gray dots are earthquake epicenters (M > 3.0, depth < 25 km, 1973-1994) from USGS NEIC catalog. GPS velocities from (McClusky et al., 2000). Study area (black box) is located along the southern shore of the Gulf of Evvia within an area of widespread extension located between the North Anatolian-Aegean trough strike slip fault system (NA-AT) and the Hellenic Subduction zone (HSZ). (b) Landsat image (band 8) with Kamena Vourla fault outlined in white with balls on the down-dropped side (after Cowie et al., 2006). Study area, highlighted and outlined in black, is located on the Arkitsa fault at the eastern end of the fault system.

Figure 2. Arkitsa fault surface. (a) Ortho-rectified photographs of eastern two panels of the Arkitsa fault exposure. Black box outlines area shown in detail in Figure 5. (b) Ortho image of data sets including: total station scan points (color-shaded in 5 m intervals of distance from a strike-parallel vertical plane with blue points closest to the observer) and structural measurements collected using field compass. (c) Interpolated fault surface grid color-shaded by orthogonal distance from best-fit planar surface. Black boxes outline areas used for roughness analysis in Figure 3. (d) Shape curvature calculated from interpolated surface. Black polygons outline areas used for orientation analysis in Figure 2e. (e) Maximum absolute curvature magnitude (color shade) and axes (arrows) for antiformal and synformal structures within regions highlighted in Figure 2d.

Figure 3. Assessment of fault roughness. (a) 58 m long fault profiles extracted at 5 m intervals from 10 m wide windows perpendicular to fault corrugations. (b) Same as (a),
but extracted from corrugation-parallel windows. See Figure 2c for location of analysis windows on fault surface. Note difference in scale for topographic axis. (c) Power spectral density calculated for fault perpendicular (black) and parallel (gray) windows. Dashed reference line is for slope of 3, indicative of self-similar scaling, with amplitude to wavelength ratio of .01.

Figure 4. Striation and corrugation orientation analysis. (a) Photograph of mineralized grooves on polished fault surface. Lens cap (7 cm diameter) for scale. (b) Equal area stereoplot of poles to fault surface (open circles) and slip vectors (filled dots) for ~10 cm scale striations measured with a field compass. Data are separated into east (light gray) and west (dark gray) panels. Cross and ellipse illustrate mean value and 2 sigma variation for each panel. (c) Same as (b), but for fault normal and minimum curvature axes extracted from scanned fault surface (Figure 2e). (d) Sketch of coordinate system and projections used to generate scatter plots in (e) and (f). Fault normal ($\hat{n}_i$) and striation orientations ($\hat{s}_i$) for individual observations (gray) are rotated into a right-handed coordinate system (black) with z axis parallel to the mean fault normal ($\vec{n}$) and y-axis 180 degrees from the mean slip direction ($\vec{s}$). $n_i'$ and $s_i'$ are projections of the fault normal and striation direction, respectively, in the x-y plane. $n_i''$ is the projection of the fault normal in the x-z plane. Angles $\alpha$, $\beta$, $\gamma$ are defined in the descriptions of (e) and (f). (e) Scatter plot of the inclination of the fault normal from the mean fault normal (clockwise positive) in the x-z plane ($\beta$) vs. the angle between striation orientation and the mean striation direction (counterclockwise positive) in the x-y plane ($\alpha$) for data presented in (b). (f) Scatter plot of the angle between the direction of the fault surface
normal and the mean striation direction (counterclockwise positive) in the x-y plane (\( \gamma \)) vs. the angle between striation orientation and the mean striation direction (counterclockwise positive) in the x-y plane (\( \alpha \)) for data presented in (b).

Figure 5. Example of variation in striation orientation across a single long wavelength corrugation. (a) Orthophotograph of fault surface with black arrows showing striation rakes measured using a field compass. See Figure 2a for location. (b) Map view of fault profile extracted at approximately the middle of the image in (a). Scale same as in (a). (c) Scatter plot of the inclination of the fault normal from the mean fault normal (\( \beta \)) vs. the angle between striation orientation and the mean striation direction (\( \alpha \)) for data illustrated in (a). Coordinate system and projections are the same as figure 4e.
Figure 1. Tectonic and structural setting. (Resor and Meer, 2009)
Figure 2. Arkitsa fault surface. (Resor and Meer, 2009)
RMS roughness
eastern: 0.589 ± 0.094 m
western: 0.745 ± 0.011 m

Figure 3. Assessment of fault roughness. (Resor and Meer, 2005)
Figure 4. Striation and corrugation orientation analysis. (Resor and Meer, 2009)
Figure 5. Example of striation orientation variation across a single long wavelength corrugation. (Resor and Meer, 2009)