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# A hectare of fresh striations on the Arkitsa Fault, central Greece

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**Abstract**

Some large new exposures of active normal faults in central Greece reveal polished surfaces that could represent as many as 50 increments of co-seismic slip. The slip surfaces are nearly two-dimensional, with the slip vector aligned down the axes of corrugations and undulations. However, small, but regular, changes in slip vector between top and bottom of the exposure and a regular asymmetry of the polishing on corrugations may be related to block rotations about a vertical axis, and show how the slip vector changes with time. © 1998 Elsevier Science Ltd. All rights reserved.

## 1. Introduction

It is very rare for fresh slip surfaces on large active faults to be exposed over a sufficient area to address the question of whether the geometry of the fault slip changes over several earthquake cycles. Yet the change in fault kinematics with time is an issue at the heart of understanding lithosphere dynamics. The purpose of this paper is to report a spectacular new exposure of active normal fault surfaces in central Greece, where quarrying has revealed pristine surfaces up to 50 m long in the direction of slip. These surfaces reveal features that can plausibly be related to change in the fault kinematics with time.

A description of large-scale continental deformation requires knowledge of both the overall deforming velocity field and how it is achieved by faulting (e.g. Jackson, 1994). The two are often closely related, since the directions of no-length-change in the velocity field, which are uniquely defined by the strain rate tensor, are the directions in which organized faulting can accommodate the motions (Jackson et al., 1992; Holt and Haines, 1993). However, in many places, such as Greece (e.g. Taymaz et al., 1991), faults rotate about a vertical axis as they move. In these circumstances, if the faults still follow no-length-change directions, either the fault geometry or the velocity field must change with time (Jackson et al., 1992). What actually occurs may depend on whether the behaviour of the seismogenic upper crust or the ductile lower lithosphere controls the overall deformation (e.g. Bourne et al., 1998). Thus the evolution of faulting with time has great significance for understanding the dynamics of the continental lithosphere. It is not an issue that is easy to address, since it is rare for active fault surfaces to be preserved in outcrop for very long after the last earthquake, and with earthquake recurrence times of typically hundreds to thousands of years we are unlikely to see exposures of active fault surfaces that represent more than one or two earthquake cycles at most.

The fault surfaces we report here are not only exceptionally exposed, but occur in a region where knowledge of the regional tectonics suggests how the faults might change with time. This in turn allows us to suggest how features on the surfaces might be related to those changes.

## 2. Regional and local setting

The geomorphology of central Greece is dominated by normal faulting with an E–W to NW–SE strike, with maximum segment lengths typically in the range 15–25 km (e.g. Roberts and Jackson, 1991; Armijo et al., 1996; Roberts, 1996). The region of Fig. 1(a) is extending by about 15–20 mm/y (Billiris et al., 1991), most of which is achieved by seismic slip on faults

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(Ambraseys and Jackson, 1997), with many earthquakes in the range of $M_s \approx 6$–7, but none known that are greater (as expected, given the maximum fault segment length).

The fault surfaces we describe here are part of the segmented north-dipping fault system along the south side of the north Gulf of Evvia (Fig. 1), a graben with a total length of almost 100 km (Roberts and Jackson, 1991). The footwalls of the fault segments in this region are prominent ridges, up to 1000 m high, of cemented Triassic–Jurassic platform carbonates, which are massively bedded and resistant to erosion. Fault surfaces are often exposed at their bases, but usually only to a height of a metre or so, and are much weath-

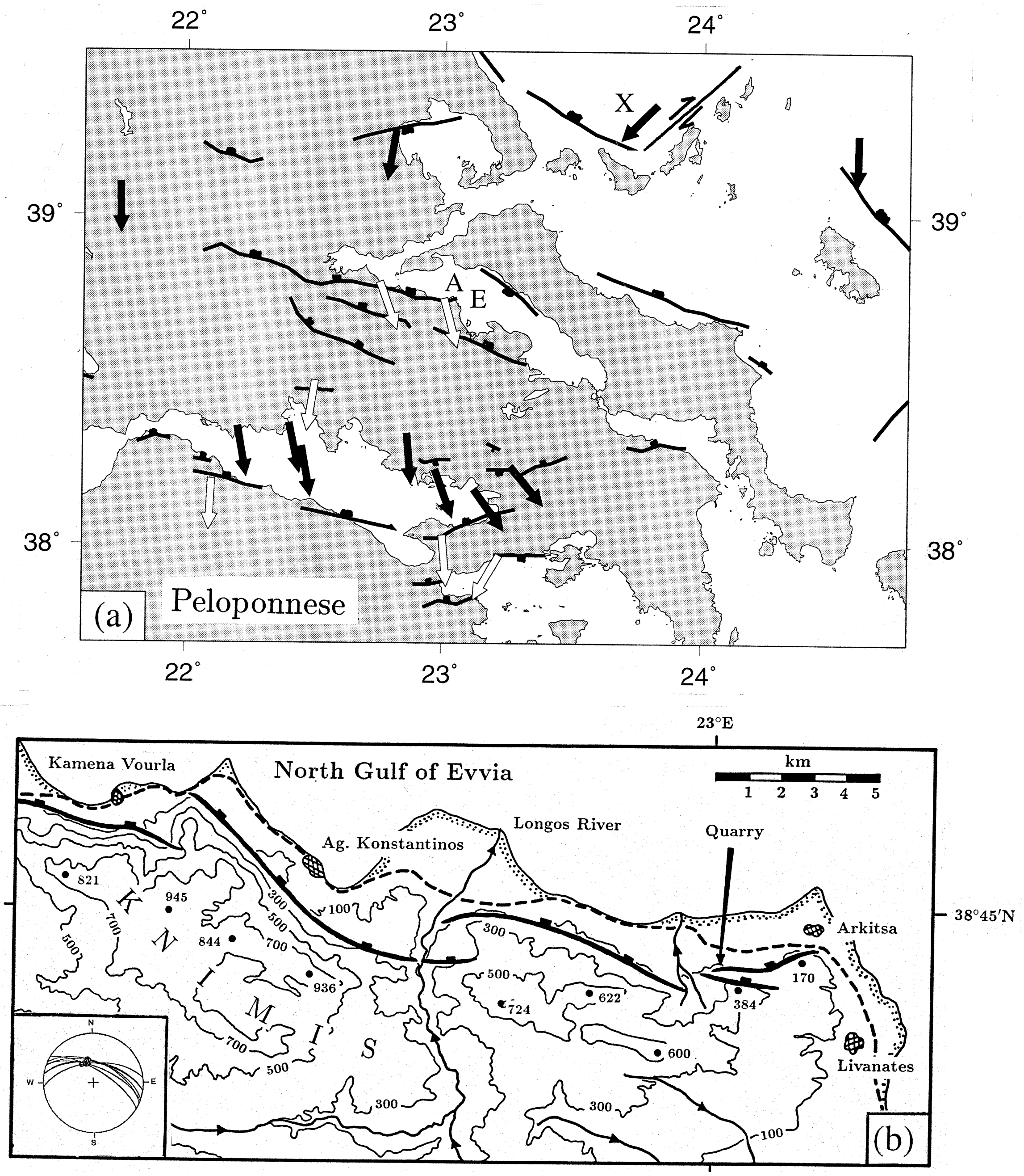


Fig. 1. (a) Map of central Greece, showing major Quaternary normal faults with slip vectors measured on fault surfaces (white arrows) and from earthquakes (black arrows). The arrows show the direction of motion of the south side relative to the north. All the earthquake vectors are from focal mechanisms well constrained by body wave modelling (mostly from Taymaz et al., 1991): only event X had a strike-slip mechanism, all the others involved normal faulting. E—north Gulf of Evvia; A—Arkitsa. (b) Map of the fault system along the south side of the north Gulf of Evvia, showing the location of the fault exposures in the quarry near Arkitsa. Spot heights and contours are in metres. The dashed line along the coast is the main road. Inset shows a lower-hemisphere equal-area projection of fault plane orientations (lines) and slip vectors (circles) at seven places over a 500 m section within the Arkitsa quarry. Note the consistency of the slip vectors.

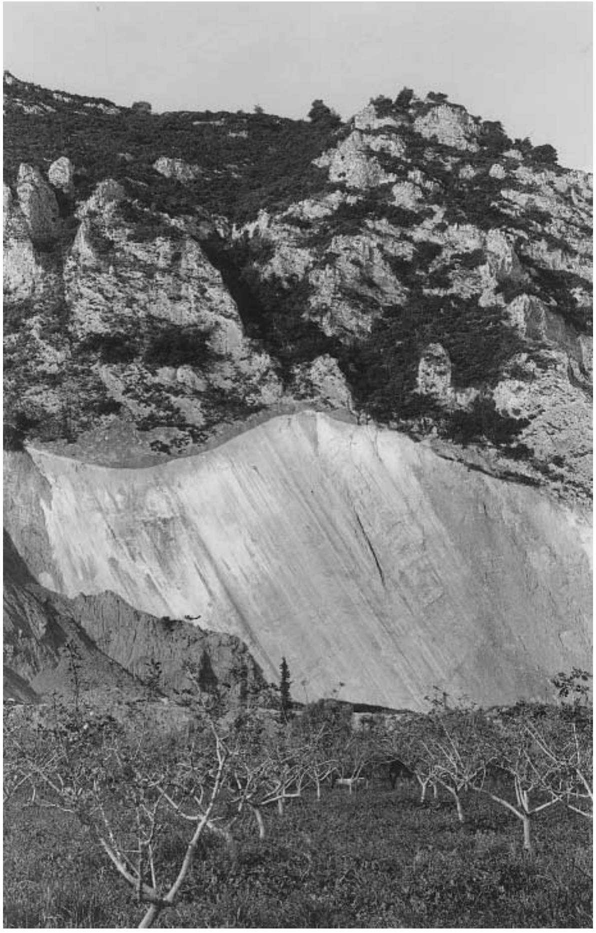

Fig. 2. View of part of the Arkitsa quarry, looking south. The height of the exposed fault surface is about 40 m. The abrupt line at the top of the exposure shows the level of the scree covering the fault before excavation, with a weathered surface 1–2 m high above that. Some scree still remains on the fault in the lower left corner.

ered. However, near Arkitsa (Fig. 1) quarrying of the limestone scree in the immediate hanging wall of the fault has exposed fresh slip surfaces over a length of 500–600 m along strike. The surfaces are remarkably continuous, with patches of up to 80 m in length and 40–50 m high (4000 $m^2$) in two places (Figs. 2 and 3).

## 3. Description of the fault surfaces

Normal fault slip surfaces are commonly preserved at the base of limestone escarpments in Greece and Turkey, sometimes 1–2 m high and often representing the last co-seismic increment of slip. Locally they may be higher if the scree or talus adjacent to the fault has been removed by landsliding or quarrying. But the surfaces at Arkitsa are by far the biggest and the freshest that we have seen anywhere. Hancock and Barka (1987) and Stewart and Hancock (1988) describe in detail the main characteristics of these limestone fault zones from exposures elsewhere in the Aegean. The most dramatic feature is a polished surface cutting through a brecciated, cemented zone that is visible only in the footwall, into which it extends for a metre or two. The scree overlying the Arkitsa Fault is mostly cemented, and where it is preserved it is often separated from the striated surface by a layer of clay a few cm thick, foliated parallel to the surface. The surface itself is corrugated on all scales with slip-parallel lineations, gutters, striations, tool tracks and channels. In places it is poorly developed, or has been partially destroyed by plucking of material as the hanging wall moved past: in these cases cemented breccia material is found either above or below the plane of the surface. The surface contains numerous open cracks or fissures, many of them sub-perpendicular to the slip direction, but with a large number also oblique to that direction. Some of these fissures offset the plane of the surface and must have formed post-slip: possibly even in response to the removal of overburden by quarrying.

A striking feature of the surface is the consistency of the slip vector, with an average azimuth of 345° and an average plunge of 52°. The fault has an overall strike of 280° and an average dip of about 60° N, but as it wraps around the range front the local strike changes by up to 40° and the local dip changes by up to 15°. Yet the slip vector direction changes by less than 10° in azimuth and 5° in inclination (Fig. 1). The surface is also virtually two-dimensional, with the axes of the corrugations all parallel and almost (but not quite, see later) no change in inclination of the axes with height up the fault surface.

The way in which these surfaces form is not well understood in detail. Earlier exposures from a previous episode of quarrying about 30 years ago (Fig. 3b) and from the 1–2 m high (Holocene?) scarp at the top of the original scree cone before quarrying (Fig. 3a) give an idea of how quickly the details on the surface are weathered. By comparison with these two, the newly exposed surfaces (less than two years old) are pristine. Thus the slip surface must be protected by the cemented scree that rests against it as it grows—but how this process works is not clear: it presumably involves some interaction between fault slip and scree deposition (and hence possibly climate also). The breccia through which the polished surface cuts contains clasts of soft Miocene(?) marls as well as of scree, so is unlikely to have formed at depths greater than a few tens, or possibly hundreds, of metres. It is possible that the whole surface forms in a single earthquake as a slip plane propagates up through a shallow-level breccia (e.g. Hancock and Barka, 1987), and that the plane then slips about a metre: which is the typical maximum length of individual tool tracks and is the expected slip increment on fault segments of 10–15 km length (e.g. Jackson et al., 1982; Scholz, 1982). However, having formed a surface as strongly corru-

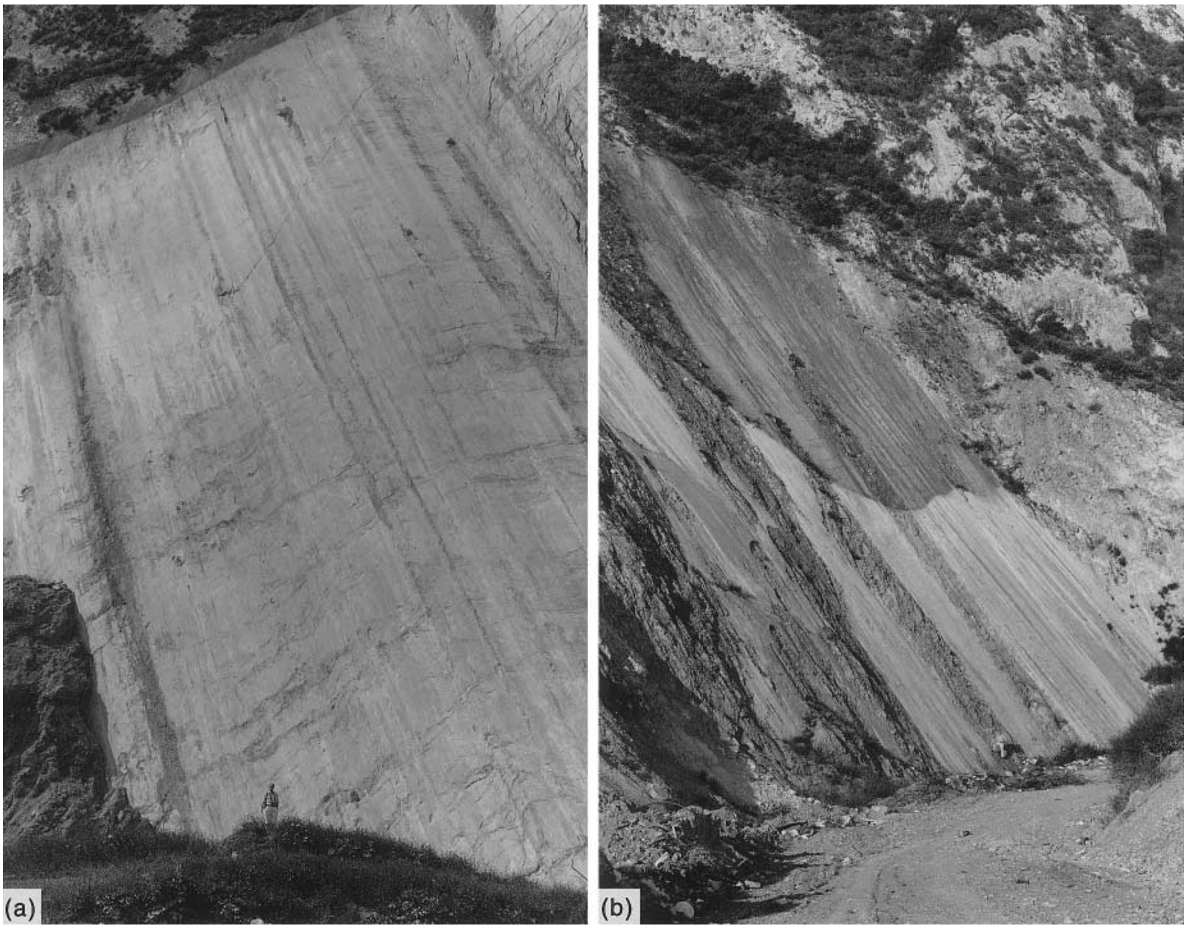


Fig. 3. (a) Close-up of the surface in Fig. 2. Dan McKenzie for scale in the bottom centre. (b) The other main patch of exposed surface, again with D. McKenzie for scale at the base. Note the scree in the background. The line halfway up the fault surface is the level of scree before the most recent quarrying activity (within the last year). Above that is a surface exposed by quarrying ~30 years ago.

gated as the one here, with corrugation amplitudes of at least 20–30 m along the rangefront, it is difficult to move it in any direction other than parallel to the axes of the corrugations. The entire down-slip exposure of 50 m may therefore represent the displacement resulting from up to about 50 earthquake cycles.

## 4. Kinematic significance

These fault surfaces offer opportunities for a variety of structural investigations, including descriptions of surface roughness (e.g. Power and Tullis, 1991; Lee and Bruhn, 1996), which is one reason for reporting them. However, this note is concerned solely with possible indications that the fault kinematics has changed with time.

The slip vector azimuth on the polished surfaces at Arkitsa is similar to those observed in earthquakes and on other polished fault surfaces in central Greece (Fig. 1a), which are all directed approximately south. Yet it is known that points in central Greece are moving to the southwest relative to Eurasia, accommodating a NE–SW right-lateral shear and N–S extension between the Peloponnese and Eurasia (Billiris et al., 1991; Jackson et al., 1992; Davies et al., 1997). The question arises: how can points in central Greece be moving to the southwest if the slip vectors on the faults are directed N–S? McKenzie and Jackson (1983) showed that these two conditions are reconciled if the fault blocks rotate clockwise about a vertical axis as they move, and paleomagnetic measurements by Kissel and Laj (1988) subsequently confirmed that this is indeed likely, with probable clockwise rotation rates in central Greece of up to 5° per million years (see also Taymaz et al., 1991).

Two features of the polished fault surfaces at Arkitsa may be related to clockwise rotation of the fault blocks. The first is that the polishing of the corrugations is not symmetrical: rising humps ('anticlines') on the surface are always polished only on the eastern side. This can be seen in the photograph in Fig. 4(a), where the light reflects from the shiny eastern side but not the relatively rough western side. This observation is compatible with an attempted change in slip vector to a more oblique (left-lateral) direction as the faults rotate clockwise. The other feature of interest is that the slip vector direction is not perfectly constant up the height of the fault, but curves very slightly (by about 1 m over 50 m) so that the slip vector at the top is less oblique than at the bottom (Fig. 4b), with the rake increasing by $\sim 1^\circ$ from the bottom to top. This change is also compatible with a clockwise block rotation. A change in rake of $1^\circ$ could be achieved by a change of $1.75^\circ$ in the slip vector azimuth relative to the footwall. If we assume the 50 m-long corrugations formed in 50 earthquakes, then a rotation rate of $5^\circ$ per Ma could be achieved if earthquakes repeated on this fault every 6.8 ka.

It is worth noting Spudich's (1992) suggestion that a change in slip vector with time, (i.e. during a single earthquake), may be related to the absolute stress level on the fault. The condition for this to be true is if the sliding frictional traction is always colinear with the particle velocity on the crack plane (for instance, if the fault is perfectly planar). In the case of the Arkitsa fault surfaces, which are heavily corrugated, this condition is plainly not satisfied, and the slip vector is not free to rotate in that way.

Our suggested analysis of the change in slip vector over several earthquake cycles raises a number of questions and difficulties. It is not clear how the slip vector can change with time at all without deforming the corrugations over the whole fault surface. Local fracture or cataclasis of the corrugations (e.g. Power et al., 1988) may solve this problem on a small scale, and may be related to the asymmetric polishing of the corrugated ridges. On a larger scale, where the amplitude of the corrugations is tens of metres, this suggestion is naive, and, in general, the distribution of aftershocks well into the footwall and hanging wall blocks indicates that the adjustment is not local (e.g. Lyon-Caen et al., 1988). Nor is it clear that the overall velocity field and block geometry should remain constant, as we have assumed. We make no apology for such uncertainties in our analysis. They arise here only because enough of the fault surface is exposed to address whether the fault behaviour changes with time: when observations are restricted to a single slip event,

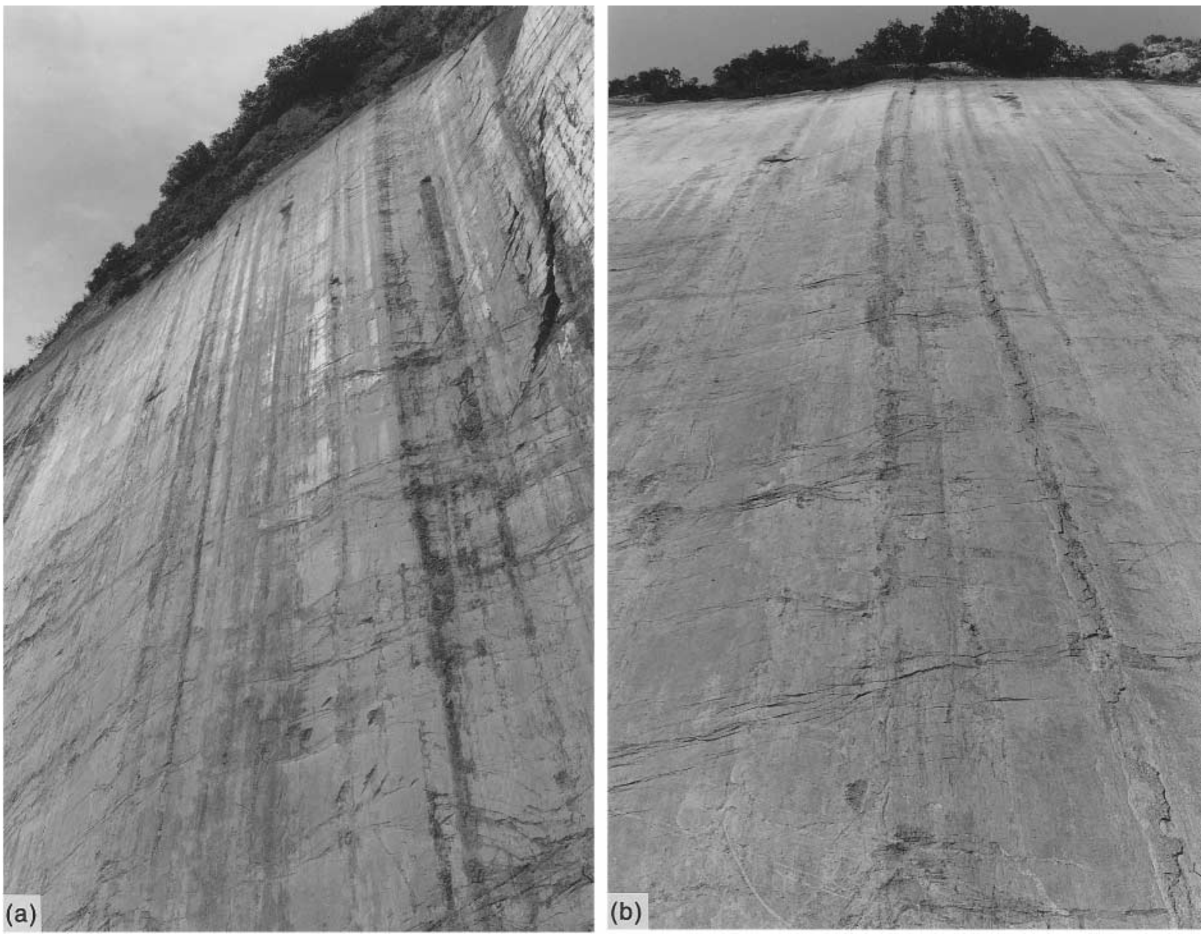


Fig. 4. (a) View looking up the corrugations (length $\sim$30 m) in the fault surface in Figs. 2 and 3(a). Note the asymmetry of the polishing, with the bright surfaces on the left (east) side of the raised corrugations. (b) View looking up the same fault surface as in (a), to show the gradual curvature of the corrugations between top and bottom of the exposure. Length of the corrugations is $\sim$30 m.

which is the usual situation, no such problems arise. With only one example, it is always difficult to distinguish unimportant curiosities from significant patterns. But we certainly expect difficulties of this sort when attempts are made to estimate finite rotations by integrating instantaneous rotation rates (McKenzie and Jackson, 1983).

## 5. Conclusions

The Arkitsa exposures reveal enough of a large, active fault surface to address whether the fault kinematics change with time. In particular, the asymmetry of the polishing on the corrugations and their gentle curvature may indicate that a slow change in azimuth of the slip vector with time is visible over as few as 50 earthquake cycles. It is not surprising that these fault surfaces raise many unanswered questions about their origin and development: exposures of such quality are rare.

## Acknowledgements

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