

FAST TRACK PAPER

Global Positioning System measurements of strain accumulation and slip transfer through the restraining bend along the Dead Sea fault system in Lebanon

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SUMMARY

Approximately 4 yr of campaign and continuous Global Positioning System (GPS) measurements across the Dead Sea fault system (DSFS) in Lebanon provide direct measurements of interseismic strain accumulation along a 200-km-long restraining bend in this continental transform fault. Late Cenozoic transpression within this restraining bend has maintained more than 3000 m of topography in the Mount Lebanon and Anti-Lebanon ranges. The GPS velocity field indicates 4–5 mm yr⁻¹ of relative plate motion is transferred through the restraining bend to the northern continuation of the DSFS in northwestern Syria. Near-field GPS velocities are generally parallel to the major, left-lateral strike-slip faults, suggesting that much of the expected convergence across the restraining bend is likely accommodated by different structures beyond the aperture of the GPS network (e.g. offshore Lebanon and, possibly, the Palmyride fold belt in SW Syria). Hence, these geodetic results suggest a partitioning of crustal deformation involving strike-slip displacements in the interior of the restraining bend, and crustal shortening in the outer part of the restraining bend. Within the uncertainties, the GPS-based rates of fault slip compare well with Holocene-averaged estimates of slip along the two principal strike-slip faults: the Yammouneh and Serghaya faults. Of these two faults, more slip occurs on the Yammouneh fault, which constitutes the primary plate boundary structure between the Arabia and Sinai plates. Hence, the Yammouneh fault is the structural linkage that transfers slip to the northern part of the transform in northwestern Syria. From the perspective of the regional earthquake hazard, the Yammouneh fault is presently locked and accumulating interseismic strain.

Key words: crustal deformation, Dead Sea fault system, fault motion, Global Positioning System (GPS), Neotectonics, transform faults.

INTRODUCTION

The central part of the Dead Sea fault system (DSFS) in Lebanon and southwestern Syria is a ~200 km long restraining bend that strikes 25°–30° from the main trend of the transform (Fig. 1). Within the geodynamic framework of the eastern Mediterranean region, the left-lateral DSFS is the continental transform boundary between the

Arabian and Sinai plates (e.g. Freund *et al.* 1970; McKenzie 1972), accommodating the differential motion of those two plates as they converge and collide with Eurasia.

Although late Cenozoic strike-slip movements of the DSFS are well documented (e.g. Quennell 1958; Freund *et al.* 1970), some debate has persisted over the past decade concerning the present-day activity of the northern DSFS and whether or not plate motion

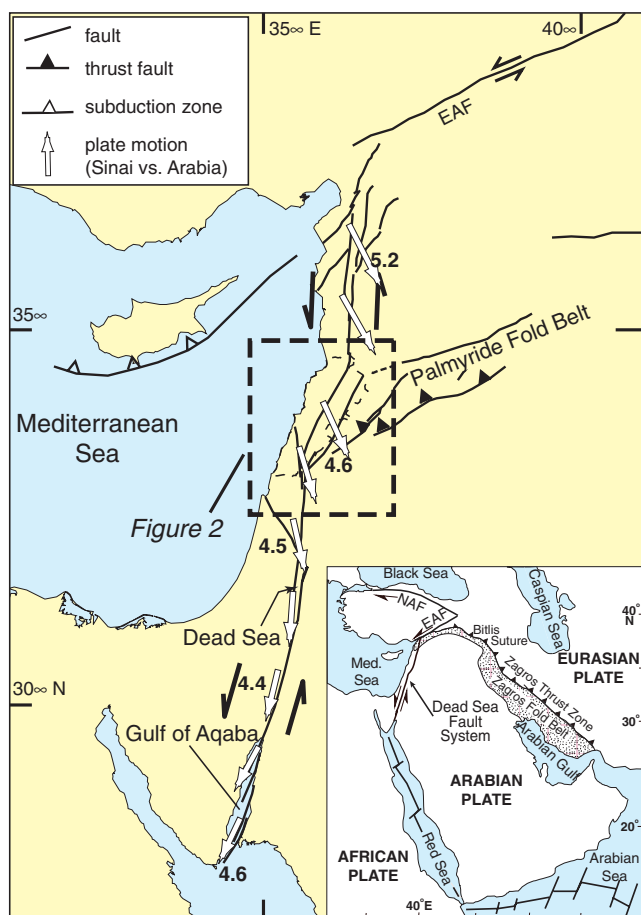


Figure 1. Regional tectonic map of the Dead Sea fault system. Also shown are the relative plate motions (mm yr^{-1}) (Sinai versus Arabia) predicted by Reilinger *et al.* (2006). Abbreviations: EAF = East Anatolian fault and NAF = North Anatolian fault.

is presently transmitted through the restraining bend (Girdler 1990; Butler *et al.* 1998). This debate was motivated, primarily, by the apparent lack of instrumentally recorded seismicity along the restraining bend and the northern portion of the transform in NW Syria. Specific questions concerning the DSFS include: Is strain presently accumulating within the restraining bend? If so, how is crustal deformation distributed? How do short-term (geodetic) estimates of fault slip compare with long-term (late Quaternary) estimates?

Whether or not the central DSFS is an active restraining bend also pertains to broader questions of how large restraining bends in major transcurrent fault systems develop. Faults within restraining bends typically have orientations that are not optimal with regard to the regional plate motions (i.e. the boundary forces). Yet restraining bends persist, often involving increased structural complexity compared with the rest of the fault system.

This 'Lebanese' restraining bend compares in scale to other large restraining bends, such as the Big Bend along the San Andreas fault system in southern California. Late Cenozoic transpression within the Lebanese restraining bend has uplifted the Mount Lebanon and Anti-Lebanon ranges to elevations in excess of 3000 m. Similar to the San Andreas fault system within the Big Bend, the single trace of the southern DSFS splays into several structures within the Lebanese restraining bend (Walley 1988, Fig. 2): the Yammounh, Serghaya, Rachaya, Roum and Akkar faults. Of those, the Yammounh fault appears to be the only through-going structure that connects the

southern and northern parts of the DSFS. The Serghaya fault, the other major NNE–SSW strike-slip fault, seems to terminate in the northern Anti-Lebanon range (Gomez *et al.* 2003, 2006). Two faults striking oblique to the transform, the Roum fault in the south and the Akkar fault in the north, appear to serve as the structural linkages between the strike-slip faults of the restraining bend and horizontal shortening of the Mount Lebanon range (e.g. Gomez *et al.* 2006; Nemer & Meghraoui 2006).

Geodetic estimates of present-day plate motion along the DSFS are relatively slow at $4\text{--}6\text{ mm yr}^{-1}$. (e.g. Wdowinski *et al.* 2004; Mahmoud *et al.* 2005). This is consistent with longer return periods (500–1000 yr) for strike-slip earthquakes within the Lebanese restraining bend (e.g. Gomez *et al.* 2003; Meghraoui *et al.* 2003; Daeron *et al.* 2005). Despite a general seismic quiescence at the present time, historical records document numerous large earthquakes within the restraining bend, most notably in 551 AD, 1202 AD, 1759 AD and 1837 AD (e.g. Sbeinati *et al.* 2005). Hence, understanding the active crustal deformation, particularly in terms of strain accumulation and the earthquake cycle, is critical to improving the estimates of the regional earthquake hazard.

Recent palaeoseismic and neotectonic studies within the Lebanese restraining bend have helped constrain the late Pleistocene/Holocene kinematics of several major faults: purely strike-slip displacement is documented along the Yammounh fault ($4\text{--}6\text{ mm yr}^{-1}$) and Serghaya fault ($1\text{--}1.5\text{ mm yr}^{-1}$) (Gomez *et al.* 2003; Daeron *et al.* 2004; Gomez *et al.* 2007). Along the Roum fault, a strike-slip rate of 1 mm yr^{-1} in the south grades into increased dip slip towards the northern end of the fault (Nemer & Meghraoui 2006).

This study reports the initial, near-field Global Positioning System (GPS) velocity estimates for the Lebanese restraining bend along the DSFS. The results permit kinematic modelling of the restraining bend and quantify the accumulation of interseismic strain along the Yammounh fault.

GPS MEASUREMENTS AND DATA PROCESSING

The regional GPS network used in this study includes one local continuous GPS station (LAUG) and 14 survey monuments (Fig. 2). Monumentation at the 14 survey sites consisted of 10 cm steel pins cemented into bedrock. Sites were distributed about Lebanon in order to facilitate 2-D analysis of the resulting velocities. The campaign sites were repeatedly measured during five survey campaigns between spring 2002 and fall 2005. In each campaign, sites were observed for a minimum of 24 hr using Trimble 5700 receivers with Zephyr Geodetic antennae atop fixed-height antenna masts in order to reduce uncertainty owing to antenna setup.

GPS data were processed in a two-step procedure using the GAMIT/GLOBK software (Herring *et al.* 1997; Dong *et al.* 1998; King & Bock 1998). In the first step, loosely constrained estimates of station coordinates, orbital and Earth orientation parameters, and atmospheric zenith delays were determined from raw GPS observables using GAMIT. Data from the Lebanon GPS network were analysed along with raw GPS data from other continuously operating GPS stations in the region. Subsequently, a global Kalman filter (GLOBK) was applied to the combined, loosely constrained solutions and their associated covariances in order to estimate a consistent set of station coordinates and velocities. As part of this second step, a six parameter transformation was estimated by minimizing the horizontal velocities of 49 globally distributed IGS stations with respect to the IGS00 realization of the ITRF 2000 no-net-rotation

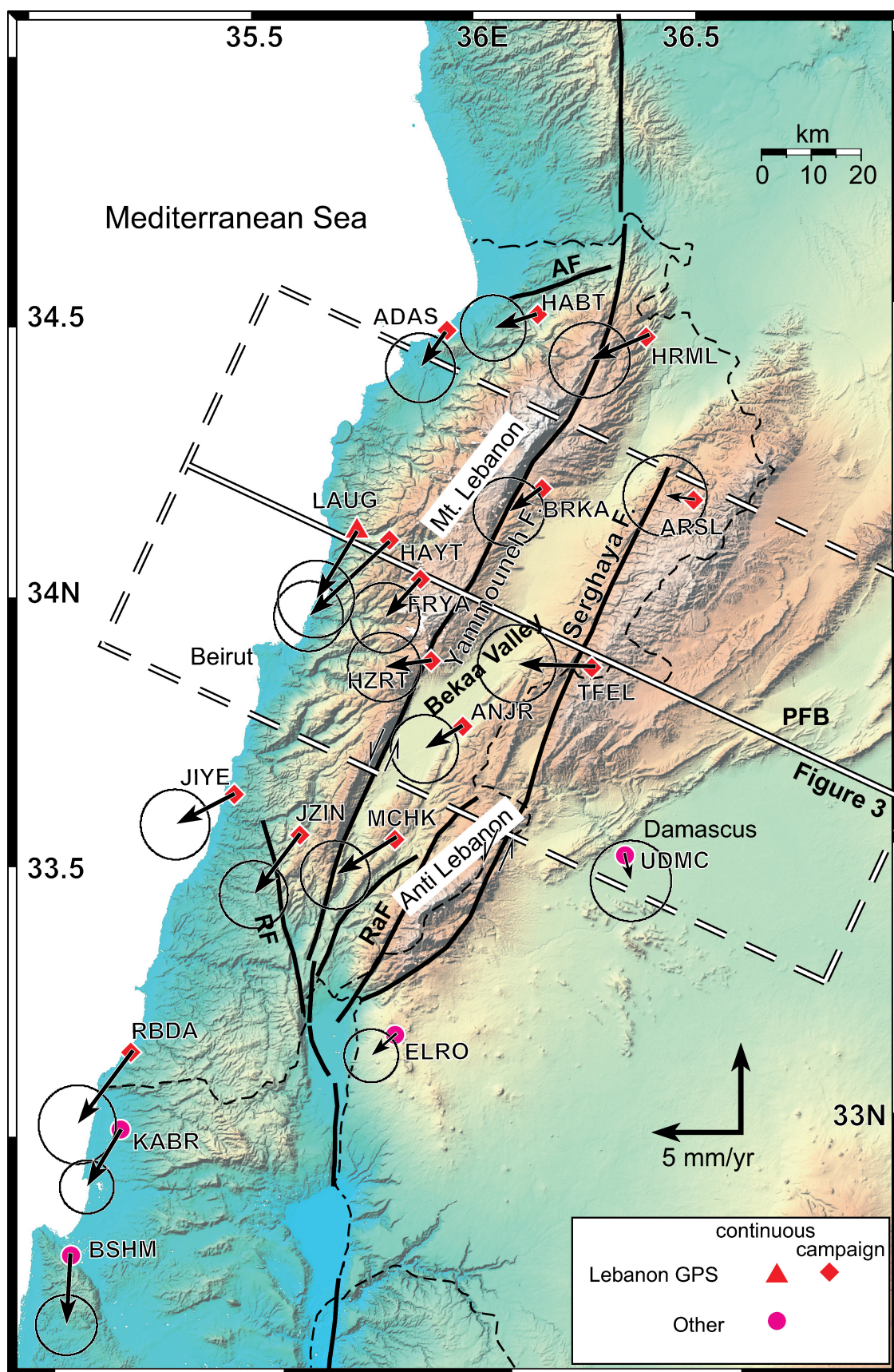


Figure 2. Map showing general structure of the Lebanese restraining bend. GPS velocities for the network used in this study are also shown in an Arabia-fixed reference frame (2σ uncertainties). Abbreviations for some key tectonic features: RF = Rour fault, RaF = Rachaya fault, AF = Akkar fault and PFB = Palmyride fold belt. Box denotes the swath encompassed by the profiles in Fig. 3.

Table 1. Velocities of GPS sites shown in Fig. 2.

Site	Longitude	Latitude	ITRF 2000		Arabia-fixed		σ E	σ N	Correlation
			Vel E	Vel N	Vel E	Vel N			
Survey sites									
ARSL	36.467	34.164	22.21	5.33	−1.66	0.22	0.94	0.91	0.007
HRML	36.379	34.412	20.37	3.65	−3.33	−1.42	0.91	0.85	0.023
TFEL	36.225	33.860	19.71	5.16	−4.37	0.13	0.88	0.88	−0.004
BRKA	36.143	34.184	22.03	3.66	−1.81	−1.34	0.80	0.77	−0.019
HABT	36.084	34.451	21.22	4.18	−2.43	−0.79	0.74	0.74	−0.003
ANJR	35.922	33.730	22.03	3.63	−2.12	−1.29	0.76	0.77	−0.001
ADAS	35.909	34.466	22.23	2.92	−1.40	−1.99	0.78	0.78	−0.013
HZRT	35.880	33.869	21.43	4.52	−2.63	−0.38	0.82	0.78	−0.011
FRYA	35.829	34.005	21.97	2.70	−1.98	−2.19	0.78	0.79	−0.013
HAYT	35.767	34.094	19.44	0.71	−4.46	−4.15	0.78	0.79	0.002
MCHK	35.771	33.526	20.92	2.76	−3.38	−2.10	0.78	0.77	−0.012
JZIN	35.589	33.555	21.70	1.40	−2.57	−3.40	0.77	0.76	−0.001
JIYE	35.411	33.651	20.90	3.03	−3.29	−1.70	0.78	0.79	−0.012
RBDA	35.162	33.139	21.43	0.55	−3.09	−4.10	0.87	0.89	0.002
Continuous stations									
LAUG	35.674	34.115	21.60	1.06	−2.27	−3.77	0.86	0.87	0.008
UDMC	36.285	33.510	24.69	3.47	0.37	−1.57	0.91	0.91	−0.002
ELRO	35.771	33.182	23.11	3.60	−1.42	−1.26	0.61	0.60	−0.001
KABR	35.145	33.023	22.70	1.45	−1.91	−3.19	0.61	0.60	0.002
BSHM	35.023	32.779	24.56	0.63	−0.21	−3.97	0.69	0.68	0.001

reference (NNR) frame. A ‘random walk’ noise of $1 \text{ mm}/\sqrt{\text{yr}}$ was also assumed in the final velocity estimation.

This study focuses on the near-field deformation constrained by repeated GPS survey campaigns and, accordingly, only data from regional stations during the time periods of the GPS survey campaigns were analysed. Previous studies have already presented regional results based on the complete time-series analyses of daily GPS solutions (e.g. Wdowinski *et al.* 2004; Mahmoud *et al.* 2005; Reilinger *et al.* 2006), and these studies have already constrained the regional plate models very well.

After stabilizing the reference frame, the site velocities were resolved to an Arabian-fixed reference frame, which facilitates assessing the local deformation. Velocities (in NNR and Arabia-fixed reference frames) for the sites around the Lebanese restraining bend are provided in Table 1.

RESULTS AND MODELLING

Fig. 2 depicts the resulting velocity field around the Lebanese restraining bend. Uncertainties for the resulting velocities are typically less than 1 mm yr^{-1} (1σ). In the Arabia-fixed reference frame shown in Fig. 2, the sites along the Lebanese coast demonstrate SSW motion of the Sinai plate relative to Arabia. South of the restraining bend, the velocities rotate to a more southward direction, maintaining their fault-parallel orientation.

Within the central part of the restraining bend, velocity variations along a WNW–ESE profile (i.e. perpendicular to the NNE–SSW strike of the Yammounh and Serghaya faults, see Fig. 2) permit an initial kinematic assessment. The profiles in Fig. 3 decompose the velocities into motions parallel and perpendicular to the Yammounh and Serghaya faults. These profiles deliberately exclude GPS survey sites at the extremities of the restraining bend and those which might be complicated by the obliquely striking Roum fault. The velocities parallel to the transform (Fig. 3a) show a progressive increase in southward velocity from east to west—a pattern that is generally consistent with basic models of elastic strain accumulation

(e.g. Savage & Burford 1973). In addition to this strike-slip deformation, the fault-normal components of displacement (Fig. 3b) suggest up to 2 mm yr^{-1} of motion (i.e. shortening) between sites in the Anti-Lebanon (TFEL and ARSL) and the continuous station along the Lebanese coast (LAUG). This convergence is demonstrated by a consistent trend in all of the Lebanese stations, although UDMC is a clear outlier.

An initial, quantitative assessment of the geodetic slip rate is based on a 1-D elastic dislocation model of a locked fault. Following Savage & Burford (1973), this profile model assumes an infinitely long strike-slip fault and expresses the station velocity, b , as a function of the long-term slip rate (V), fault locking depth (D) and distance from the fault (x):

$$b = (V/\pi) \tan^{-1}(x/D). \quad (1)$$

Owing to the size of the uncertainties relative to the velocities, present observations, warrant only a single fault model (i.e. the Yammounh fault). Despite the simplifications and assumptions, this analytical model permits assessing a range of values of fault slip rates and locking depths consistent with the GPS data using a grid search. The 1σ contour shown in Fig. 3(c) is based on a Monte Carlo simulation to assess the noise level in the data (e.g. Sandvol & Hearn 1994). As demonstrated in Figs 3(a) and (c), the entire range of geological slip estimates (3.5 – 6.5 mm yr^{-1}) can be modelled to fit nearly all of the velocities, with locking depths of 8–25 km. As shown in Fig. 3(c), the peak of the probability distribution corresponds with a slip rate of 4.4 mm yr^{-1} and a locking depth of 13 km.

A more appropriate elastic model and robust estimate of the fault slip rate involves 2-D blocks bounded by faults of finite lengths, rather than a 1-D profile. This modelling follows the methodology of Meade & Hager (2005), and considers the spatial variations in the velocity field due to fault geometry, and the effect of block rotations that are not accounted for in 1-D models, and both can significantly impact deduced slip rates. In this approach, an optimal fit between plate motion, fault slip, and GPS velocities is determined using a

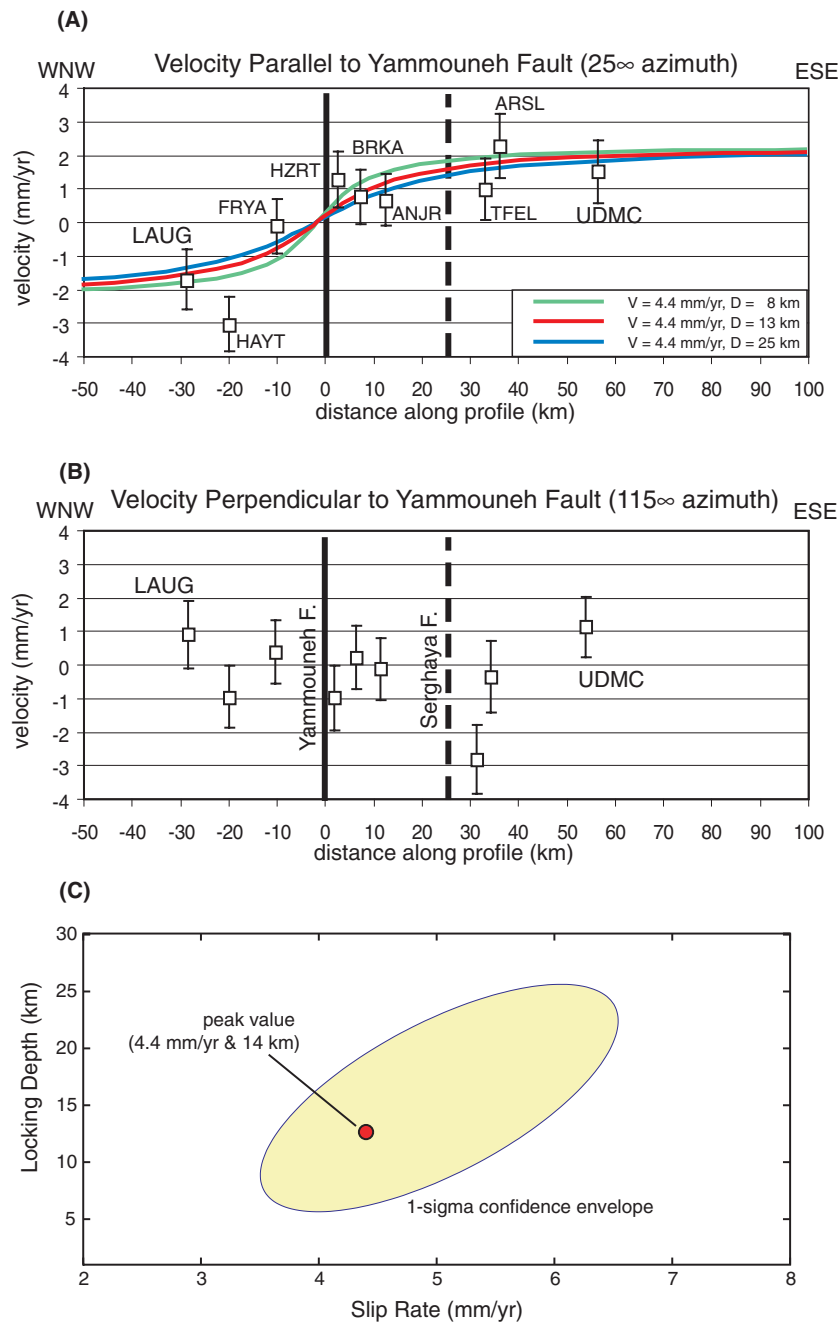


Figure 3. Plots showing GPS velocities (a) parallel and (b) perpendicular to the Yammouneh fault across the central part of the Lebanese restraining bend (positive N and E, respectively). Position is shown relative to the Yammouneh fault. The fault parallel velocities also include predicted velocities for different elastic dislocation models (i.e. combinations of locking depth and slip rate). The locations of the Yammouneh (solid) and Serghaya (dashed) faults are shown, although the model in 3a only includes the former. See Fig. 2 for location. (c) A plot depicting the 1σ confidence limits on slip rate and locking depth. Confidence limits are based on a grid search approach and a Monte Carlo simulation to estimate the noise level in the data. The peak of the probability distribution corresponds to a slip rate of 4.4 mm yr^{-1} and a locking depth of 14 km.

linearized least-squares inverse method. In our 2-D modelling, we assume a fault locking depth of 15 km because present uncertainties preclude solving for this additional parameter. Furthermore, the anticipated $\sim 1.5 \text{ mm yr}^{-1}$ of slip along the Serghaya fault is less than the 2σ uncertainties for the present results. Hence, the present block model is simplified to a single fault bend.

The residual fit to the optimal model is shown in Fig. 4, along with derived components of strike-slip and fault-normal movement.

Within the restraining bend, the block model reports a left-lateral slip rate of $3.8 \pm 0.3 \text{ mm yr}^{-1}$ (formal uncertainty reflecting only data fit and not uncertainties in fault parameters), along with $1.6 \pm 0.4 \text{ mm yr}^{-1}$ of convergence across the fault. South of the restraining bend, a slip rate of $4.0 \pm 0.3 \text{ mm yr}^{-1}$ is accompanied with a small component of extension ($0.8 \pm 0.3 \text{ mm yr}^{-1}$), whereas north of the restraining bend, $4.2 \pm 0.3 \text{ mm yr}^{-1}$ of strike-slip is accompanied by an insignificant component ($0.2 \pm 0.5 \text{ mm yr}^{-1}$) of convergence

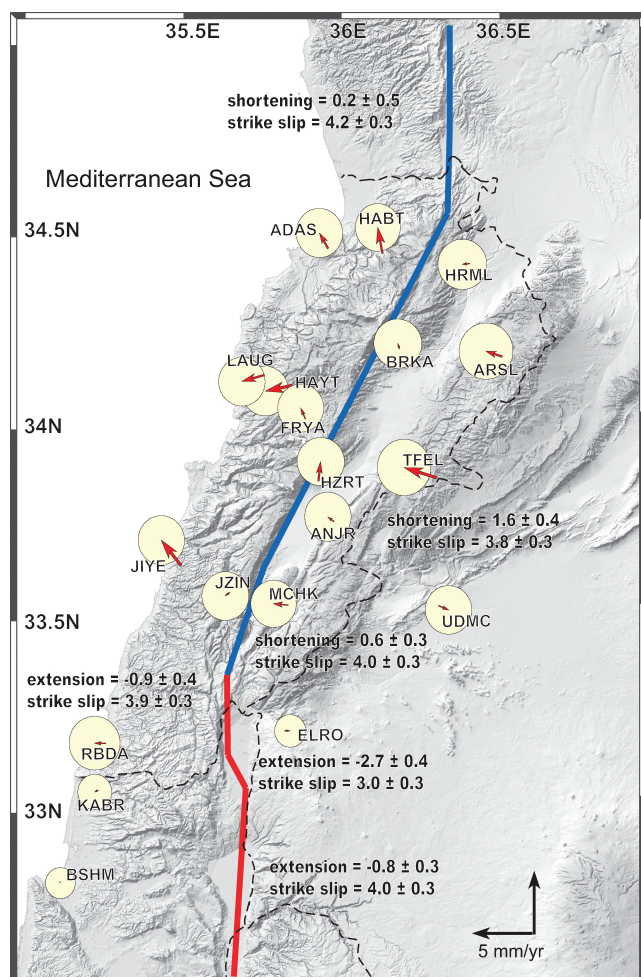


Figure 4. Map depicting elastic block model of a bend along a single fault trace. Strike-slip and fault-normal components of slip are shown for each segment. Heavy red lines denote fault segments under extension, and heavy blue lines denote fault segments with orthogonal shortening. Residuals of the velocities (mm yr⁻¹) to the best model and 2σ uncertainties are also shown.

across the DSFS. As previously noted, late Pleistocene/Holocene slip rates along the Yammounh fault suggest a slip rate of 3–6 mm yr⁻¹, and the block model is consistent with the lower end of this range.

Our block model assumes a single Sinai plate encompassing the entire western block of the DSFS. Salamon *et al.* (1996) have suggested the region might be subdivided into a southern and northern microplate. However, we believe this additional complexity is not warranted by the present GPS data. With a few exceptions located within the near field of the transform, the residual block motions are all within the uncertainties. Hence, the single block approximation presented here is reasonable and sufficient.

DISCUSSION

The block model describes the relative motion of the Sinai and Arabian plates with an Euler pole at 14.2° ± 3.8° N and 21.9° ± 2.3° E (with an angular velocity of 0.23° ± 0.044° Myr⁻¹). This pole position is located distinctly to the SW of other GPS-based estimates of plate motion (e.g. Wdowinski *et al.* 2004; Mahmoud *et al.* 2005; Reilinger *et al.* 2006), and we recognize this pole position may be

biased by our focus on the near-field sites in Lebanon. However, with all of these GPS-based, plate motion estimates, the trace of the DSFS does not define a small circle centred about its Euler pole. Consequently, these poles of motion predict a general northward increase in the magnitude of plate motion, as well as an increasing plate convergence north of the Lebanese restraining bend (Fig. 1).

In the near field, our GPS velocities conclusively demonstrate the present-day accumulation of strain along left-lateral faults in central and northern Lebanon. Furthermore, the velocity field yields insight into the kinematics of slip transfer through this restraining bend. Specifically, the velocity field demonstrates: (1) the predominance of strike-slip faulting inside the restraining bend and (2) less shortening than is expected from plate motions. These observations are consistent with regional strain partitioning that involves strike-slip displacements in the core of the restraining bend, and crustal shortening in the outer part of the restraining bend.

The velocity vectors in Fig. 2 bend parallel to the major strike-slip faults through the restraining bend. This is well demonstrated by the northward change in the orientations from BSHM (south of the restraining bend) to JIYE and LAUG (within the restraining bend). With the near-field constraints, the elastic block model suggests rates of strike-slip faulting that are similar inside and outside the restraining bend—that is, the rates of strike-slip do not decrease significantly as might be expected from a simple, geometric decomposition of plate motion into slip perpendicular and parallel to the restraining bend (e.g. Gomez *et al.* 2003).

Our elastic block model suggests about 1.6 mm yr⁻¹ of convergence across the restraining bend—nearly half of the convergence predicted by the regional block model of Reilinger *et al.* (2006). The model of Reilinger *et al.* (2006) constrained the motion along the DSFS solely with continuous GPS stations (primarily in the far-field), whereas our model includes additional survey sites in the near-field of the restraining bend. We suggest this difference may, in part, reflect the fact that the GPS stations in Lebanon do not measure the full convergence, and this may bias our block model.

In an analogous study of the Big Bend along the San Andreas fault system, Lisowski *et al.* (1991) concluded that the convergent component across a restraining bend seems to be accommodated across a zone with a width comparable to the length of the bend. Applying this to the Lebanese restraining bend suggests that sites along the Lebanese coast might not be expected to demonstrate the total convergent component of motion—some of the convergence may be accommodated offshore, as suggested by recent studies (e.g. Briais *et al.* 2004). Additionally, seismicity in the Palmyride fold belt suggests that some of the shortening associated with the Lebanese restraining bend may be accommodated by internal deformation of the northern Arabian plate (e.g. Chaimov *et al.* 1990). Hence, it seems likely that the convergence measured by our network of survey sites located entirely within the near-field of the DSFS will be underestimated.

Although the residuals for the block model are smaller than the uncertainties, an apparently systematic westward residual motion may reflect the need for a more complicated model involving reverse faults to accommodate WNW–ESE directed crustal shortening. Alternatively, a dip on the Yammounh fault could be added to accommodate plate motion with oblique slip. However, landforms offset by the Yammounh fault demonstrate only strike-slip displacements (e.g. Daeron *et al.* 2004; Gomez *et al.* 2007)—therefore, shortening perpendicular to the sub-vertically dipping Yammounh fault is likely accommodated by different structures.

These GPS measurements, as with recent palaeoseismic studies, unambiguously refute suggestions that the plate boundary is located

offshore to the west (e.g. Butler *et al.* 1998). The DSFS within the restraining bend is active despite the significant obliquity of plate motion relative to the restraining bend. Hence, changes in relative motion between the Arabian and Sinai plates (Garfunkel 1981; Butler *et al.* 1998) did not cause a change in this plate boundary as suggested by Butler *et al.* The persistence of the restraining bend implies that the DSFS is sufficiently weaker than the surrounding continental crust such that it is mechanically preferable to reactivate the transform, rather than develop new faults.

CONCLUSIONS

The GPS results presented herein provide direct geodetic measurement of present-day fault slip transferring through the Lebanese restraining bend. The GPS velocities maintain their fault parallel orientation along the restraining bend indicating that regional compression required by Sinai-Arabia relative plate motion is accommodated by structures other than the main through-going Yammouneh strike-slip fault. Fault slip rates deduced from simple elastic models constrained by the GPS results are consistent with the total 4–5 mm yr⁻¹ of relative plate motion between the Arabia and Sinai plates, and generally consistent with the lower range of geological estimates of slip rates along the Yammouneh fault. The displacement field suggests that the Yammouneh fault accommodates most of the expected strike-slip motion—hence, the DSFS (and specifically the Yammouneh fault) represents the main Sinai-Arabia plate boundary.

The GPS measurements also yield initial constraints on near-field deformation around the northern DSFS. The near-field velocities suggest that the Yammouneh fault is presently accumulating strain. Hence, the apparent lack of present-day seismicity is likely a reflection of the slow rates of strain accumulation about a locked fault system. These results reinforce concerns about earthquake potential of the Yammouneh fault, which has a historical record of producing large earthquakes ($M \sim 7.5$) (Sbeinati *et al.* 2005).

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