DEFORMATION IN THE EASTERN MEDITERRANEAN

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Tectonic motion and deformation in the eastern Mediterranean can now be monitored from the analysis of high-precision Satellite Laser Ranging (SLR) data from sites distributed across the region. The SLR results are based on the SL8.6 solution which utilizes LAGEOS I tracking data from the global network of tracking sites spanning the period January 1980 to July 1994. Tracking data acquired by the sites in the eastern Mediterranean region span an 8 year period; from 1986 to mid-1994. Deformation across the Aegean and Greece is nominally sampled by data acquired and analyzed from six sites which exhibit largely southwesterly motion along the Aegean arc. Data from the sites at Melengiçlik and Yozgat provide the means to assess broad-scale Anatolian Block motion and, in conjunction with data from Yigilça, allows for the monitoring of North Anatolian fault deformation. Arabia plate motion is detected for the site at Diyarbakir, in southeastern Turkey and data from the Israeli tracking site, near Jerusalem and the Dead Sea Rift, provides an estimate of Sinai Block motion. Africa plate motion is nominally sampled by data acquired and analyzed from a site in Egypt, south of Cairo. Estimates of the horizontal components of the site velocities and their implied relative motions are compared and contrasted with existing regional kinematic models to assess the level of agreement and to identify areas where present-day SLR estimates of motion conflict with prevailing geophysical models.

1. INTRODUCTION

The determination and monitoring of the kinematic behavior of points on the Earth's surface provides important information that is useful in constructing comprehensive dynamic models of regional and global tectonics. Here, we wish to report on the latest results for the motions of Satellite Laser Ranging (SLR) observation sites in the eastern Mediterranean based on the SLR tracking of the LAGEOS I (LAser GEOdynamic Satellite) spacecraft. The SLR measurement involves recording the round-trip travel time of laser pulses emitted and received by an SLR tracking site on the Earth's surface after having been reflected by corner cube prisms on board LAGEOS I [*Degnan*, 1993]. Globally, approximately 50 such sites have been established since the mid 1970's from which SLR observation have been or are currently being acquired. These observations are processed to eliminate outliers and are used to estimate the orbital parameters of the satellite, Earth orientation parameters, tracking site coordinates and their respective velocities in three dimensions. The latest series of such solutions performed by the Goddard Space Flight Center SLR analysis center (i.e. the SL8 series) was described in *Smith et al.* [1994b]. In this work, we present results from the global solution known as SL8.6. This

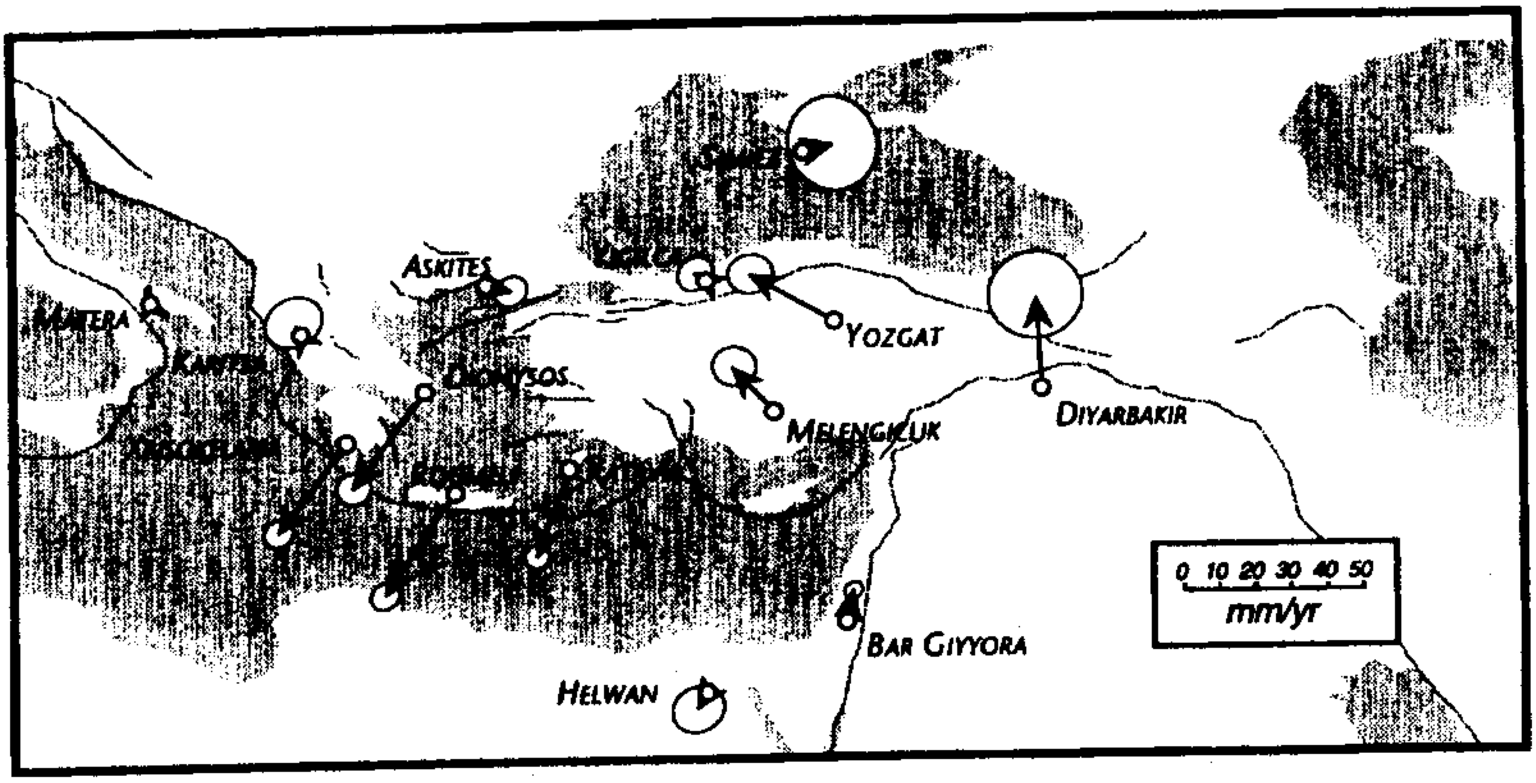

Figure 1: Estimates of motion for SLR tracking sites in the eastern Mediterranean relative to northern Europe. Error ellipses represent 1-σ estimates of error.

solution contains data spanning the period between January 1980 and July 1994. This paper focuses exclusively on the eastern Mediterranean portion of the WEGENER/MEDLAS project tracking sites. The results from SL8.6 provide an update, including corrections (as noted), to the SL8.4 solution [*Smith et al.*, 1994a] which covered the central and eastern Mediterranean. We also will examine in greater detail some implications of these results, particularly with regard to currently accepted kinematic models.

2. TECTONIC SETTING

The tectonics of the eastern Mediterranean region are largely influenced by north/south compressional plate dynamics arising from the collisions of the Africa and Arabia plates with the Eurasia plate. Caught in between these major plates are a variety of crustal blocks, such as Anatolia and Aegea which escape to the west and southwest, respectively, away from the Arabia/Eurasia collision [*Jackson & McKenzie*, 1984, 1988 and *Mueller & Kahle*, 1993]. In the case of Aegea, its southwestward motion overrides a portion of African oceanic lithosphere. The seismicity associated with the boundary defined by the Aegean Arc is characterized by largely shallow thrust earthquakes (between depths of 5 and 30 km) right at the boundary and grows slowly deeper to the north until reaching the central Aegean where it grows considerably deeper (>50 km) following the gross shape of the subducting slab [*Hatzfeld*, 1994]. The northern Aegean Sea exhibits shallow seismicity as well, but contains more strike/slip character due to the interaction of and transfer of strain from the Anatolia block to Aegea coupled with thrust and reverse faulting in western Greece associated with the collision against the Apulia block which lies to the west-northwest [*Jackson*, 1994].

To the east lies the Anatolia block which undergoes a predominantly westward lateral escape due to forces associated with the Eurasia/Arabia collision. The northern boundary of the block is defined by the North Anatolian Fault which extends from eastern Turkey westward,

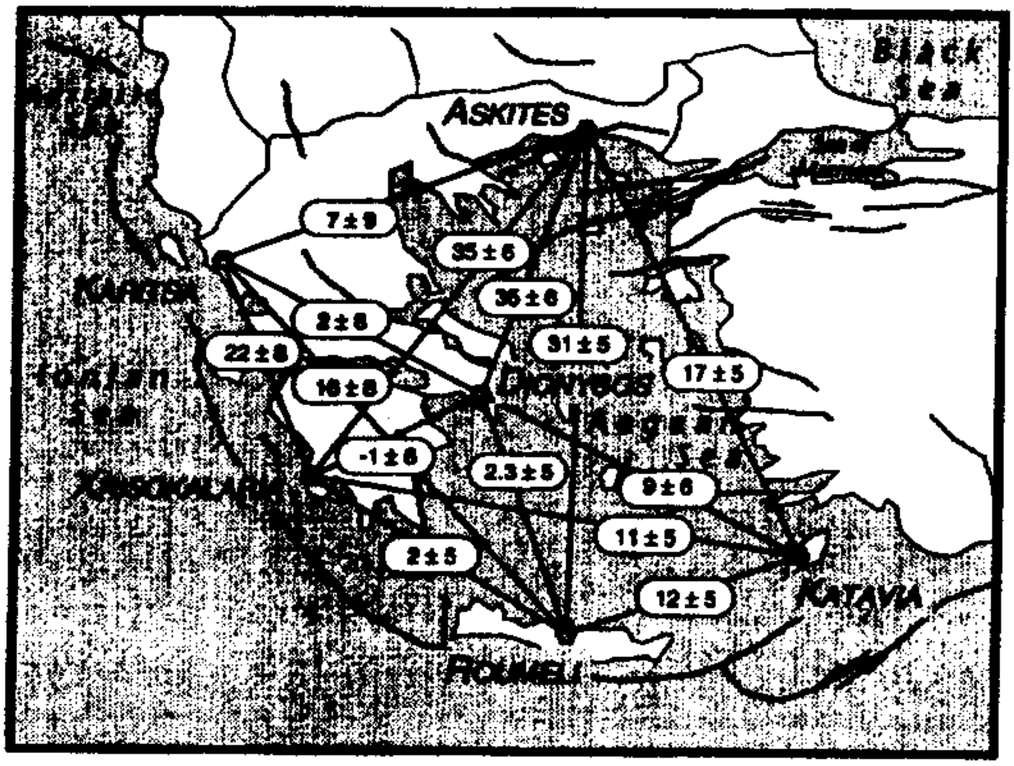

Figure 2: Rates of relative motion in mm/yr for SLR tracking sites in the Aegean region. Uncertainties represent 1-σ estimates of error.

following approximately an arc of a small circle [*Oral*, 1994], until reaching the Sea of Marmara where the boundary splays into a series of parallel fault systems extending into the northern Aegean Sea [*Eyidoğan*, 1988]. The southern boundary of the Anatolian block is defined along its western length by the subduction of Africa under Anatolia along the Cyprian arc south of the Gulf of Antalya. The Cyprian arc then takes on more of a strike/slip regime east of the Island of Cypress through the Gulf of Iskenderun terminating in a region of complex tectonics associated with the somewhat diffuse Africa/Arabia/Anatolia triple junction. From there, the southeast boundary of Anatolia with Arabia is defined by the East Anatolia fault zone [*Kiratzi*, 1993]. To the south of Anatolia, the boundary separating the African plate/Sinai block and Arabian plates is defined by the Dead Sea transform which runs south for more than 1000 km to the Red Sea spreading center [*Joffe and Garfunkel*, 1987].

3. SLR ANALYSIS AND RESULTS

The processing of the laser range data and formation of the SL8.6 solution for tracking site motions follows essentially the same procedure used for the SL8.4 solution described in *Smith et al.* [1994a & 1994b]. The solution takes its form through a single inversion for site coordinates and their velocities (along with other parameters, e.g., polar motion and other parameters pertaining to the satellite's orbit) within a kinematic reference frame defined by the adoption of NUVEL-1A motion [*DeMets et al.*, 1994] mapped into a no-net-rotation reference frame [*Argus & Gordon*, 1991]. Specifically, the frame is defined by modeling the north and east components of motion for the tracking site at Greenbelt, MD, USA and the north component of motion for the tracking site on the Island of Maui in the Hawaiian Islands.

To investigate the velocities of sites in the Mediterranean region, a transformation to a northern European kinematic frame is made. This is done by computing a plate rotation vector which

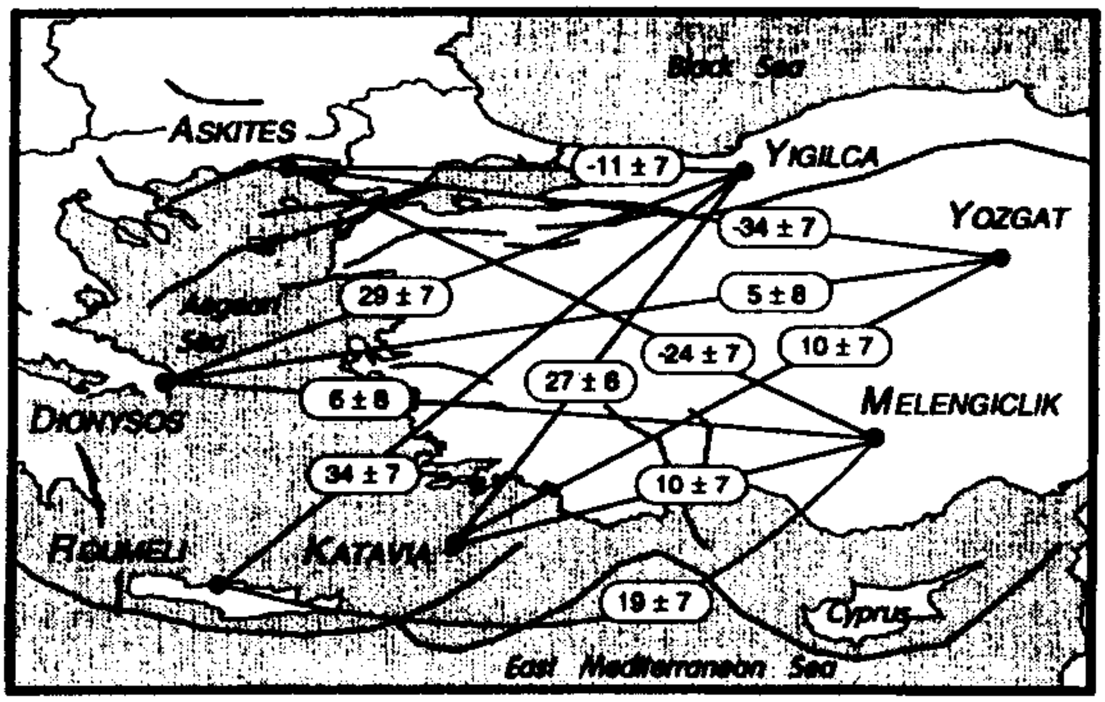

Figure 3: Rates of relative motion in mm/yr for SLR tracking sites in the Aegean and central Anatolia regions. Uncertainties represent 1-σ estimates of error.

best fits, via least-squares, the velocities of five European sites estimated within the global frame described above. These five sites include; RGO, UK; Wettzell, Germany; Potsdam, Germany; Zimmerwald, Switzerland and Graz, Austria. The pole of rotation computed from the velocities of these five sites is located at: latitude = 46.7°, longitude = -99.9° and has a rotational rate of 0.227 °/Ma. To calculate the velocities of the sites across the Mediterranean relative to Northern Europe, velocities based on this rotation pole were calculated and differenced from the velocities estimated in the global solution. These are given in Table 1 and

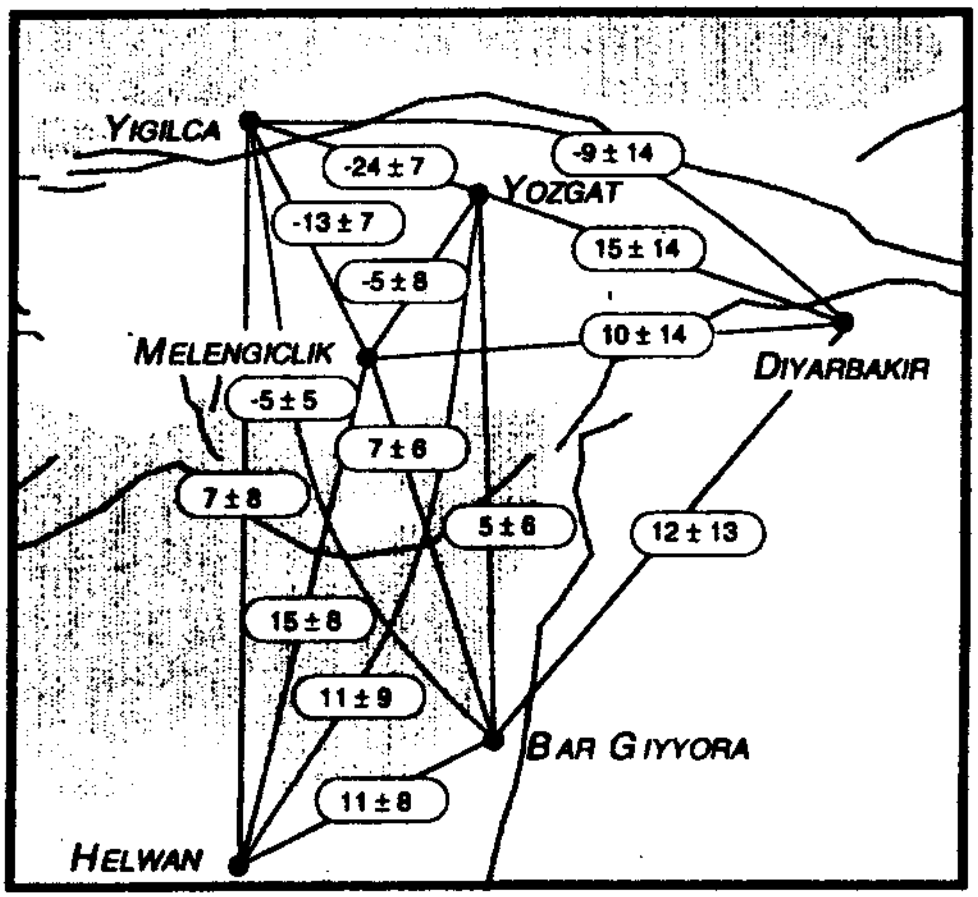

Figure 4: Rates of relative motion in mm/yr for SLR tracking sites in Anatolia and the southeast Mediterranean regions. Uncertainties represent 1-σ estimates of error.

Table 1. Tracking Site Motions from SL8.6 for the SLR Sites in the Eastern Mediterranean Relative to Northern Europe.

Station Name	SLR Velocities		Error Ellipse Parameters			NUVEL-1A Model*	
	Az. (deg)	Rate (mm/yr)	Semi-Maj. (mm/yr)	Semi-Min. (mm/yr)	Orientation (deg)	Az. (deg)	Rate (mm/yr)
			Eurasian Plate				
Askites	104	7.7	4.7	4.0	53	0	0
Dionysos	217	34.1	4.8	4.3	76	0	0
Karitsa	329	3.6	8.6	7.1	49	0	0
Katavia	200	27.0	3.6	3.5	-73	0	0
Roumeli	214	35.4	4.3	3.5	53	0	0
Simeiz	77	8.9	13.6	12.6	-21	0	0
Xrisokellaria	217	32.4	4.3	3.7	63	0	0
Yigilça	301	4.0	5.3	4.4	53	0	0
			Adriatic Block				
Matera	348	4.1	1.2	0.9	14	340†	8.6†
			African Plate				
Bar Giyyora	12	9.2	2.7	2.4	53	2	11.0
						344‡	19.9‡
Helwan	213	5.7	7.4	6.4	62	2	10.5
Lampedusa	17	5.2	4.8	4.6	48	343	7.7
			Anatolian Block				
Melengiçlik	317	17.2	6.0	5.5	-86	-	-
Yozgat	299	27.6	6.3	5.6	84	-	-
			Arabian Plate				
Diyarbakir	357	26.0	13.2	12.1	85	337	25.5

* The NUVEL-1A motion is relative to Eurasia.

† African NUVEL-1A motion used to approximate Adriatic Block motion.

‡ Arabian NUVEL-1A motion.

are shown in Figure 1. It should be noted that most of the sites discussed here were visited periodically by mobile systems between the years 1986 and 1994.

4. DISCUSSION

The discussion here only highlights changes in the results and new interpretations beyond those given in *Smith et al.* [1994a]. We begin in the west and will work eastwards.

From Table 1 and, as seen in Figure 1, the horizontal motion of the Karitsa site now shows no significant motion relative to northern Europe. This is a considerable change of the previously estimated velocity of Karitsa [*Smith et al.*, 1994a] which exhibited significant westward motion. The revised estimate of motion for Karitsa is due to the discovery that an azimuth orientation error of 2.1° had corrupted the eccentricity measurement during the MTLRS-1 occupation of the Karitsa site in spring 1986 which was subsequently announced [*CDDIS*, 1994]. This orientation error caused a ~85 mm coordinate error in the 1986 position of Karitsa, manifested primarily in the east component. Since the only other occupation of the site occurred in 1989, then the motion vector of Karitsa recovered before taking this error into account would be in error by about 85/3 ≈ 28 mm/yr to the west, nearly the 31.7 mm/yr value recovered by *Smith et al.* [1994a]. After taking the error into account, the estimated motion of Karitsa falls much better into line with respect to other geophysical evidence and theories regarding the tectonics of northwestern Greece [*Taymaz et al.*, 1991 and *Jackson*, 1994]. The spherical rates across the Aegean region are shown in Figure 2. It is noteworthy that the rates emanating from Karitsa to Dionysos and Askites (in central and northern Greece, respectively) show no significant deformation below the ~8 mm/yr 1-σ uncertainty level. Extension to points south of Karitsa, along the Aegean arc exhibit extension on the order of 16 to 22 mm/yr. Although not shown in Figure 2, the spherical rate to Matera is -1 ± 8 mm/yr, a result which does not conflict with the suggestion that shortening of 9 mm/yr is occurring between northwest Greece and the Apuglia region of Italy [*Mueller and Kahle*, 1993]. Karitsa is scheduled to be reoccupied by an SLR system in late 1994. The additional data from this, its third occupation, will help to resolve remaining questions regarding the motion in northwest Greece.

In Figure 3, spherical rates are shown for lines connecting the Aegean sites with those in Anatolia. In the north, between Askites and Yigilça, shortening of 11 ± 8 mm/yr is seen. This is consistent with the relative rates implied by the velocity field derived from moment tensors of earthquakes [*Jackson et al.*, 1992], with rates of deformation determined from seismicity for the Marmara Sea region of 9-10 mm/yr shortening in the east-west direction [*Kiratzi*, 1991] and with regional Global Positioning System analyses [*Straub and Kahle*, 1994]. On the other hand the motion of Yigilça is consistent with Eurasian motion.

Between sites in central Turkey (Yozgat and Melengiçlik) and central Greece (i.e. Dionysos), little extension beyond the 1-σ uncertainty is notable. This bodes well for those who suggest that the motion of the Anatolian block transfers almost continuously across the Aegean Sea. Relative rates between Yozgat and Melengiçlik to Katavia exhibit extension of about 10 mm/yr and grows larger to sites further south in the Aegean arc (e.g., Roumeli).

The estimated relative rate between Yigilça and Yozgat provides a measure of the amount of right lateral slip occurring along the North Anatolian fault, which, given the angle that the great circle between these sites makes with the fault, is on the order of 30 mm/yr, consistent with rates estimated from seismic sources [*Jackson and McKenzie*, 1988] but somewhat slower than the 50-80 mm/yr rates estimated from geological evidence [*Kiratzi*, 1993]. No significant motion is detectable across the bulk of the Anatolian block, between Yozgat and Melengiçlik.

The motion estimated for the site at Bar Giyyora is substantially improved from that reported in *Smith et al.* [1994a and 1994b].In the latter half of 1993 and the beginning of 1994, the system tracked LAGEOS I quite extensively. Relative to northern Europe, the estimated motion for Bar Giyyora is 9.2 mm/yr with an azimuth of 12° clockwise from north. In comparison, the motion predicted by NUVEL-1A relative to Eurasia is 11 mm/yr at 2° for Africa and 20 mm/yr at 344° for Arabia. Recently, improved plate rotation models for Africa, Arabia and Somalia have been developed [*Joffe and Garfunkel*, 1987 and *Jestin et al.*, 1994] which differ somewhat from NUVEL-1A. The plate rotation poles of *Jestin et al.* [1994] were determined with a constraint to ensure plate circuit closure and are given relative to one another as well as with respect to Antarctica. We have used this connection to Antarctica along with the NNR-NUVEL1A motion of Antarctica to navigate the motions of these three plates into the NUVEL-1A no-net-rotation frame. Then it becomes a simple matter of differencing plate rotation vectors to determine relative rotation poles and the implied relative motion vectors for sites of interest. We have done this for Africa and Arabia given by the *Jestin et al.* [1994] plate model relative to NNR-NUVEL1A Eurasia. The *Jestin et al.* [1994] predicted motion of Bar Giyyora relative to Eurasia is 11 mm/yr with an azimuth of 14° for Africa and 19 mm/yr at 12° for Arabia. The SLR result, although ~2 mm/yr shorter than the vectors implied by both NUVEL-1A and *Jestin et al.* [1994], are better aligned with the latter, but the uncertainty of the SLR results (and presumably those from the plate models themselves) prevents us from stating this definitively. However, it is interesting to note that the SLR estimate of motion for the site at Diyarbakir (26 mm/yr at 357°) is also better aligned with the model of Arabian motion relative to Eurasia given by *Jestin et al.* [1994], (23 mm/yr at 356° azimuth) than with NUVEL-1A (25 mm/yr at 337°). Finally, the present SLR estimate of motion of Bar Giyyora implies that Bar Giyyora behaves more like an African site and exhibits, within its uncertainty, very little transfer of Arabian motion across the Dead Sea Fault Zone. As mentioned in *Smith et al.* [1994a], densification campaigns by Global Positioning System receivers throughout the Dead Sea region will help to settle the issue of distributed strain across this transform fault.

5. CONCLUSION

The results described here update and extend those described in *Smith et al.* [1994a]. All known corrections have been applied and new interpretations provide a more consistent perspective regarding the kinematics of northwestern Greece and the southeastern Mediterranean region. The results of the SL8.6 solution agree well with those independently determined and discussed by *Noomen et al.* [1994] thus lending more credibility to both solutions. Of particular interest, is that the SLR estimates of motion for Bar Giyyora and Diyarbakir taken with respect to northern Europe more consistently agree with recently developed plate motion models for Africa and Arabia by *Jestin et al.* [1994] than with those implied by NUVEL-1A.

REFERENCES

Argus, D. F. and R. G. Gordon, "No-Net-Rotation Model of Current Plate Velocities Incorporating Plate Motion Model NUVEL-1", *Geophys. Res. Lett.*, Vol. 18, pp. 2039-2042 (1991).

CDDIS, Crustal Dynamics Data Information System Bulletin, Vol. 9, No. 6, p.9, (1994).

Degnan, J. J., "Millimeter Accuracy Satellite Laser Ranging: A Review", in *Contributions of Space Geodesy to Geodynamics: Technology*, edited by D. E. Smith and D. L. Turcotte, pp. 133-162, publ. by Amer. Geophys. Union, Vol. 25, Geodynamics Series, Washington, DC (1993).

DeMets, C., R. G. Gordon, D. F. Argus and S. Stein, "Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions", *Geophys. Res. Lett.* in press (1994)

Eyidoğan, H., "Rates of Crustal Deformation in Western Turkey as Deduced from Major Earthquakes", *Tectonophysics*, Vol. 148, pp. 83-92 (1988).

Hatzfeld, D., "On the Shape of the Subducting Slab Beneath the Peloponnese, Greece", *Geophys. Res. Lett*, Vol. 21, pp. 173-176 (1994).

Jackson, J., "Active Tectonics of the Aegean Region", *Annual Rev. Earth Plan. Sci.*, in press (1994).

Jackson, J. and D. McKenzie, "Active Tectonics of the Alpine–Himalayan Belt Between Western Turkey and Pakistan," *Geophys. J. R. astr. Soc.*, Vol. 77, pp. 185-264 (1984).

Jackson, J. and D. McKenzie, "The Relationship Between Plate Motions and Seismic Moment Tensors, and the Rates of Active Deformation in the Mediterranean and Middle East," *Geophys. J.*, Vol. 93, pp. 45-73 (1988).

Jackson, J., J. Haines and W. Holt, "The Horizontal Velocity Field in the Deforming Aegean Sea Region Determined from the Moment Tensors of Earthquakes", *J. Geophys. Res.*, Vol. 97, pp. 17,657-17,684, (1992).

Jestin, F., P. Huchon and J. M. Gaulier, "The Somalia Plate and the East African Rift System: Present-Day Kinematics", *Geophys. J. Int.*, Vol. 116, pp. 637-654, (1994).

Joffe, S. and Z. Garfunkel, "Plate Kinematics of the Circum Red Sea–A Re-evaluation", *Tectonophysics*, Vol. 141, pp. 5-22 (1987).

Kiratzi, A. A., "Rates of Crustal Deformation in the North Aegean Trough-North Anatolian Fault Deduced from Seismicity", *Pure Appl. Geophys.*, Vol. 136, pp. 421-432, (1991).

Kiratzi, A. A., "A Study of the Active Crustal Deformation of the North and East Anatolia Fault Zones", *Tectonophysics*, Vol. 225, pp. 191-203 (1993).

Mueller, S. and H-G. Kahle, "Crust-Mantle Evolution, Structure and Dynamics of th Mediterranean-Alpine Region," in *Contributions of Space Geodesy to Geodynamics: Crusta Dynamics*, edited by D. E. Smith and D. L. Turcotte, pp. 249-298, publ. by Amer Geophys. Union, Vol. 23, Geodynamics Series, Washington, DC (1993).

Noomen, R., B. A. C. Ambrosius, K. Herzberger, D. C. Kuijper, G. J. Metz, B Overgaauw, T. A. Springer and K. F. Wakker, "Rigid Block Deformations in Southeas Europe", in this volume, (1994).

Oral, M. B., *Global Positioning System (GPS) Measurements in Turkey (1988-1992) Kinematics of the Africa-Arabia-Eurasia Plate Collision Zone*, PhD Dissertatio Massachusetts Institute of Technology, Cambridge, MA (1994).

Smith, D. E., R. Kolenkiewicz, J. W. Robbins, P. J. Dunn and M. H. Torrence, "Horizont Crustal Motion in the Central and Eastern Mediterranean Inferred from Satellite Las Ranging Measurements", *Geophys. Res. Lett.*, Vol. 21, pp. 1979-1982 (1994a).

Smith, D. E., R. Kolenkiewicz, R. S. Nerem, P. J. Dunn, M. H. Torrence, J. W. Robbin S. M. Klosko, R. G. Williamson and E. C. Pavlis, "Contemporary Global Horizont Crustal Motion", *Geophys. J. Int.*, in press, (1994b).

Straub, C. and H-G. Kahle, "Global Positioning System (GPS) Estimates of Crust Deformation in the Marmara Sea Region, Northwestern Anatolia", *Earth Plan. Sci. Let* Vol. 121, pp. 495-502, (1994).

Taymaz, T., J. Jackson and D. McKenzie, "Active Tectonics of the North and Central Aege Sea", *Geophys. J. Int.*, Vol. 106, pp. 433-490, (1991).