Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 700

Tectonic History and Present-Day Deformation in the Zagros Fold-Thrust Belt

BY

KHALED HESSAMI

ACTA UNIVERSITATIS UPSALIENSIS
UPPSALA 2002

Dissertation for the Degree of Doctor of Philosophy in Mineralogy, Petrology, and Tectonics presented at Uppsala University in 2002.

Abstract

Hessami, K., 2002. Tectonic history and present-day deformation in the Zagros fold-thrust belt. Acta Universitatis Upsaliensis. *Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 700. 13 pp. Uppsala. ISBN 91-554-5285-5.

This thesis uses various approaches such as observation of satellite images, field investigations, analogue modeling and GPS measurements to constrain deformation of the basement and sedimentary cover of the Zagros fold-thrust belt in time and space.

Focal mechanism solutions of most earthquakes indicate that deformation in the Zagros basement is due to shortening and thickening through numerous thrust faults. However, observations of strike-slip faulting recognized on satellite images imply that N-S trending faults in the Zagros, inherited from Pan-African basement, rotated about vertical axes to accommodate the convergence between Arabia and central Iran.

Field studies suggest that southwestward advance of the Zagros front has been recorded by syn-sedimentary structures. These structures indicate that deformation started as early as end Eocene in the northeast of the Simply Folded Zone and propagated progressively to the southwest. The deformation front drove the foreland basin to its present position along the Persian Gulf and Mesopotamia.

Scaled analogue models suggest that the seismicity due to orogenic shortening depends largely on the friction between the cover and its basement. Models show that fold-thrust belts with low tapers shortened above low friction ductile decollements involve several long-lived thrust faults generating low to moderate earthquakes over wide areas at the same time. By contrast, earthquakes with larger magnitudes are expected to occur along a few short-lived thrust ramps in fold-thrust belts with larger tapers shortened above high-friction decollments.

GPS-derived velocities across and along the Zagros suggest that only about one third (10 ± 3 mm/yr) of the current convergence between Arabia and Eurasia is accommodated within the Zagros by thickening to the east of the Kazerun Fault and thickening and lateral movement to the west. The remaining (21 ± 3 mm/yr) is transferred beyond the Zagros suture to central Iran and the northern Iranian mountains.

Key Words: Zagros, orogeny, unconformities, Iran, growth folds, Middle-East, tectonics, models, GPS, basement, seismicity.

Khaled Hessami, Department of Earth Sciences, Hans Ramberg Tectonic Laboratory, Villavägen 16, SE-752 36, Uppsala, Sweden

© Khaled Hessami 2002

ISSN 1104-232X
ISBN 91-554-5285-5

Printed in Sweden by Geotryckeriet, Geocentrum, Uppsala 2002

Introduction

Current tectonic activity in the Zagros fold-thrust belt is the consequence of continental convergence between Arabia and Asia since late Cretaceous/early Miocene. Being the youngest continental suturing zone on our planet, the Zagros fold-thrust belt is a key area for studying the processes that occur in the early stages of convergence zones. The tectonic picture of the Zagros fold-thrust belt is complicated by a Phanerozoic sedimentary cover which is partially decoupled from its underlying basement above a mechanically weak layer of Hormuz salt and anhydrite.

This thesis uses various approaches (such as field data, tectonic modelling and GPS measurements) to address different fundamental aspects of the Zagros fold-thrust belt. Satellite images and maps of seismicity have been used to explain how the Zagros basement accommodates the convergence between Arabia and central Iran (Asia). Field studies show that deformation within the Zagros Simply Folded Zone began as early as End Eocene and has been propagating to the south and southwest ever since. Analogue modelling suggests that the Hormuz salt along which the sedimentary cover is partially decoupled from the underlying basement plays a major role in cover deformation and seismicity. Lastly, Global Positioning System (GPS) measurements constrain the rates and directions of shortening for different parts of the Zagros.

This thesis argues that the kinematics of the Zagros are complicated by the orogenic cover being decoupled from its basement by a layer of weak salt to the east of the Kazerun Fault and not to the west. It discusses the interplay between coupling and decoupling between the Zagros basement and its cover in order to explain the 4-D evolution history in different parts of the Zagros fold-thrust belt.

The following four papers support the thesis and will be referred to in the text by their Roman numerals.

I. Hessami, K., Koyi, H.A. and Talbot, C.J., 2001. The Significance of strike-slip faulting in the basement of the Zagros fold and thrust belt, *Journal of Petroleum Geology*, Vol. 24 (1), 5-28.

This paper emphasizes the significance of strike-slip faulting in the deformation of the basement of the Zagros fold-thrust belt. It is shown that shortening in the Zagros basement is partitioned into vertical escape via NW-SE striking thrusts and lateral escape recorded by the rotation of fault blocks which increases in significance from NW to SE along the SE Zagros.

The idea of this paper was developed by KH who also prepared the initial manuscript. It was reworked to its final stage in cooperation with HAK and CJT.

II. Hessami, K., Koyi, H.A., Talbot, C.J., Tabasi, H. and Shabanian, E., 2001. Progressive unconformities within an evolving foreland fold-thrust belt, Zagros Mountains. *Journal of the Geological Society, London,* Vol. 158 (6), 969-981.

This study uses field evidence of local syn-sedimentary structures in Cenozoic stratigraphic units to argue that the front of the Zagros Simply Folded Zone has propagated from NE to SW since end Eocene to Present.

KH, HT and ES conducted the field investigations. The idea was developed by KH and formulated in cooperation with HAK and CJT.

III. Koyi, H.A., Hessami, K. and Teixell, A., 2000. Epicenter distribution and magnitude of earthquakes in fold-thrust belts: insights from sandbox models, *Geophysical Research Letters*, Vol. 27 (2), 273-276.

Scaled analogue models are used to illustrate the effect of basal friction and erosion on fault activity and hence on epicentre distribution and magnitude of earthquakes in the sedimentary cover of active fold-thrust belts.

HAK had the idea developed in this paper. KH helped HAK construct and deform the models. The manuscript was written together with KH providing details of Zagros seismicity.

IV. Hessami, K. and Nilforoushan, F. 2002. Seventeen months of movements in the Zagros Mountains, SW Iran. Manuscript submitted to Geology.

This paper presents the results of Global Positioning System (GPS) measurements for the period December 1999 to June 2001 at 36 stations in and near the Zagros Mountains.

KH initiated the idea and had the GPS surveys conducted in the Zagros within the framework of scientific cooperation between National Cartographic Centre and International Institute of Earthquake Engineering and Seismology, Tehran, Iran. FN processed most of the GPS data and wrote part of the manuscript. KH interpreted the GPS velocities and wrote most of the manuscript.

Other publications produced during the study period but not included in support of this thesis are:

V. De Martini, P.M., Hessami, K., Pantosti, D., D'Addezio, G., Alinaghi, H., Ghafory-Ashtiani, M., 1998. A geologic contribution to the evaluation of the seismic potential of the Kahrizak fault (Tehran, Iran), *Tectonophysics*, 287, 187-199.

VI. Hessami, K., Tabasi, H., Shabanian, E., Abbasi, M.R., Feghhi, K., Soleymani, S., 2000. Preliminary results of trenching across the North Tabriz Fault, NW Iran. In: Okumura, K., Takada, K., & Goto, H. (eds.) Proceedings of the Hokudan International Symposium and School on Active Faulting, Hokudan, Japan, pp. 89-91.

VII. Karakhanian, A.S., Trifonov, V.G., Philip, H., Avagyan, A., Hessami, K., Jamali, F., Bayraktutan, M.S., Bagdassarian, M., Arakelian, S. and Davtian, V., 2002. Active faulting and natural hazards in Armenia, eastern Turkey and north-western Iran. *Tectonophysics*, in press.

Summary of the papers

Paper I.

The pattern of seismicity defines a linear zone along the Zagros fold-thrust belt (Fig. 1a). Lateral offset of this zone indicates segmentation of the Zagros fold-thrust belt along transverse faults that root to deep-seated strike-slip faults in the Pan-African Arabian basement. The dominant NW-SE trending features of the belt have undergone repeated horizontal offsets along these transverse basement faults. These faults controlled the deposition of the Phanerozoic cover and the entrapment of hydrocarbons on the NE margin of Arabia before Tertiary-Recent deformation of the Zagros fold-thrust belt. Faults identified on Landsat satellite images were used in conjunction with the spatial distribution of earthquakes and their focal mechanism solutions to infer a tectonic model for deformation of the Zagros basement.

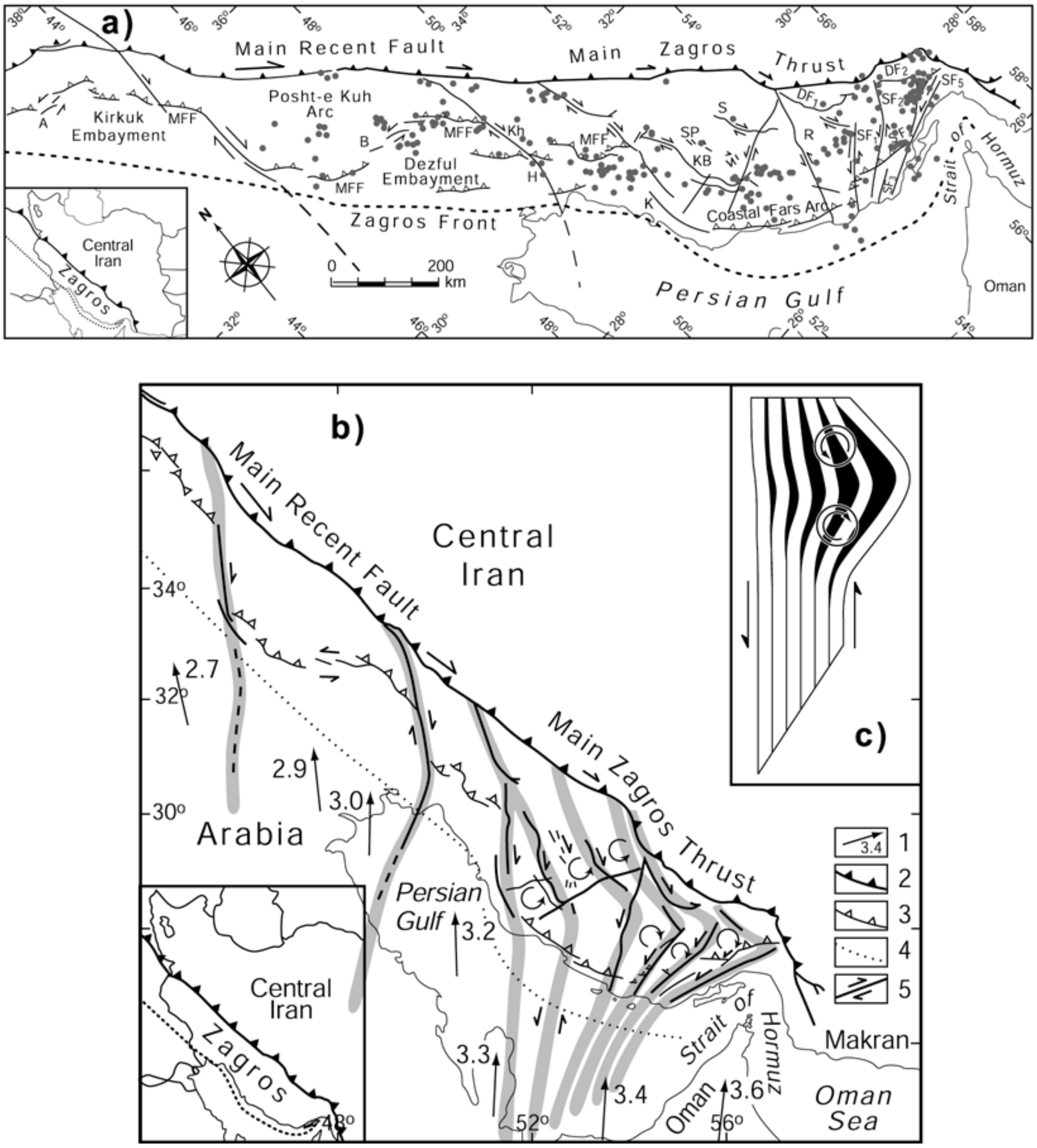

Figure 1. a) Earthquakes with mb > 5.0 (Jackson and McKenzie, 1984) along seismogenic basement thrusts offset by major strike-slip faults. b) Schematic interpretative map of the main structural features in the Zagros basement. The overall north-south motion of Arabia increases along the belt from NW to SE (arrows with numbers). Central Iran acted as a rigid backstop and caused the strike-slip faults with N-S trends in the west to bulge increasingly eastward. Fault blocks in the north (elongated NW-SE) rotate anticlockwise; while fault blocks in the south (elongated NE-SW) rotate clockwise. c) Simple model involving parallel paper sheets illustrating the observed strike-slip faults in the Zagros. Opening between the sheets (i.e. faults) helped salt diapirs to extrude.

The geometry and distribution of transverse strike-slip faults differ when traced from NW to SE along the Zagros fold-thrust belt (Fig. 1b). In the NW, strike-slip faults are widely spaced with the same original north-south strikes presumed in the Arabian foreland. In the SE, east of the

Kazerun Fault however, strike-slip faults can be grouped into two domains, northern and southern, which are elongated respectively to the NNW and NE. Right-lateral faults dominate in the northern domain and have strikes that increasingly diverge eastward from their inherited original N-S to NW-SE trends (Fig. 1b). By contrast, left-lateral faults dominate in the southern domain and their strikes increasingly rotate eastwards from NNE-SSW to ENE-WSW. The change in strike of faults from nearly north-south to about N 55^o W is attributed to the 55^o anticlockwise rotation of the right-lateral faults in the northern domain. The change in strike of left-lateral faults from N 15^o E to N 62^o E suggests 48^o clockwise rotation of blocks in the southern domain. These values constrain the rate of rotation to about 3.3^o / Ma in the northern domain and 2.9^o/Ma in the southern domain.

A simple 2-D analogue of deformation between a rigid backstop and a converging foreland has been proposed to explain the kinematics of the strike-slip basement faults and their rotation (Fig. 1b and c). The pole of rotation of Arabia relative to Eurasia is at 31^o 37' 48" north, 15^o 21' 00" east (Jackson et al., 1995). This accounts for the increase in the rate of convergence from NW to SE along the strike of the Zagros fold-thrust belt along small circles concentric about the rotation pole (Fig. 1b). Increasing convergence rate from NW to SE results in left-lateral simple shear along north-south trending faults in the Zagros basement (Fig. 1c). However, post-suturing convergence between Arabia and Central Iran rotated both the basement blocks in the east and the faults bounding them and possibly led to deep-seated lateral escape along the belt from west to east. Continued convergence led to so much anticlockwise rotation of blocks in the north that initial left-lateral movements converted to right-lateral movement along NW-SE trending faults adjacent to the Main Zagros Thrust. By contrast, left-lateral movement along NE-SW trending faults in the south intensified because of clockwise rotation of the fault blocks.

The tectonic model presented here (Fig. 1c) accounts for the geometry and kinematics of the basement faults and also the lateral offset of the seismogenic zone along the belt and the tensional features of earthquake focal mechanism solutions along transverse faults in the Zagros fold-thrust belt. In addition, the model explains a deviation in the pattern of oil-fields visible across the Gulf in the Arabian Peninsula. It is also suggested that the lack of salt extrusions in the NW Zagros, usually attributed to the Hormuz Salt being absent there, could alternatively be attributed to the gaps required to allow salt intrusion not having opened along the fewer widely spaced transverse faults in the NW Zagros.

Deep-seated shortening in the Zagros basement can be partitioned into vertical escape via NW-SE striking thrusts and lateral escape recorded by the rotation of deep-seated basement blocks which increases in significance from NW to SE along the SE Zagros. More seismic data are required to more precisely constrain the direction and amount of rotation of the basement blocks discussed in Paper I.

Paper II.

The Zagros Simply Folded Zone forms the most southwesterly deformation zone of the Zagros fold-thrust belt (Fig. 2). The northeastern limit of the Simply Folded Zone is marked by the southwestern boundary of a narrow (70-90 km wide) imbricate zone of southwest-verging overthrust anticlines. The front of the Simply Folded Zone, where folding is gentle both on land and beneath the Persian Gulf, can be defined at different levels by the shape in map view of the oil- and gas fields (Talbot & Alavi 1996; Fig. 2).

A major angular unconformity between the Bakhtyari conglomerates and the underlying Agha Jari Formation has long been interpreted as indicating that orogeny in the Zagros Simply Folded Zone took place in Plio-Pleistocene times (James & Wynd 1965; Motiei, 1993). New field evidence for offlap and onlap associated with angular unconformities and conglomerates within the Cenozoic stratigraphy of the Zagros demonstrates that stratigraphic breaks, previously attributed to epirogeny, are the result of separable pulses of deformation propagating across the Simply Folded Zone.

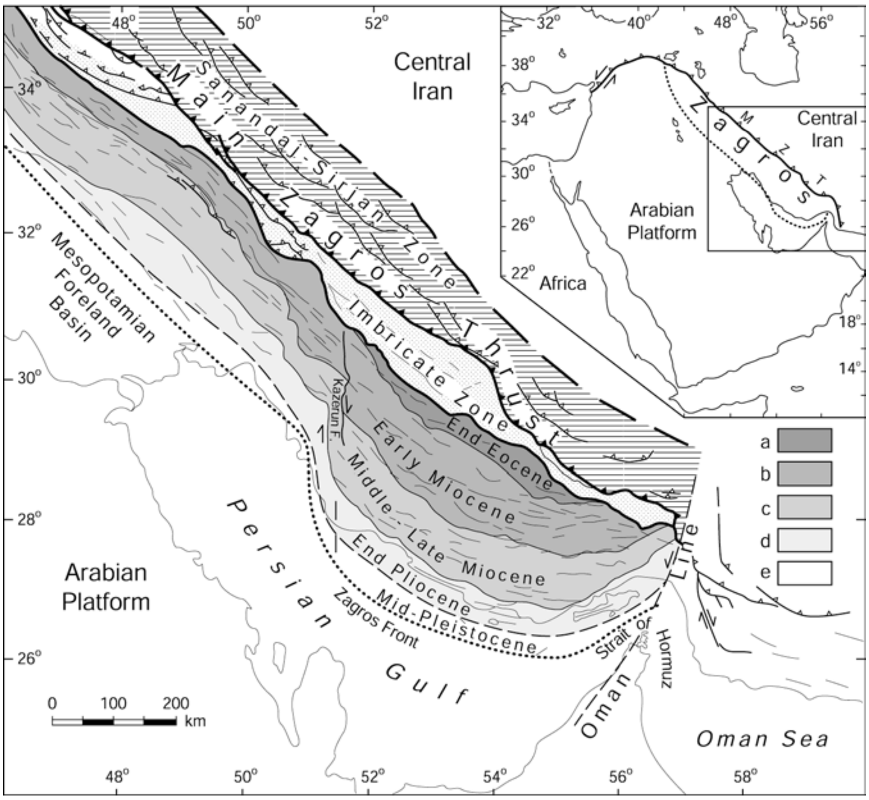

Figure 2. Summary of the increments of progressive growth recorded by syn-sedimentary structures in the Simply Folded Zone as it widened from end Eocene to the present. The deformation front of the Zagros Simply Folded Zone has been driving the foreland basin in front of it as it has propagated episodically to the southwest since end Eocene. Shading lightens successively through strips of frontal folds that become younger southwestward; a) end Eocene, b) Early Miocene, c) Middle-Late Miocene, d) end Pliocene, e) Mid-Pleistocene. The entire Simply Folded Zone folded simultaneously as it widened progressively towards the southwest.

Each of the unconformities documented in the Zagros Simply Folded Zone represents a belt-parallel zone in which specific stratigraphic units were lifted by deformation between particular time intervals. The fold belt episodically widened by the addition of a few active folds at a time. The front of the Zagros Simply Folded Zone therefore underwent progressive advance, as described below.

Outcrops of the Paleocene-Eocene Jahrom Formation are limited to the northeast rim of the Simply Folded Zone where they were uplifted by folding at end Eocene (Fig. 2) and have been subject to subaerial weathering ever since (James & Wynd 1965; Motiei 1993). Contemporaneous with the end Eocene phase of folding, the shallow-water shelf carbonates of the Oligo-Miocene Asmari Formation accumulated in the foreland basin, which had been driven to the southwest by the serial migration of frontal folds.

After its deposition in the Oligocene-Early Miocene, the Asmari Limestone and older units record local erosion of anticlinal crests confined to a narrow strip in the Simply Folded Zone (Fig. 2). Loading by marls of Razak Formation along synclinal troughs aided the rise of anticlines of Asmari limestone which forced local regression of the Gachsaran basin southwestward and resulted in onlapping of the Razak Formation on the Asmari Limestone along the deformation front. The growth of these anticlines was coeval with deposition of shallow marine sediments of the Early-Middle Miocene Gachsaran and Mishan Formations in the foreland basin now further southwest. The Early-Middle Miocene marine trough, in turn, was uplifted when the deformation front migrated through the Gachsaran and Mishan Formations in the Middle-Late Miocene. The Middle-Late Miocene phase of folding documented here was coeval with a change from shallow-marine sediments of the Mishan Formation to estuarine sediments of the Agha Jari Formation in a narrow foredeep as well as along synclinal troughs across the rest of the already existing Simply Folded Zone in the northeast.

The most dramatic phase of the Zagros orogeny in the Simply Folded Zone was when estuarine sediments (marls and sandstones) of the Agha Jari (and lower Bakhtyari) were buried by massive conglomerates of the upper Bakhtyari deposited across the whole width of the Simply Folded Zone at end Pliocene. Post-end Pliocene conglomerates of the (upper) Bakhtyari Formation overlie older formations, conformably in front of the deformation front and unconformably over the rest of the belt to the northeast. The upper Bakhtyari Formation was folded right across the zone (Falcon 1974) during the mid-Pleistocene orogenic phase (Pedrami 1987) and the white area was added to the southwest of the Zagros Simply Folded Zone (Fig. 2). The present foreland basin is located along the Mesopotamian foredeep and the Persian Gulf.

The orogenic phase that occurred at end Eocene was the least widespread and confined to the northeast rim of the present Simply Folded Zone (Fig. 2). As the Simply Folded Zone widened progressively towards the southwest, old folds continued to shorten so that the entire belt folded simultaneously. The evidence for this claim is the simultaneous Early-Middle Miocene folding of both the littoral sediments of the Razak Formation (deposited in synclinal troughs between rising anticlines in the northeast) and its time-equivalent, the Gachsaran Formation (deposited in the main marine depocentres). In addition, the folding of the continental Agha Jari and Bakhtyari formations deposited right across the Simply Folded Zone indicates that the end Pliocene and mid-Pleistocene phases of orogeny folded the whole width of the Zagros Simply Folded Zone. This is borne out by seismic activity which indicates that the Simply Folded Zone is still deforming across most of its width (Fig. 1a). As a result, the youngest units of the sedimentary cover at the present-day deformation front have folded only during the latest phase of orogeny whereas successively older units have been deformed by increasing number of orogenic phases with increasing distances behind.

Local unconformities at end Eocene, Early Miocene [Burdigalian], Middle-Late Miocene, end Pliocene and mid-Pleistocene indicate a southwest-ward migration of the Zagros deformation front that was pulsed in space but may have been continuous (but not necessarily steady) in time. Changes in lithology and salt extrusion contemporaneous with each unconformity also demonstrate episodic tectonic movements.

Paper III.

According to the critical-taper Coulomb wedge model (David and Engelder, 1985; Dahlen, 1990), thrust faults in a fold-thrust mountain belt propagate sequentially until a wedge with a steady-state taper angle is built. Subsequent deformation involves transport of the whole wedge along the basal décollement. Wedges shortened above a ductile décollement develop a low-angle taper compared to the high-angle taper that characterises wedges shortened above a high friction décollement (Davis and Engelder, 1985).

Two sets of analogue models were used to study the effect of basal friction on the distribution of active thrust faults, their slip rates and life-times within a fold-thrust belt. In both sets, a sequence of passively layered loose sand with an angle of internal friction of 30 degrees simulated sedimentary rocks in the upper 10 km of the brittle crust. Models were shortened from one end by advancing the "backstop" under normal gravity (Fig. 3). The only parameter which was varied in the two sets of models was the basal friction. In the first set, models were shortened above a high-friction décollement (coefficient of basal friction μ_b = 0.47, referred to as models with frictional décollement). In the second set, models were shortened above a ductile substrate representing a low-friction décollement (referred to as models with ductile décollement). The ductile substrate was a Newtonian silicone polymer with a viscosity of ($\mu = 5.10^4$ Pa s) which is independent of strain rate. This material simulated rock salt or fluid-overpressured shales and introduced a low friction décollement in the model.

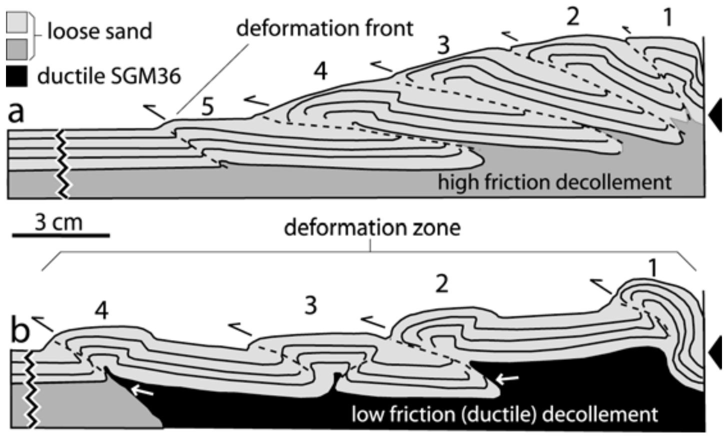

Figure 3. Line drawings of profiles of two models shortened above (a) frictional and (b) ductile decollements. Deformation zone is concentrated along the active thrust at the front of the wedge in (a) whereas in (b) the entire wedge is active.

In models shortened above a frictional décollement, piggy-back thrust faults formed serially where each younger thrust developed in the footwall of the previous thrust (Fig. 3a). As new thrusts developed, older thrusts rotated to higher angle relative to the prevailing stress field and eventually locked. With progressive shortening, only foreland verging thrusts formed and propagated spatially from the hinterland to the foreland as the basal décollement propagated in a discontinuous mode towards the foreland. At any given time, shortening above the frictional décollement was accommodated by slip along a single thrust fault which displayed a high averaged slip rate ($2.3 \cdot 10^{-2} – 4.4 \cdot 10^{-2}$ mm/s) compared to the bulk shortening rate of $3.3 \cdot 10^{-2}$ mm/s. It was concluded that successive thrust ramps have limited lifetimes in model fold-thrust belts shortened above frictional décollements. Only one thrust was active at a time, this started with its own initiation and ended when the next ramp thrust developed in front of it (Koyi, 1995).

In models shortened above a ductile substrate (ductile décollement), thrusts verged towards both the foreland and hinterland (Fig. 3b). Shortening of models above a ductile décollement involved several thrust faults being active simultaneously. Here, older thrust faults remained active as new thrusts formed in front of them. Each thrust accommodated only part of the bulk shortening. Therefore, at any given percentage bulk shortening, slip rate along individual thrust faults was relatively low ($2 \cdot 10^{-3} – 1.8 \cdot 10^{-2}$ mm/s i.e. about 1/16 to ½ of bulk shortening rate). In these models, every ramp thrust had a long lifetime and all remained active throughout the shortening.

In one of the models shortened above a frictional decollement, the top 30% of the wedge was eroded after 15% bulk shortening to study the effect of erosion on the lifetime of the thrust faults. Erosion lowered the wedge taper beneath critical. Subsequent shortening, rebuilt the wedge taper by tectonic thickening. This was achieved partly by internal strain within the wedge and partly by reactivation of older thrusts located in the eroded section. Reactivation of these older inactive thrusts was necessary to rebuild the wedge taper and further propagate the basal décollement in front of the wedge. After the wedge was rebuilt back to its critical taper, the reactivated older thrusts ceased activity and thereafter only one thrust was active at any one time.

A suitable area to test our model results is the Zagros fold-thrust belt (southwest Iran). The basal decollement along which the sedimentary cover is shortening in the Zagros is divided into two main domains. In the southeastern part of Zagros fold-thrust belt, the sedimentary cover is shortening above a layer of salt acting as a ductile decollement. Our models account for the wide spatial distribution of shallow earthquakes in the southeastern part of the Zagros fold-thrust belt which indicate that many of the thrust faults in the sedimentary cover are still active. In contrast, in the northwestern part of Zagros, where the salt layer may be thin or missing, the sedimentary cover is shortened above a frictional decollement. The epicentres of earthquakes in this area are restricted to a narrower zone of the sedimentary cover implying that they are generated along one or two of the frontal thrust ramps.

Paper IV.

Intense GPS investigations have determined the velocity field between Africa-Arabia and Eurasia west of the Zagros (i.e. Turkey, the Aegean region and Greece, see e.g. Reilinger et al., 1997). This paper presents the first results of Global Positioning System (GPS) measurements for the period December 1999 to June 2001 at 36 stations in and near the Zagros fold-thrust belt (Fig. 4). The main objective of this study was to determine how closely measured present-day convergence between Arabia and central Iran resemble the rates estimated on the basis of evidence from geology, seismology, and plate rotation models.

The results of two campaigns of GPS measurement useing dual frequency GPS receivers in 1999 and 2001 were interpreted for a preliminary study of deformation in the Zagros fold-thrust belt. These campaigns were measured with six Trimble 4000 SSI dual frequency receivers with choke-ring antennas to considerably decrease the multipath errors. The limited number of receivers did not allow the complete network to be measured in one session. Instead, six GPS receivers on tripods were used simultaneously to measure stations in different 8-hour sessions day by day with common triangles. However, since each station was re-measured in different sessions, the minimum time of observation for each station was 24 hours to yield millimeter accuracy over inter-station distances on the order of about 100 km.

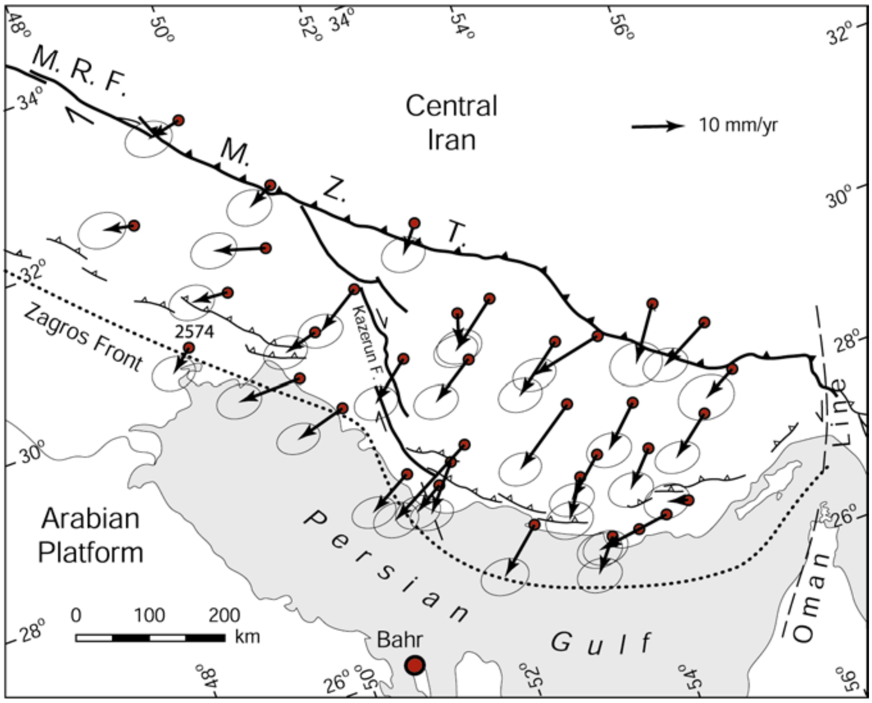

Figure 4. GPS horizontal velocities in a Bahr-fixed reference frame over 17.5 months. The errors represented by the ellipses are 20 times the formal statistical error.

The GPS data was processed using Bernese 4.2 software (Hugentobler et al., 2001). In order to achieve the required accuracy, the most important steps in processing involved detection and repair of cycle slips and the resolution of ambiguities. Nearly all possible baselines in each session were processed and saved with their variance-covariance matrix and adjusted on the way to a single session solution. All single-session solutions were then combined with ADDNEQ (Brockmann, 1996; Hugentobler et al., 2001) to compute multi-session solutions. Finally these multi-session solutions were used to compute horizontal station velocities with their covariances.

The precision of relative station coordinates is estimated from the repeatabilities (root-mean-square scatter, or dispersion about their mean) of independent daily baseline solutions. To assess session-to-session scatter, solutions for every session were independently computed and compared with the total solution for different campaigns. This comparison indicated that a factor of 20 is an appropriate ratio between the realistic random error and the formal error.

GPS velocities related to a fixed IGS station (Bahr) well in front of the Zagros (Fig. 4) discloses four areas of movement within the Zagros network. East of the Kazerun Fault, stations moved SW between 8-12 mm/yr. West of the Kazerun Fault stations moved 7 to 12 mm/yr with a greater westward component that increased westward. Northwest of the Kazerun Fault, stations moved west-northwest at 6 to 10 mm/yr (notice that North is not up the page in Figure 4). Stations just NE of the Main Zagros Thrust moved between 6-12 mm/yr SW with westward components increasing northwestward.

Velocities measured by GPS in the sedimentary cover east of the Kazerun Fault are 6-10 times larger than estimates of thick-skinned shortening of 1-1.5 mm/yr based on cumulative seismic moments of medium to large earthquakes. Two obvious explanations for this discrepancy are possible. The first is that 1-1.5 mm/yr seismic shortening really represents all the motion between Arabia and central Iran but is disguised by gravity spreading of a low taper wedge decoupled from the basement by Hormuz salt east of the Kazerun Fault. However, a more likely explanation is that the discrepant 8-9 mm/yr must be accommodated by aseismic creep in the basement. Movements west of the Kazerun Fault, where the Hormuz salt may be thin or missing are close to our level of accuracy but appear to involve lateral movement to the west-northwest.

GPS measurements and analyses of the 1999 and 2001 campaigns indicate that the current average rate of convergence across the Zagros (10 ± 3 mm/yr) is only about one third of the 31 mm/yr convergence between Arabia and Eurasia. The remaining convergence, of about 21 mm/yr, may account for the widespread seismicity in Iran northeast of the Main Zagros Thrust.

Concluding remarks

This thesis has not solved all the complications and ambiguities in Zagros deformation represented by decoupling of the orogenic cover from its basement by a layer of weak salt.

There is an apparent discrepancy between paper I on one hand and papers II and IV on the other. The emphasis in Paper I (Fig. 1) is on block rotation and possible eastward lateral escape east of the Kazerun Fault. However, Papers II and IV involve southwestward movement of the Zagros. The most likely explanation for this apparent discrepancy is that fault-bounded basement blocks east of the Kazerun Fault did indeed rotate about vertical axes and may well have moved eastward (paper I). Meanwhile, the cover really does move to the south (papers II and VI) because it is decoupled from its basement by the weak Hormuz salt. Since the basement is nowhere exposed in the Zagros fold-thrust belt, geological observations and paleomagnetic and GPS measurements cannot resolve these problems. There is, therefore, a need for using geophysical techniques such as deep seismic profiling and accurate earthquake monitoring to establish the nature of any deformation in the basement.

Acknowledgement

I would like to express my appreciation to all those whose cooperation and support allowed the completion of this study. I wish to acknowledge, most gratefully, my obligation to Prof. Christopher Talbot for his supervision and help during different stages of this undertaking and for his effort in many directions in my behalf throughout my career as a student. Special thanks are likewise expressed to Dr. Hemin Koyi whose co-supervision, help, encouragement and inspiring advice contributed significantly to this end. I am also indebted to Dr. Bertram Schott, now at Utrecht University, Taher Mazloomian and Kersti Gløersen for help. I acknowledge a PhD grant from Uppsala University which supported my research.

References

Brockmann, E., 1996. Combination of solutions for geodetic and geodynamic applications of the Global Positioning System (GPS), PhD Thesis, Astronomical Institute, University of Bern.

Dahlen, F.A., 1990. Critical taper model of fold-and-thrust belts and accretionary wedges, *Earth and Planetary Science Letters*, 19, 55-99.

David, D.M., and Engelder, T., 1985. The role of salt in fold-and-thrust belts, *Tectonophysics*, 119, 67-88.

Falcon, N.L. 1974. Southern Iran: Zagros Mountains. *In*: SPENCER, A. (ed) Mesozoic-Cenozoic Orogenic Belts, Geological Society, London, Special Publications, 4, 199-211.

Hugentobler, U., Schaer, S. and Fridez, P., 2001. Bernese GPS software, version 4.2, Astronomical Institute, university of Bern, pp 515.

Jackson, J. and McKenzie, D., 1984. Active tectonics of Alpine-Himalayan belt between western Turkey and Pakistan. *Geophys. Journ. Roy. Astr. Soc.*, 77, 185-264.

Jackson, J., Haines, J. and Holt, W., 1995. The accommodation of Arabia-Eurasia plate convergence in Iran. *Journ. Geophys. Res.*, 100, 15205-15219.

James, G.A. & Wynd, J.G. 1965. Stratigraphic nomenclature of Iranian oil consortium agreement area. *The American Association of Petroleum Geologists Bulletin*, 49, 2182-2245.

Koyi, H., 1995. Mode of internal deformation in sand wedges, *Journal of Structural Geology*, 17, 293-300.

Motiei, H. 1993. Geology of Iran: Stratigraphy of Zagros. Geological Survey of Iran. No. 1, pp. 536 [in Farsi].

Pedrami, M. 1987. Quaternary stratigraphy of Iran. Geological Survey of Iran. Internal report, Serial No. 551.79 (55) Pe, pp. 134 [in Farsi].

Reilinger, R.E., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O. and Sanli, I., 1997. Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, Journal of Geophysical Research, *102*, 9983-9999.

Talbot, C.J. and Alavi, M., 1996. The past of a future syntaxis across the Zagros. *in*: G.I. ALSOP, D.J. BLUNDELL and I. DAVISON (Eds.), *Salt Tectonics*, Geological Society, London, Special Publications, 100, 89-109.