Backstripping dip-slip fault histories: apparent slip rates for the Miocene of the Vienna Basin

Michael Wagreich* and Hanns Peter Schmid
Institute of Geology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

ABSTRACT

Backstripped basement subsidence histories from both the hanging wall and the footwall blocks adjacent to synsedimentary normal faults can be used to reconstruct the sense of fault motion through time and to quantify the vertical component of fault slip. Consequently, apparent dip-slip rates of faults can be calculated for each stratigraphic interval and times of increased fault activity can be distinguished. An application of this method to well data along a transect through the central part of the Miocene Vienna Basin indicates that two distinct phases of faulting occurred during the Karpatian, with rates as high as 3000 m Myr^{-1}. Changes in the sense of movements during the early Karpatian and the earliest Badenian indicate a major rearrangement in the fault patterns. During the early Sarmatian another short pulse of dip-slip is recorded along the investigated faults.

Terra Nova, 14, 163–168, 2002

Introduction

Analysis of deformational histories along polyphase reactivated faults commonly is based on the dating of cross-cutting relationships using relative ages of offset strata or geochronological ages of syntectonically grown minerals within fault planes. However, ten Veen and Postma (1999) and ten Veen and Kleinspehn (2000) introduced a new approach to reconstructing the vertical component of synsedimentary fault movements by geohistory analysis of sedimentary sections from both the hanging wall and the footwall blocks. The present contribution further elaborates this method to calculate apparent dip-slip rates for given time slices within sedimentary basins, and to quantify several distinct phases of faulting events in the Miocene Vienna Basin. This demonstrates the applicability of this method to transtensional basins.

Methods

Backstripping of sedimentary columns is generally used as a tool for reconstructing the subsidence history of sedimentary basins. The backstripping process includes corrections for palaeobathymetry and stepwise decompaction of stratigraphic units (Steckler and Watts, 1978; Roberts *et al*., 1998), using measured or empirical porosity–depth curves (Bond and Kominz, 1984). Palaeobathymetry estimates are based mainly on known depth ranges of sedimentary structures and palaeoecological proxies, e.g. benthic foraminiferal assemblages or planktonic/benthic ratios. Decompacted thicknesses and palaeo-water depths for each stratigraphic unit result in a basement (sediment-loaded) subsidence curve, which may or may not include a correction for eustatic sea-level changes.

The backstripping method introduced by ten Veen and Postma (1999) and ten Veen and Kleinspehn (2000) uses basement subsidence curves without sea-level corrections for sedimentary successions on two fault blocks adjacent to major synsedimentary normal faults (Fig. 1a). Segments of convergence or divergence record times of dip-slip activity. Parallel curved segments record either times of inactivity or pure strike-slip motion. Intervals of faulting can be dated according to the achieved chronostratigraphic resolution, commonly based either on biostratigraphic data and their correlation to chronostratigraphic scales or on geochronological dating of marker beds. The relative sense of fault movement can be determined directly, with converging or crossing basement subsidence curves indicating reversals in the sense of faulting (Fig. 1b). This method can only be applied to synsedimentary faults and assumes no hiatuses or erosion in the investigated sections.

In the present article the method of ten Veen and Kleinspehn (2000) is expanded to calculate apparent dip-slip rates, i.e. the vertical component of displacement, for individual faults based on backstripping. Basement subsidence values, seen in the differences in vertical position of two basement surface points at a given time for each stratigraphic interval (cf. Fig. 1b), are calculated. Assuming similar stratigraphic timing within both sections and the absence of significant erosion, the difference of the basement subsidence values on either side of the fault are calculated stepwise for each stratigraphic unit. These dip-slip values (Fig. 1c) are divided by the time duration to give apparent dip-slip rates for each fault. Results of this fault backstripping method are presented in step plots of the slip rate vs. time (Fig. 1c). Positive or negative values indicate the sense of dip-slip, i.e. which block moved faster; fault inactivity or pure strike-slip motion result in zero values. Given the uncertainties in the backstripping process (e.g. Gallagher, 1989), slip rates are regarded as significant if they are larger than the possible error range introduced by the difference between minimum and maximum palaeowater depth estimates (ten Veen and Kleinspehn, 2000).

Geological setting

The Vienna Basin (Fig. 2), which is part of the Neogene Paratethys basin system (Steininger and Wessely, 2000), constitutes a complex pull-apart basin

*Correspondence: Dr Michael Wagreich, Institute of Geology, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria. Tel.: +43/ 1 4277 53465; fax: +43/ 1 4277 9543; e-mail: michael.wagreich@univie.ac.at

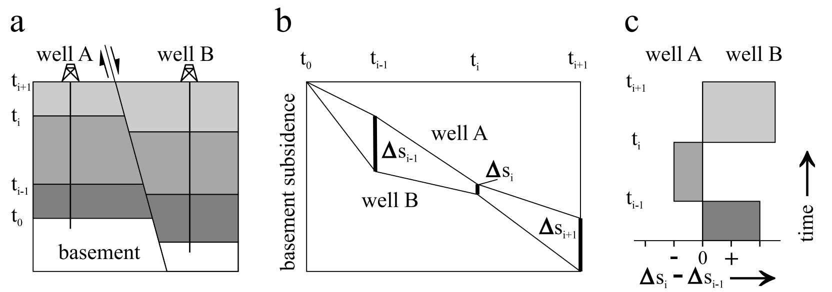

Fig. 1 Sketch illustrating the fault backstripping procedure modified from ten Veen and Kleinspehn (2000). (a) Two wells A and B on the footwall and the hanging wall of a synsedimentary normal fault, are considered. (b) Backstripping of the two wells results in basement subsidence curves. Differences in basement subsidence are expressed by Δs. (c) Step plot of apparent dip-slip rates vs. stratigraphic time along fault between wells A and B. Rates are calculated by subtracting Δs_{I-1} from Δs_i, and dividing the difference by the duration of the stratigraphic interval.

along the junction of the Eastern Alps and the Western Carpathians (Royden, 1985). The structural evolution of the Vienna Basin is characterized by an interplay of compression, strike-slip movements and extension, related to compression and lateral extrusion within the Eastern Alps (Ratschbacher *et al.*, 1991; Decker and Peresson, 1996).

In general, the evolution of the Vienna Basin started during the early Miocene (Eggenburgian–Ottnangian–Karpatian; for timescales see Fig. 3) with the development of a partly non-marine piggyback basin on top of N/NW-moving Alpine thrusts to the north-east of Vienna (Decker, 1996; Hamilton *et al.*, 2000). Palaeostresses changed to sinistral transtension (Fodor, 1995; Decker, 1996) around the early/middle Miocene boundary, leading to the formation of small-scale, rapidly subsiding lows and relatively stable highs during the Badenian and Sarmatian. A renewed marine transgression started in the early Badenian and also reached the southern part of the basin. Up to 3000-m thick successions of marls and sandstones characterize the central parts of the basin, whereas delta sands and carbonates were deposited at the basin margins or at shallow depths (Sauer *et al.*, 1992; Seifert, 1996; Weissenbäck, 1996). Maximum water depths in the central part of the basin probably never exceeded 250 m and thus basement subsidence values are mainly controlled by stratigraphic thicknesses. During Sarmatian and Pannonian times, salinity decreased, leading to limnic-fluvial deposits (Seifert, 1996).

Within the central part of the basin, where most of the investigated wells are situated, hiatuses and erosion are very minor. The only documented break in sedimentation was around the early/middle Miocene boundary, where block tilting and erosion is known north of the investigated area. Syntectonic stratal geometries within the Vienna Basin are well known from well log correlations and seismic data (e.g. Hamilton *et al.*, 2000). Coeval syntectonic sedimentation on hanging wall and footwall blocks can be demonstrated in several cases (e.g. Seifert, 1996).

Backstripped basement subsidence

Subsidence curves are based on wells along a WNW–ESE transect in the northern Vienna Basin (Fig. 4), including lithology data from cores and well logs provided by OMV, and revised stratigraphic correlations. Palaeodepth estimates rely mainly on the interpretation of foraminiferal assemblages (e.g. Brix and Schulz, 1993). Most of the wells are within relatively unfaulted blocks, although some of them, e.g. AdUT1 (Fig. 4), drilled through faults. Thus, thicknesses in the Karpatian/Badenian part may be reduced and basement subsidence may be slightly underestimated from this well.

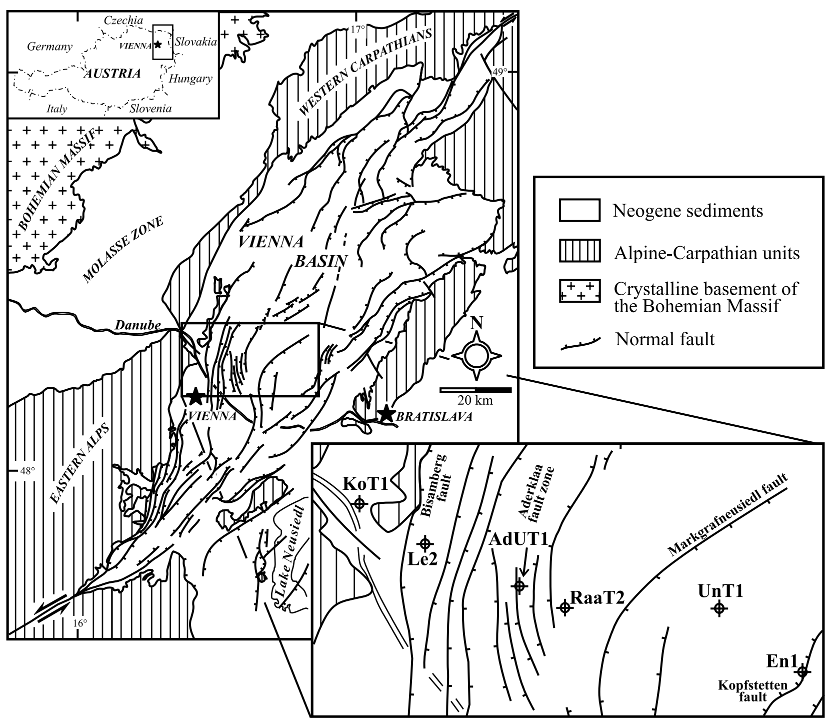

Fig. 2 Tectonic sketch map of the Vienna Basin (redrawn from Wessely, 1984; Decker, 1996) and locations of studied wells. Abbreviations: KoT1, Korneuburg T1; Le2, Leopoldau 2; AdUT1, Aderklaa UT1; RaaT2, Raasdorf T2; UnT1, Untersiebenbrunn T1; En1, Engelhartstetten 1.

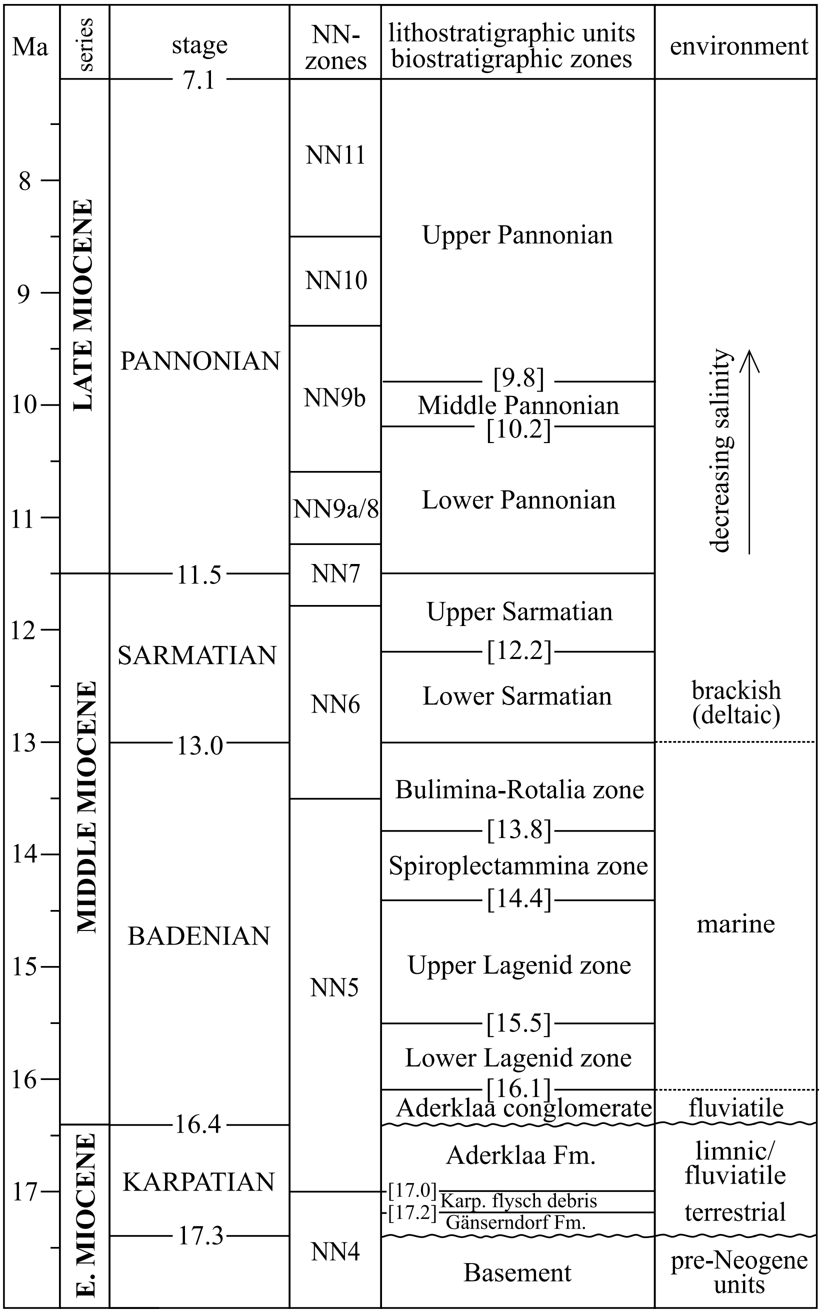

Fig. 3 Chronostratigraphic chart of Western ('Central') Paratethys Stages (Berggren *et al.*, 1995; Vakarcs *et al.*, 1998; Steininger and Wessely, 2000) and stratigraphic subdivisions used in this paper. Transgression on the pre-Neogene basement in this part of the Vienna Basin is assumed at 17.3 Ma. Correlation to nannofossil NN-zones according to Rögl (1996) and Steininger and Wessely (2000). Ages of Badenian zones and subdivisions of stages according to Rögl (1996) and Harzhauser (pers. comm.).

The subsidence history of this part of the Vienna Basin is characterized by high basement subsidence rates exceeding several 100 m Myr^{-1} during the Karpatian and the Badenian/Sarmatian (Fig. 5; see also Lankreijer *et al.*, 1995). Extremely high basement subsidence rates of more than 2000 m Myr^{-1} are recorded during the Karpatian, although these high rates may be the consequence in part of poor dating of these fluvial deposits. Subsidence rates decreased during the middle Miocene, although several intervals of increased subsidence, e.g. during the middle Badenian and the Sarmatian, have been observed (Fig. 5).

Backstripped dip-slip fault histories

Applying the method of fault backstripping to the investigated section results in a complex dip-slip history along individual faults. The positions and orientations of major faults along the transect are based on mapping, seismic sections and well data (Brix and Schulz, 1993; Hamilton *et al.*, 2000). Most of the faults strike nearly N–S and are regarded as predominantly normal faults within step-over areas of a sinistral strike-slip fault pattern. These faults generally have dip angles of 45–70° (Fig. 4), which makes the choice of well pairs for the fault backstripping method critical. In order to avoid major faults cutting through the well sections, wells were chosen that were relatively far from the faults. However AdUT1 and En1 are cut by faults in the Karpatian/Badenian (AdUT1) and the Pannonian (En1), which results in a higher uncertainty of calculated values. Lateral, non-fault-controlled thickness changes resulting from large horizontal distances of wells (e.g. UnT1–En1) are minor as a consequence of the basinal facies recorded in these wells (e.g. Seifert, 1996).

Apparent dip-slip rates were calculated by consistently subtracting basement subsidence values of the western well from the eastern well along the transect, regardless of whether the well is situated on the hanging wall or the footwall of a major synsedimentary normal fault. Thus, positive values indicate a relative downthrow on the eastern side of the fault, whilst negative values indicate a relative downthrow on the western side, irrespectively of the fault geometry (Fig. 6). High subsidence areas forming depocentres are thus defined by opposing peaks.

The most significant result for the basin history is indicated during the Karpatian, in which two phases of subsidence can be recognized (Fig. 6). During the early Karpatian (Gänserndorf Formation and Karpatian flysch debris, see Fig. 3) sedimentation was

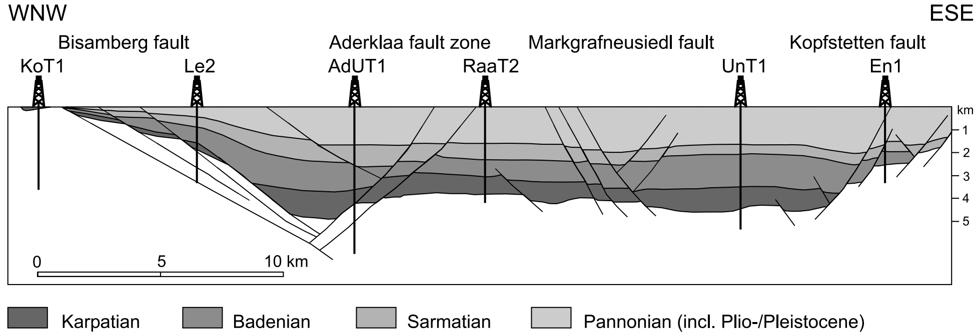

Fig. 4 WNW–ESE cross-section of the Vienna Basin along the investigated transect, based on the interpreted seismic section NV-8601/N-845D of Zych and Wessely (in Brix and Schulz, 1993). For abbreviations see Fig. 2.

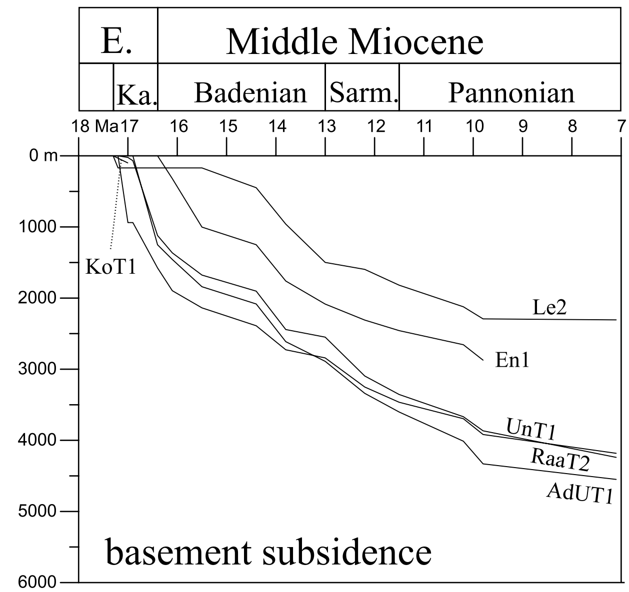

Fig. 5 Backstripped basement subsidence curves for the investigated wells. No sea-level corrections included. For location of wells see Fig. 2. E., Early Miocene, Ka., Karpatian; Sarm., Sarmatian.

confined largely to the central part of the basin, east of the Bisamberg fault and west of the Kopfstetten fault. Compared to today's fault geometries, reverse motions along the faults are indicated. The sense of fault movement changed during the late Karpatian (Aderklaa Formation), indicated by a change in the sign of the dip-slip rates. In general, deposits of this time interval show larger thicknesses on today's hanging wall blocks, which also correspond to later, Badenian depocentres, situated more to the basin margins than during the Karpatian. During the lowermost Badenian (Aderklaa conglomerate) a brief reversal of the sense of movement is indicated along several faults. Although the apparent dip-slip rates for this time interval are rather low, this time of apparent reverse faulting correlates nicely with the coeval uplift and erosion to the north of the investigated section (Weissenbäck, 1996).

The Bisamberg Fault, which bordered the basin to the west during Badenian–Sarmatian times, displays almost no dip-slip activity during the Karpatian to earliest Badenian. This marginal fault indicates a two-fold subsidence history, with a Badenian cycle followed by a Sarmatian–Pannonian cycle.

A second significant increase in fault activity is indicated by fault backstripping during the early Sarmatian. Although this peak may be partly the result of incorrect dating of this relatively short time interval (see different values for the beginning of the Sarmatian in Rögl, 1996 and Vakarcs *et al.*, 1998), some wells show also a reversal in the sense of faulting, which calls for a tectonic explanation. Apparent slip rates range up to 400 m Myr^{-1}.

During the Pannonian, slip rates along faults in the basin are rather insignificant. Subsidence seems to have been concentrated along basin margin faults. Especially for the late Pannonian, the method is rather inaccurate, because significant amounts of Middle to Upper Pannonian deposits were eroded during late Pannonian/Pliocene inversion and uplift within the basin (Decker, 1996).

Discussion and conclusions

Apparent dip-slip rates of synsedimentary normal fault movements can be calculated by backstripping basement subsidence from both the hanging wall and the footwall blocks. The results from applying this method along a transect from the central Vienna Basin corroborate and complement results from previous studies concerning the tectonic evolution and palaeostress history of the basin (Fodor, 1995; Lankreijer *et al.*, 1995; Decker, 1996). The method indicates that the major fault activities during the Karpatian were previously underestimated. The Karpatian tectonic history of the basin differs strongly from the Badenian–Sarmatian–Pannonian history (Decker, 1996). Significant thicknesses of Karpatian

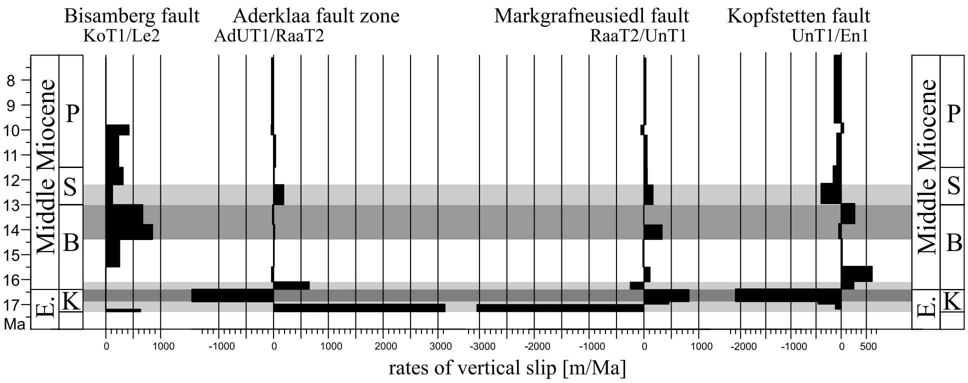

Fig. 6 Step plot of apparent relative dip-slip rates vs. stratigraphic time for four synsedimentary faults along a Vienna Basin transect from west to east. Interpreted times of main fault activities are marked in grey. E, early Miocene; K, Karpatian; B, Badenian; S, Sarmatian; P, Pannonian.

deposits are present mainly in the wells from the central part of the basin, predominantly in areas which later become hanging wall blocks of major normal faults, thus indicating an apparent 'reverse fault' motion during the early Karpatian in backstripped fault history plots (Fig. 6). According to published seismic data (Brix and Schulz, 1993), it is not clear whether middle Miocene faults were already active during the Karpatian. If so, the present data indicate reverse sense of faulting during the early Karpatian, which is not in accordance with later pull-apart basin geometries and, thus, supports the interpretation of the early basin history as a piggyback basin (e.g. Decker, 1996).

During the late Karpatian, fault senses in the central basin indicate a normal sense of dip-slip, marking the beginning of the development of the typical small-scale depocentre geometry of hanging wall blocks of the middle Miocene Vienna Basin. The amount of strike-slip displacement during this time cannot be assessed using the backstripping method. However, this type of faulting is regarded as marking the beginning of pull-apart basin formation, which has been inferred for the late Karpatian, based on changing basin geometries and facies patterns (e.g. Wessely, 1988; Sauer *et al.*, 1992; Hamilton *et al.*, 2000).

A short time of apparent reverse movement indicated along several faults during the lowermost Badenian (Fig. 6) marks the sedimentation of the Aderklaa conglomerate. This reversal seems to be a consequence of tectonism, as coarse deposits and uplift and erosion north of the investigated transect call for a tectonic explanation for this event. However, the ultimate reason for the reversal of fault movements during this time remains unclear and significant strike-slip motion and a local rearrangement of fault patterns around the Matzen structural high may be considered also.

In general, the following time intervals show fault histories that are in accordance with the general tectonic evolution of the basin, with ongoing extension and basin subsidence from the middle Badenian to the middle Pannonian. Apparent dip-slip rates are low compared to the Karpatian and show no significant peaks, with the exception of the early Sarmatian. Fault activity during this time cannot be correlated with any significant phase in the tectonic interpretations of the basin's history given by Fodor (1995) and Decker (1996), although tectonism is known to the south of the Vienna Basin, also, within the Styrian Basin (Krainer, 1984; Sachsenhofer *et al.*, 1997), and may be related to a regional extensional phase (Sachsenhofer *et al.*, 1997).

According to the present study, fault backstripping gives reasonable results not only in extensional basins (ten Veen and Kleinspehn, 2000) but can be also applied to pull-apart basins such as the Vienna Basin. Although there are several sources of uncertainties associated with the method, e.g. errors in backstripping calculations, the absence of significant erosion, or errors in palaeodepth estimates, the method indicates the sense of fault movements and gives estimates for the apparent vertical component of displacement. On a basinal scale, the method provides information about fault kinematics through time, and can be used to constrain time intervals of intensified faulting. Furthermore, step plots of apparent dip-slip rates, arranged in transects perpendicular to major faults, give a clear indication of shifting areas of subsidence, acting as depocentres, during the history of the basin.

Acknowledgments

Financial support was provided by the Austrian Science Foundation (FWF grant P13470-Geo: Stratigraphic Simulations in Neogene Basins). We thank the OMV AG, especially W. Hamilton and G. Arzmüller, for providing seismic and log data, and R. Sachsenhofer, K. Decker, R. Hinsch, H. Rice and an anonymous reviewer for discussions and reviews of earlier versions of this paper.

References

Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: *Geochronology, Time Scales and Global Stratigraphic Correlations* (W.A.Berggren *et al.*, ed.). *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **54**, 129–212.

Bond, G.C. and Kominz, M.A., 1984. Construction of tectonic subsidence curves for the Early Paleozoic miogeocline, southern Canadian Rocky

Mountains: implications for subsidence mechanisms, age of breakup and crustal thinning. *Bull. Geol. Soc. Am.*, **95**, 155–173.

Brix, F. and Schulz, O. (eds), 1993. *Erdöl und Erdgas in Österreich*, 2nd edn. Naturhistorisches Museum, Vienna.

Decker, K., 1996. Miocene tectonics at the Alpine-Carpathian junction and the evolution of the Vienna Basin. *Mitt. Ges. Geol. Bergb. Österr.*, **41**, 33–44.

Decker, K. and Peresson, H., 1996. Tertiary kinematics in the Alpine-Carpathian-Pannonian system: links between thrusting, transform faulting and crustal extension. In: *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe* (G. Wessely and W. Liebl, eds). *Spec. Publ. EAGE*, **5**, 69–77.

Fodor, L., 1995. From transpression to transtension: Oligocene-Miocene structural evolution of the Vienna basin and the East Alpine-Western Carpathian junction. *Tectonophysics*, **242**, 151–182.

Gallagher, K., 1989. An examination of some uncertainties associated with estimates of sedimentation rates and tectonic subsidence. *Basin Res.*, **2**, 97–114.

Hamilton, W., Wagner, L. and Wessely, G., 2000. Oil and gas in Austria. *Mitt. Österr. Geol. Ges.*, **92**, 235–262.

Krainer, B., 1984. Zur zeitlichen Einstufung, Stratigraphie und Tektonik im Nordteil des Gleisdorfer Sarmatsporns (Oststeiermark). *Mitt. Naturwiss. Ver.Steiermark*, **114**, 95–106.

Lankreijer, A., Kovác, M., Cloetingh, S., Pitonák, P., Hloska, M. and Biermann, C., 1995. Quantitative subsidence analysis and forward modelling of the Vienna and Danube Basins: thin-skinned versus thick-skinned extension. *Tectonophysics*, **252**, 433–451.

Ratschbacher, L., Frisch, W., Linzer, H.-G. and Merle, O., 1991. Lateral extrusion in the Eastern Alps, 2. Structural analysis. *Tectonics*, **10**, 257–271.

Roberts, A.M., Kusznir, N.J., Yielding, G. and Styles, P., 1998. 2D flexural backstripping of extensional basins: the need for a sideways glance. *Petrol. Geosci.*, **4**, 327–338.

Rögl, F., 1996. Stratigraphic correlation of the Paratethys Oligocene and Miocene. *Mitt. Ges. Geol. Bergb. Östexrr.*, **41**, 65–73.

Royden, L.H., 1985. The Vienna Basin: a thin-skinned pull-apart basin. In: *Strike-Slip Deformation, Basin Formation and Sedimentation* (K.T. Biddle and N. Christie-Blick, eds). *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **37**, 319–338.

Sachsenhofer, R.F., Lankreijer, A., Cloetingh, S. and Ebner, F., 1997. Subsidence analysis and quantitative basin modelling in the Styrian Basin (Pannonian Basin system, Austria). *Tectonophysics*, **272**, 175–196.

Sauer, R., Seifert, P. and Wessely, G., 1992. Guidebook to Excursions in the Vienna Basin and the adjacent Alpine-Carpathian Thrustbelt in Austria. *Mitt. Österr. Geol. Ges.*, **85**, 1–264.

Seifert, P., 1996. Sedimentary-tectonic development and Austrian hydrocarbon potential of the Vienna Basin. In: *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe* (G. Wessely and W. Liebl, eds). *Spec. Publ. EAGE*, **5**, 331–341.

Steckler, M.S. and Watts, A.B., 1978. Subsidence of the Atlantic-type continental margin off New York. *Earth Planet Sci. Lett.*, **41**, 1–13.

Steininger, F.F. and Wessely, G., 2000. From the Tethyan Ocean to the Paratethys Sea: Oligocene to Neogene stratigraphy, paleogeography and paleobiogeography of the circum-Mediterranean region and the Oligocene to Neogene basin evolution in Austria. *Mitt. Österr. Geol. Ges.*, **92**, 95–116.

ten Veen, J.H. and Kleinspehn, K.L., 2000. Quantifying the timing and sense of fault dip slip: New application of biostratigraphy and geohistory analysis. *Geology*, **28**, 471–474.

ten Veen, J.H. and Postma, G., 1999. Rollback controlled vertical movements of outer-arc basins of the Hellenic subduction zone (Crete, Greece). *Basin Res.*, **11**, 243–266.

Vakarcs, G., Hardenbol, J., Abreu, V.S., Vail, P., Várnai, P., Tari, G., 1998. Oligocene – middle Miocene depositional sequences of the Central Paratethys and their correlation with regional stages. In: *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins* (P.C. de Graciansky *et al.*, ed.). *Spec. Publs Soc. econ. Paleont. Miner., Tulsa*, **60**, 209–231.

Weissenbäck, M., 1996. Lower to Middle Miocene sedimentation model of the central Vienna Basin. In: *Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe* (G. Wessely and W. Liebl, eds). *Spec. Publ. EAGE*, **5**, 255–363.

Wessely, G., 1984. Der Aufschluß auf kalkalpine und subalpine Tiefenstrukturen im Untergrund des Wiener Beckens. *Erdöl-Erdgas Z.*, **100**, 285–292.

Wessely, G., 1988. Structure and development of the Vienna Basin in Austria. In: *The Pannonian Basin – a Study in Basin Evolution* (L.H. Royden and F. Horvath, eds). *Mem. Am. Ass. Petrol. Geol.*, **45**, 333–346.

Received 16 August 2001; revised version accepted 31 January 2002

