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Stratigraphic and kinematic modeling of thrust evolution, northern Apennines, Italy

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ABSTRACT

We present a quantitative kinematic model of thrust evolution that allows detailed interpretation of the stratigraphic record of foreland basins. Simulation of thrusting and syntectonic sedimentation shows that changes in the relative rate of thrusting and mode of thrust activation can be determined by their expression in basin stratigraphy. Truncations and offlaps reflect thrust activity, and hinterland migration of basin depocenters indicates out-of-sequence thrusting. Forward modeling of the stratigraphic record of the Pliocene-Quaternary Po basin, Italy, enables the quantitative reconstruction of the displacement sequence of the thrust sheets prograding into the basin during the Pliocene. Deep-seated middle Pliocene thrusting accompanied by out-of-sequence thrusting provides a consistent explanation for the observed stratigraphic record of the Po piggyback basins.

INTRODUCTION

Foreland basins result from downward flexure of the lithosphere by the overriding fold and thrust belt (Beaumont, 1981; Jordan, 1981; Zoetemeijer et al., 1990). During the orogeny, thrust nappes propagate into the basin and cut the foreland basin sediments. This pattern of progressive incorporation of the foreland sedimentary wedge into the fold and thrust belt is a characteristic feature of foreland basins (Allen et al., 1986).

The proximal localities to which these features are restricted have not been well investigated in structural studies, because the large-scale effects of crustal loading are overprinted by the complexity of local faulting and associated sedimentation processes (Miall, 1978; Wiltchko and Dorr, 1983). However, studies of the internal stratigraphic geometry of piggyback basins that have been transported entirely by deforming thrust sheets (Ori and Friend, 1984) have demonstrated in detail the local control of thrust dynamics (Burbank and Reynolds, 1988; Puigdefabregas et al., 1992). Thrust deformation, with simultaneous syntectonic sedimentation, results in angular unconformities in the stratigraphic record of the growth structure (Medwedeff, 1989; Suppe et al., 1992). The specific shape of the angular unconformities in proximal basins mirrors the tectonic evolution of adjacent fold and thrust belts (Beer et al., 1990), allowing the reconstruction of thrust evolution.

Herein we present a quantitative model linking the stratigraphic record to thrust activation. The forward kinematic simulation of thrust deformation and syntectonic sedimentation shows that the shape and nature of the unconformities reflect sedimentation rate, thrust velocity, and the timing of thrust activation. We incorporate into the model the flexural response to loading, representing a thickening of the sedimentary beds toward the hinterland. We apply the model to the northern Apennines, Italy, to test structural hypotheses of thrust activity, using seismic-stratigraphic data from the Po plain (Pieri, 1989). The modeling shows that truncations are indications of new thrust activation, and that piggyback basin depocenter migration reflects deep-seated thrust activity.

FORWARD KINEMATIC MODEL

Structural modeling of fault-related fold systems is a useful tool for generating geological cross sections and testing the coherency of the structural interpretations. Geometric analyses including fault projections to depth (De Paor, 1986) and predictions of detachment levels (Kligfield et al., 1986) are essentially a result of extrapolations based on simple geometric rules. Assumptions of mass conservation lead to geometric constraints for balancing cross sections (Bally et al., 1986; Moretti and Larrère, 1989) and kinematic modeling (Mount et al., 1990; Contreras and Suter, 1990). The purpose of these models is to approximate the observed data with as much detail as possible. The same is true for forward modeling (Medwedeff, 1989; Endignoux and Mugnier, 1990). Palinspastically restored sections can be modeled in a forward sense, producing a deformed wedge that fits the present structural configuration.

Zoetemeijer and Sassi (1992) introduced a new forward approach that facilitates geometric analyses and provides new constraints on thrust deformation evolution by incorporating sedimentation and erosion processes into a computerized fault-bend fold model. This method enables the calculation of the internal geometry of the syntectonic basin. Deformation in foreland fold and thrust belts is characterized by parallel folding and bedding-plane slip. Therefore, the model is based on the principles of flexural slip (Ramsey, 1967). We realize that different structural models for folding exist (Suppe et al., 1992). In our approach, we have adopted

Figure 1. Simulation of growth structure illustrating effect of changes in thrust velocity on internal structures of sedimentary infill. A: Increasing thrust velocity; B: decreasing thrust velocity. For both cases total displacement and sedimentation rate are constant. Diagrams at right show relative thrust velocity as function of time.

the fault-bend fold method (Suppe, 1983) to describe the internal thrust deformation. We extend the method to couple multiple thrusting events contemporaneous with sedimentation and erosion processes, allowing the quantitative simulation of the thrust-system development, from restored section to present configuration and its consequences in the stratigraphy of the basin. Figure 1A shows the deformation of two half-syncline basins, in which time lines record the evolution of thrusting. Upon an increase of displacement rate, synorogenic deposits show angular unconformities and erosional surfaces (Fig. 1A). When displacement slows, sediments are onlapping the crest of the thrust tip (Fig. 1B).

A major uncertainty in the analysis of thrust-system evolution deals with the timing of thrust activation. Forward modeling facilitates the process of testing different scenarios of thrust activation. Figure 2A shows the deformation of a double ramp-thrust structure. A piggyback basin develops between two growing structures. At the foreland side the basin is

flanked by the thrust tip, moving along the upper fault-ramp structure cutting the basin. The basin is flanked at the inner side by the fault-bend fold stepping up from the deeper detachment level to the intermediate level. During the next step in evolution (Fig. 2B) displacement is transferred to an identical double ramp thrust located farther toward the foreland. As the piggyback basin develops, migration of the depocenter toward the foreland occurs in the new structural situation (Fig. 2C). These modeling predictions are consistent with observations by Roure et al. (1991) on the relation of piggyback basin depocenter migration to deep-seated thrusting in the Southern Apenninic accretionary wedge.

The model results displayed in Figure 2, D-F, are obtained by using the same fault configuration. However, in Figure 2, A-C, the thrusts are activated in a piggyback sense, whereas in D-F thrust activation is out of sequence. The difference in the predicted geometries of the sedimentary infill for the two cases is noteworthy. In out-of-sequence deformation,

Figure 2. Simulation of two double-ramp thrust structures with simulation of stratigraphic horizons recording thrust evolution. Figures from top to bottom give sedimentary structures for three different stages in evolution. A: Displacement along fault 1; B: thrust deformation transferred to fault 2; C: displacement along fault 2. Left: Modeling results for thrusting in piggyback sequence. Note that basin depocenter migration is toward foreland, marked by dot. Right: Modeling results for out-of-sequence thrusting. Note that basin migration for out-of-sequence model is toward hinterland, marked by dots.

Figure 3. Migrated seismic reflection profile through Ferrara-Romagna thrust arc, northern Apennines, Italy. Inset shows location of profile A-B. Mes = Mesozoic, Mio = Miocene, EPI = early Pliocene, MPI = middle Pliocene, LPI = late Pliocene, Qua = Quaternary. Pliocene-Quaternary sediments show angular unconformities formed by tectonic movement (after Pieri, 1989). Arrow points to truncation indicating new thrust activation. Box shows significant wedging of horizons, supporting deep-seated thrust activation.

migration of the basin depocenter is toward the hinterland rather than toward the foreland, as in the case of fault activation in the piggyback sense.

APPLICATION TO THE NORTHERN APENNINES

The synthetic examples presented in the previous section demonstrate that the stratigraphic record of proximal basins contains valuable information on thrust evolution. Forward kinematic and stratigraphic modeling is useful for interpreting this information. To illustrate this aspect we apply the model to the northern Apennines.

The Po Plain, imaged by numerous seismic reflection profiles (Cassano et al., 1986; Pieri, 1989) has been extensively investigated (Ricci Lucchi, 1986; Castellarin and Vai, 1986). The basin is filled by Tertiary and Quaternary clastic rocks and was deformed from late Miocene time to the present; the deformation is associated with the subduction of the northern part of the Adriatic plate underneath the Apennines (Royden, 1988). In the southern part of the Po Plain, subsurface structures correspond to the most external thrusts of the northern Apennines. A seismic line through the Ferrara-Romagna thrust arc (Fig. 3) shows various detachment levels, one at the base of the Mesozoic carbonate sequence and others in the Tertiary clastic section. Furthermore, this profile gives an excellent display of stratigraphic onlaps and truncations (see Fig. 3). These features result from syntectonic deposition of erosional products of the emerging Apenninic front and, in the early stages, from the Alps. The restored structural configuration at the time of first convergence is obtained by unfolding a depth-converted seismic section with a computer cross-section balancing program (Moretti and Larrère, 1989). The reflector of the top Miocene sequence was used as the upper reference level in the balancing. The initial situation and indicators for the displacement along the faults form the input parameters for the balanced forward modeling (Fig. 4A).

We have tested different scenarios for the sequence and timing of thrust activation. The calculated basin geometry is compared to the structural interpretation; Figure 4, B–D, shows the results that obtain the best fit. Shortening began along the upper detachment level with a displacement rate of 4.5 mm/yr, which is probably associated with deeper thrusting situated more internally (south-southwest) from the profile. At the end of the early Pliocene, the main shortening was taken over by the more external ramp along the same detachment level. This produces the truncation in the most internally situated half-syncline basin (Fig. 4B), which can be compared to the truncation observed at that position in Figure 3.

In the middle Pliocene section, seismic-stratigraphic horizons close to the second thrust tip show significant wedging of the horizons (Fig. 3). Truncations alternate abruptly with onlaps, and erosional surfaces are visible. These critical observations suggest that the stratigraphic record is locally disturbed, possibly by the activation of the underlying fault. The process of hanging-wall deformation right under the second thrust tip causes these irregularities (Fig. 4C). As a consequence of the activation of the deep structure at this stage, out-of-sequence thrusting will occur, because the more internally located intermediate detachment level is not yet activated (Fig. 4C).

Figure 4D shows the predicted structural configuration at the end of the Pliocene. At that time the total displacement along the faults was 27 km, 7 km of which occurred along the first activated fault, 12 km along the second activated fault, and 4 km along both the deep and intermediate detachment levels; the displacement passed on into the basin along the upper detachment level and most external thrust ramp of the profile (Fig. 4D). The average rate of shortening was 6.7 mm/yr; single-thrust velocity reached a maximum of 4.5 mm/yr. Although we can determine the timing of individual thrust activation, deformation took place simultaneously along different fault surfaces.

In the kinematic and stratigraphic simulation of thrust-system development described above, we ignored the flexural response to loading. However, the observed overall thickening of the sedimentary beds toward the thrust belt demonstrates that the flexural response is important. Fur-

thermore, in the most internally located half-syncline basin (Fig. 4D), the model predicts important erosional surfaces that cannot be correlated with the seismic reflectors along the middle to late Pliocene interval (Fig. 3). This discrepancy can be explained by the effect of a nonzero flexural rigidity, which is consistent with previous studies of large-scale lithospheric flexure of the Apennine foreland-basin system (Royden, 1988). The results of modeling that incorporates flexural response, thrusting, and syntectonic sedimentation are shown in Figure 5. For an effective elastic thickness of 20 km, the average subsidence rate is 1.9 mm/yr at the most internal location of the profile. Figure 5 shows the structural situation in the late Pliocene (cf. Fig. 4D). The tilting effect of the flexural subsidence is superimposed on the effects of thrust dynamics. Angular unconformities can still be recognized as a result of local control of thrust activity, whereas the overall thickening of the sedimentary beds toward the hinterland re-

Figure 4. Reconstruction of foreland deformation in northern Apennines during Pliocene. A: Balanced restoration. B: Configuration after activation of second fault along shallow detachment level, at lower part of lower Pliocene. Note truncation structure formed in innermost syncline basin. C: Thrust tip of deep structure deforms overlying basin stratigraphy. D: Intermediate level is activated out of sequence. Area between X and X' is delimited by seismic line given in Figure 3. Shortening is represented by convergence of point X relative to X'. In A, position of X is 10.5 km from left-hand margin of figure toward south-southwest.

Figure 5. Combined results of kinematic and flexural modeling of foreland basin and associated thrust-belt development. Tilting effect of flexural subsidence is superimposed on effects of thrust dynamics. Flexural response is for elastic thickness of 20 km, consistent with studies of dynamic response of Apennine foreland system to subduction of Adriatic plate (Royden, 1988). Arrow points to truncation indicating new thrust activation. Box shows significant wedging of horizons, supporting deep-seated thrust activation.

sults from the flexural response to the subduction of the Adriatic lithosphere underneath the Apennines.

CONCLUSIONS

Modeling of the seismic-stratigraphic record in foreland basins allows quantification of the thrust-system evolution. Kinematic reconstruction of a palinsparastically restored section to its present configuration with incorporation of syntectonic sedimentation provides an effective tool for detailed analyses of the stratigraphic record. The modeling shows that changes in thrust velocity and sedimentation rate can lead to different patterns in the stratigraphic record. Computer simulation of the basin stratigraphy allows determination of the timing of thrust activation. A multiple fault system, activated in the piggyback sense, results in basin depocenter migration toward the foreland, whereas out-of-sequence activation results in depocenter migration toward the hinterland.

Local thrust dynamics control the internal stratigraphy of proximal basins, dominating the large-scale effects of flexural loading. However, as demonstrated by the modeling of the Po Plain, the stratigraphic record allows estimation of the flexural response of the lithosphere. The control of thrust dynamics on the Po basin stratigraphy is reflected by angular unconformities; truncations are likely to be indicators of new thrust activity, and local disturbances in the stratigraphy reflect deep-seated thrusting. The model supports a scenario in which the stratigraphic record of the Po piggyback basins is explained by the activation of the deep-seated thrust, in an out-of-sequence sense, during middle Pliocene time.

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