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Seismic restorations: a new technique for sequence boundary identification and correlations

SCHUMAN WU[1], PAUL WEIMER[2] AND GARETH TAYLOR[3]

[1]CogniSeis Development, Inc., 4775 Walnut Street, Suite 2A
Boulder, Colorado 80301

[2]Department of Geological Sciences
Energy and Mineral Applied Research Center
University of Colorado, Boulder, Colorado 80309

[3]CogniSeis Development, Inc., Zhen Yi Building, 05–02,
35 Jalan Pemimpin, Singapore 2057

Abstract: A new technique of using seismic restoration to correlate and identify sequence boundaries is discussed and applied to a post-stack depth-migrated seismic section from offshore of Kushiro, Hokkaido Island, Japan. The seismic section displays shallow marine Cretaceous and younger units. Three major unconformities are recognizable, the two older unconformities are deformed by a reverse fault and folded. Detailed stratigraphic correlation is problematic and sequence boundaries are obscure in the deformed state. Different interpretations and correlations are tested through sequential restorations. One of the viable interpretations is used for tracing all seismic reflections. The interpreted seismic section with traced reflections was restored to different stages in the depositional history by a flexural-slip algorithm, in which both bed-length and unit area were conserved. Sequence boundaries were picked from the restored-state sections rather than on the faulted and folded seismic section. The depositional history, sequence boundaries, and structural evolution are clearly revealed by this process.

Eight depositional sequences and three major unconformities (A, B, and C) have been recognized and correlated in the seismic section from offshore Kushiro, Hokkaido, Japan. There are four sequences between the oldest unconformity (A) and the second unconformity (B). Onlap direction was from northwest to southeast. A reverse fault developed after the formation of the second unconformity. The onlap direction in the two piggyback basins associating the reverse faulting was from southeast to northwest. In the post-faulting three sequences, the onlap direction reversed again, was again from northwest to southeast. The sequence above the youngest unconformity (C) shows parallel horizontal reflections.

INTRODUCTION

Recognizing and correlating stratigraphic units and sequence boundaries in faulted and folded regions can be difficult tasks. Stratigraphic correlations across faults are often equivocal, and fault offsets and deformation can obscure reflection relationships critical for interpreting seismic facies and systems tracts. By sequentially retrodeforming a seismic section with traced reflections, cryptic stratigraphic relationships and correlations can be revealed, along with a more unequivocal record of the depositional and deformational sequence. A post-stack depth-migrated seismic section is used to illustrate the procedure. The seismic section displays shallow marine Cretaceous and younger units from offshore of Kushiro, Hokkaido Island, Japan (Fig. 1). Three major unconformities are recognizable based on stratal terminations (Fig. 2a), the two older unconformities are deformed by a reverse fault and folding. Detailed stratigraphic correlation across the fault is problematic and sequence boundaries are obscure in the deformed state. Different versions of interpretation of the seismic data were made and then iteratively modified and validated using GEOSEC, a geologic cross section interpretation and validation program. An algorithm for seismic restoration was presented by Nunns (1991). In this study we used traced seismic reflections, instead of real seismic traces, for structural restorations. Seismic reflections were traced on one of the viable interpretation and retrodeformed to several different stages in the depositional history. Sequence boundaries were picked from the restored-state sections rather than on the faulted and folded seismic section. The depositional history, sequence boundaries, and structural evolution are more clearly revealed by this process.

SOLUTION RANGE AND INTERPRETATION VALIDATION

Fault interpretations and horizon correlations

The original seismic data, provided by DIA Consultants Co., Ltd., were reprocessed and depth migrated (Fig. 2a) by CogniSeis Development, Inc. (Marsh *et al.*, 1991). The seismic data display very distinctive folds and one fault. However, there is no unique fault interpretation without more data constraints. For the seismic data only, there will be a range of solutions that could fit the seismic data and can be validated through a series of restorations to some key horizons using a flexural-slip deformation. The fault can be interpreted either as a southeast dipping thrust fault with a detachment approximately at the depth of the seismic section (Fig. 2b fault #1), a southeast dipping reverse fault with a detachment much deeper than the depth of the seismic section (Fig. 2b fault #2), or a northwest dipping high-angle *normal fault* (Fig. 2b fault #3).

Seismic reflection terminations reveal a prominent unconformity (labeled "C" in Fig. 2b) near the sea floor which truncated the folded strata and is overlain by concordant horizontal reflections. Within the folded and faulted units, there is an upper onlap surface (labeled "B" in Fig. 2b) on each side of the fault. The onlap terminations of seismic reflections, wedge-shape sediments body, and

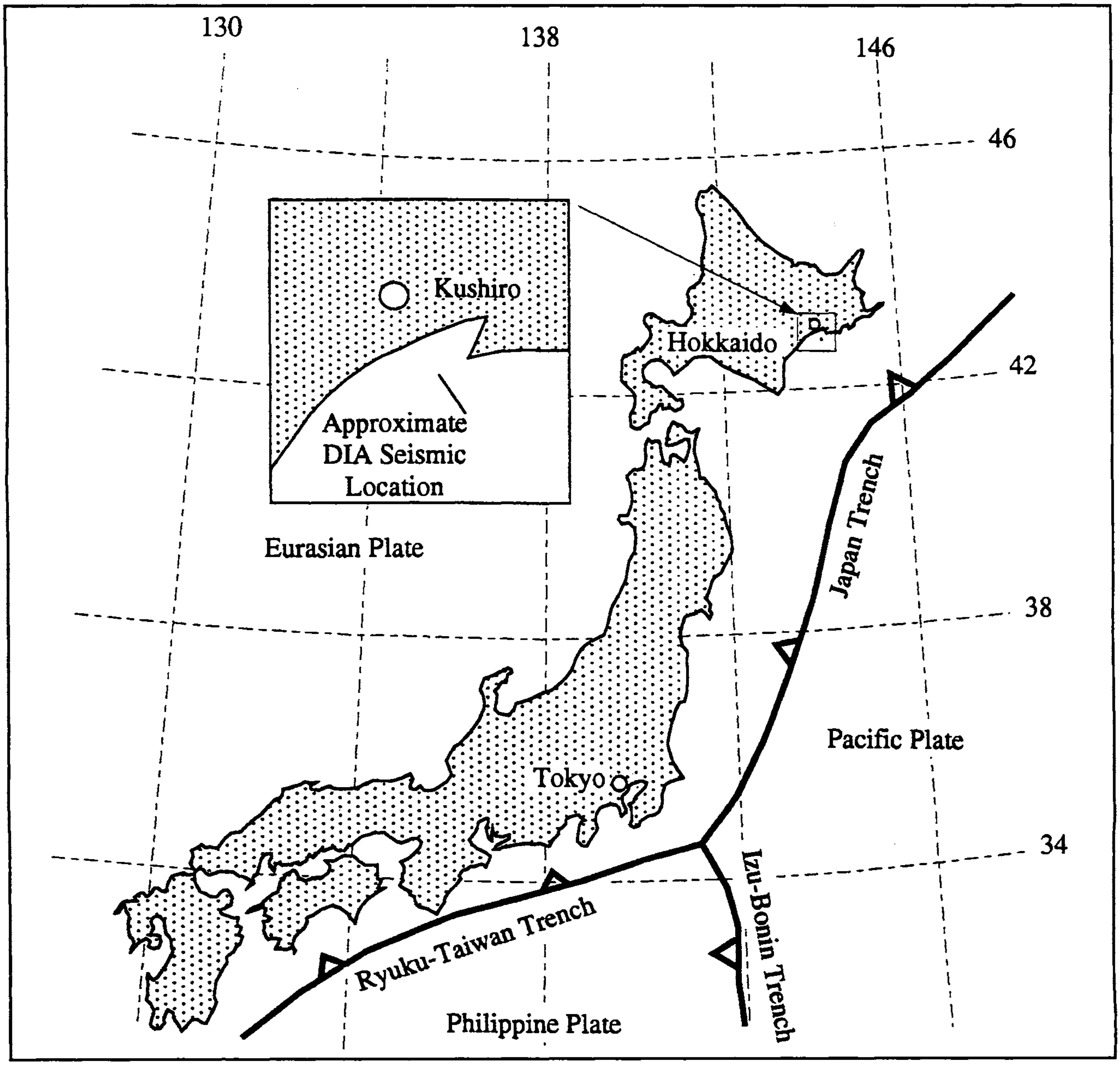

Figure 1. Location map of seismic data and tectonic elements around Japan.

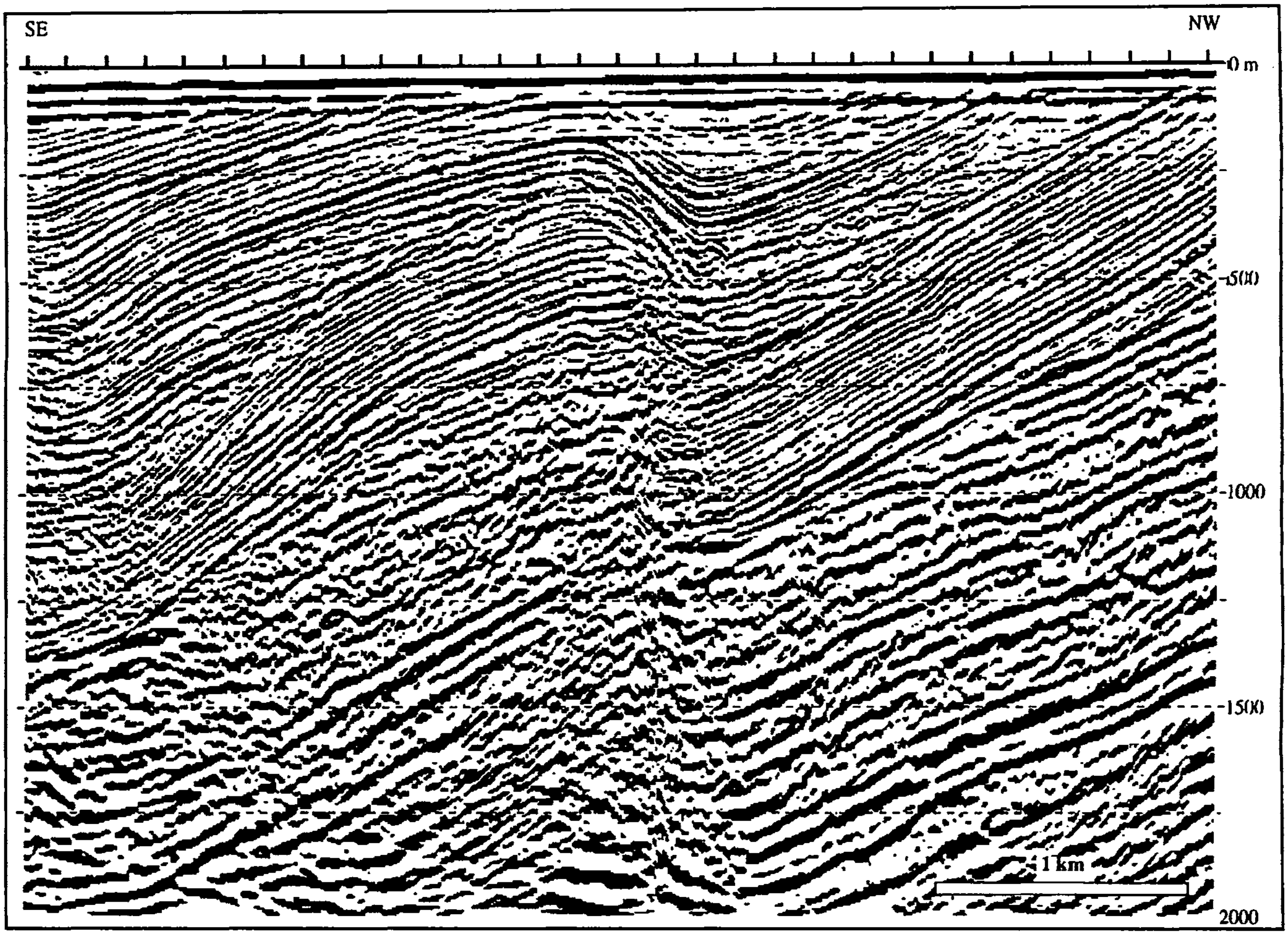

Figure 2(a). Post-stack depth migrated seismic data, reprocessed by CogniSeis Development. Data courtesy of DIA Consultants Co., Ltd., Tokyo, Japan. See Figure 1 for approximate location.

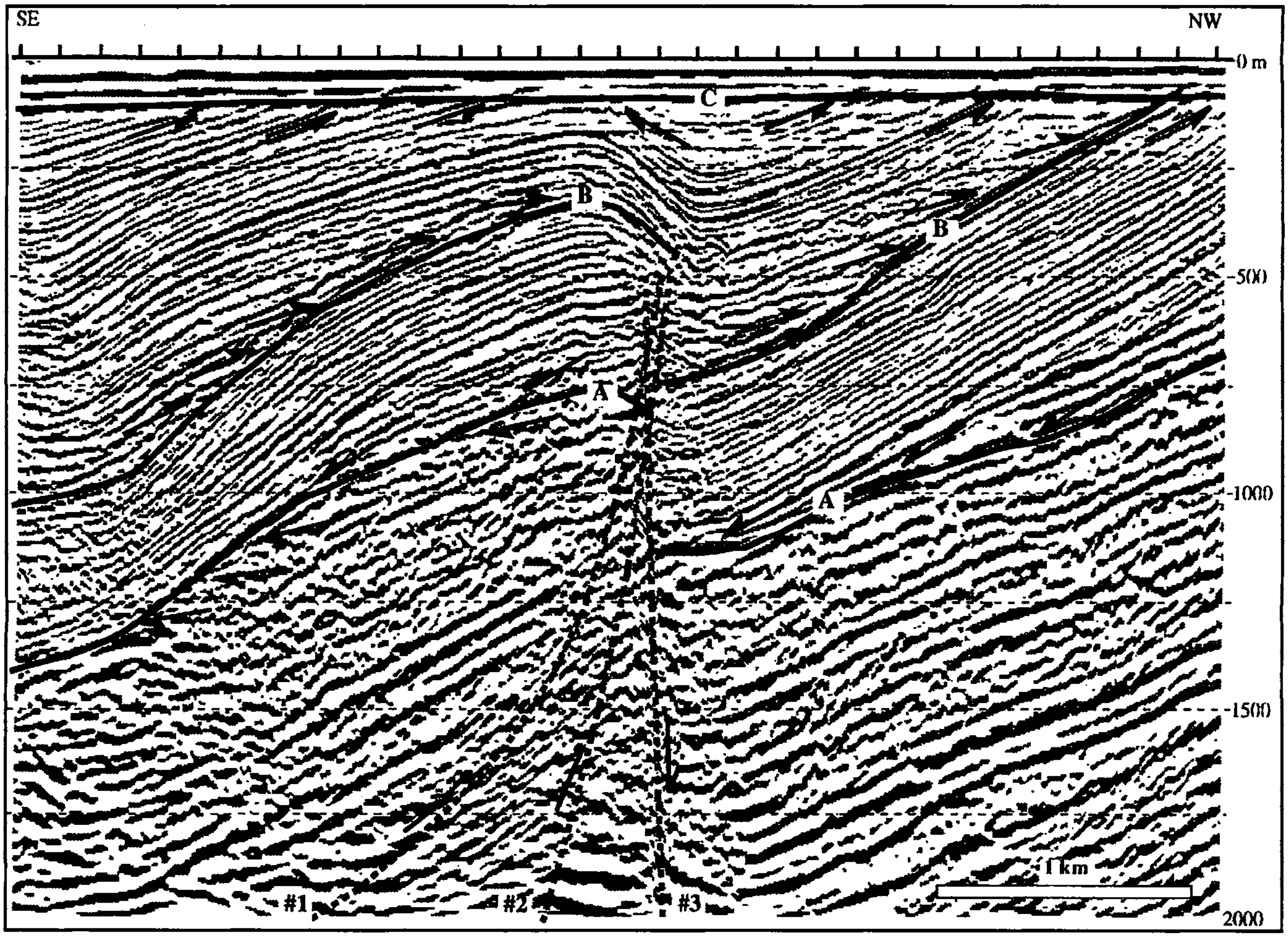

Figure 2(b). A primary horizon correlation and three different fault interpretations. Faults from left to right are thrust fault (#1), reverse fault (#2), and normal fault (#3).

concordant with seismic reflections below are very similar for the onlap surface on both sides of the fault. There is a lower prominent sequence boundary (labeled "A" in Fig. 2b) on each side of the fault. On both sides of the fault, seismic reflections onlap above the unconformity A, and truncations of seismic reflections occur below the unconformity A (Fig. 2b). Seismic reflections have higher frequency above A and lower frequency below A. This correlation seems to best match the characteristics of the sequence boundaries and seismic reflections across the fault. In the following discussion, this correlation scheme will be used in all three different fault interpretations. However, this correlation implies that the two piggyback basins formed simultaneously. It is possible that one piggyback basin is either older or younger than its counterpart across the fault. These alternative correlations will be discussed in the reverse fault interpretation.

Reverse fault interpretation

The reverse fault interpretation (Fig. 2c) was modified from Marsh *et al.* (1992) to produce a viable interpretation that can be sequentially restored to some key horizons (Fig. 3). As indicated in the two restored-state sections (Fig. 3), prior to the formation of unconformity B none of the pre-existing units had been folded or faulted. Strata onlap on to unconformity A from northwest to southeast. Reverse faulting started shortly after the formation of the unconformity B and produced two wedge-shaped piggyback basins. For the fault-related sequences in these piggyback basins, the onlap direction is from southeast to northwest. The folded sequences were truncated below the unconformity C; the overlying sequence is not deformed.

In the above interpretation, stratal onlap on to unconformity B in the two piggyback basins was assumed to have been formed simultaneously. Alternatively, the same onlap surface B in the footwall can be interpreted either younger or older than the onlap surface in the hanging wall. Consequently, the alternative interpretations imply that the faulting sequence (if indeed there is a series faults and the available seismic data only one fault) is forward stepping or backward stepping. To verify the faulting sequence, we built a simple model for backward stepping and forward stepping, respectively. For the backward stepping model (Fig. 4), a fault northwest of the seismic profile developed first and a piggyback basin with onlap

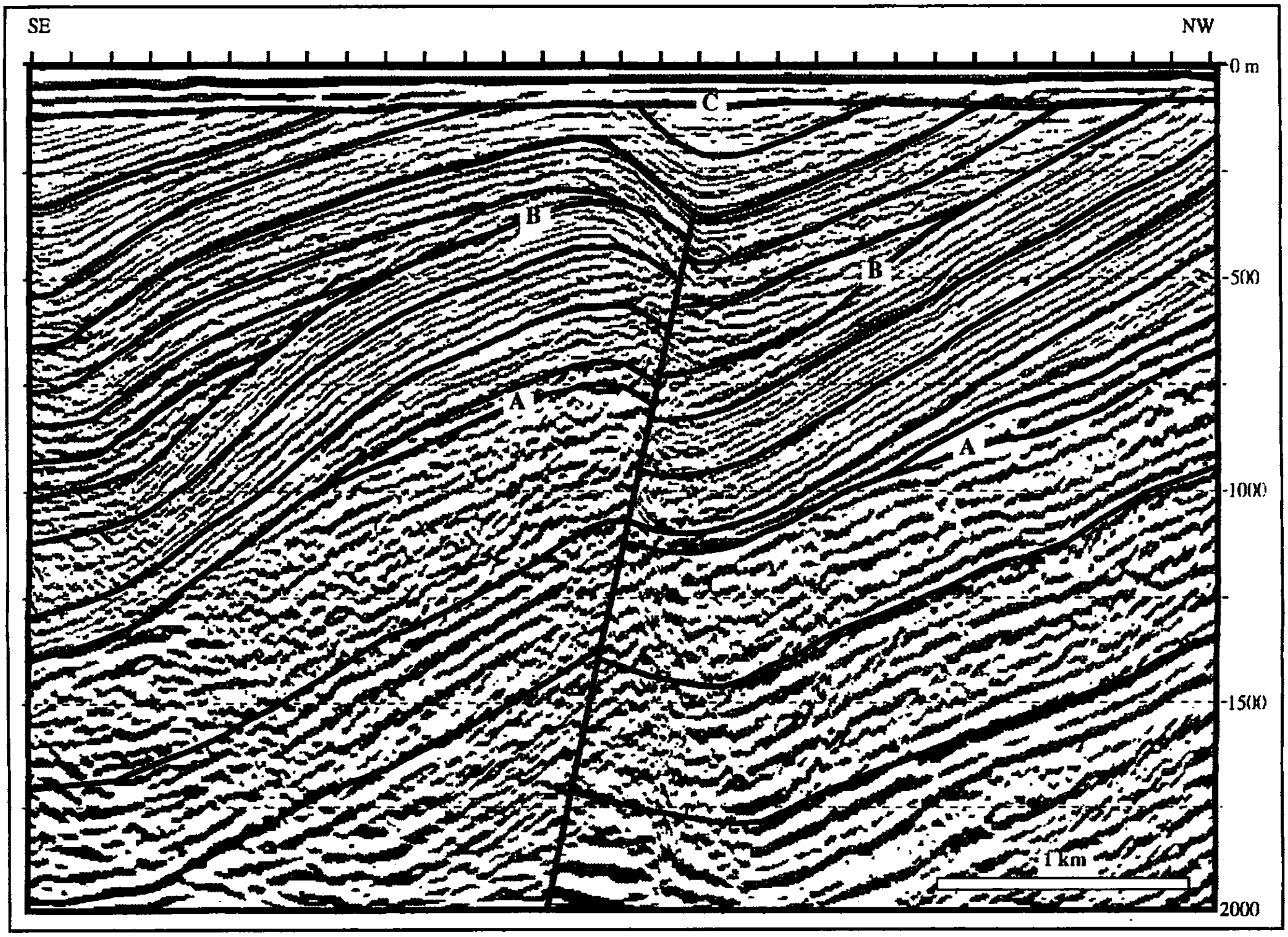

Figure 2(c). Reverse fault interpretation with correlation horizons.

sediments formed in response (Fig. 4a, b). The fault on the seismic profile then formed in the back of the earlier fault with a similar piggyback basin (Fig. 4c). All units were then folded or tilted and an erosional truncation surface (labeled "C" in Fig. 4d) formed.

This back-stepping fault model leads to an alternative correlation of sequence boundaries across the fault (Fig. 5a). The two onlap surfaces labeled "B" may be, in fact, of different ages, with the onlap surface in the hanging wall younger than that in the footwall. We now call the onlap surface in the hanging wall B2, and is coeval to a younger surface in the footwall. Then, the onlap surface in the footwall B1 is coeval to an older surface in the hanging wall. There are corresponding changes for the correlation of the former A boundaries as well (Fig. 5a). Although this interpretation is viable as

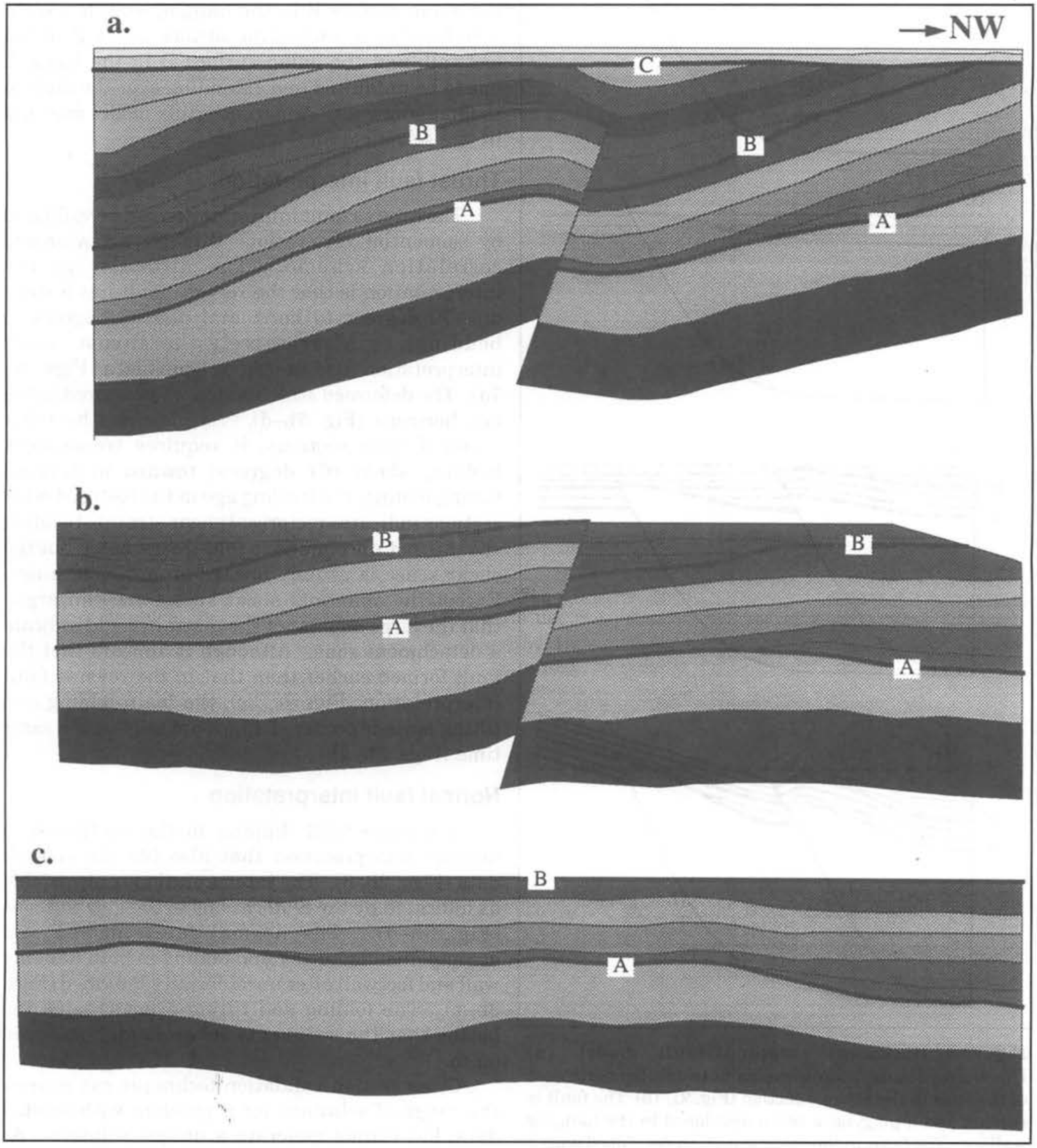

Figure 3. Restorations of the reverse fault interpretation. (a) The reverse interpretation. (b) The restoration to the tip horizon. (c) The restoration to the unconformity B.

indicated by the sequential restorations (Fig. 5b–d), the correlation has at least three problems. The interpretation correlates the low-frequency reflections in the hanging wall to the high-frequency reflections in the footwall between A1 and A2; the fault has very small displacement and produced a fold of high amplitude; and the interpretation requires a backward stepping of fault development.

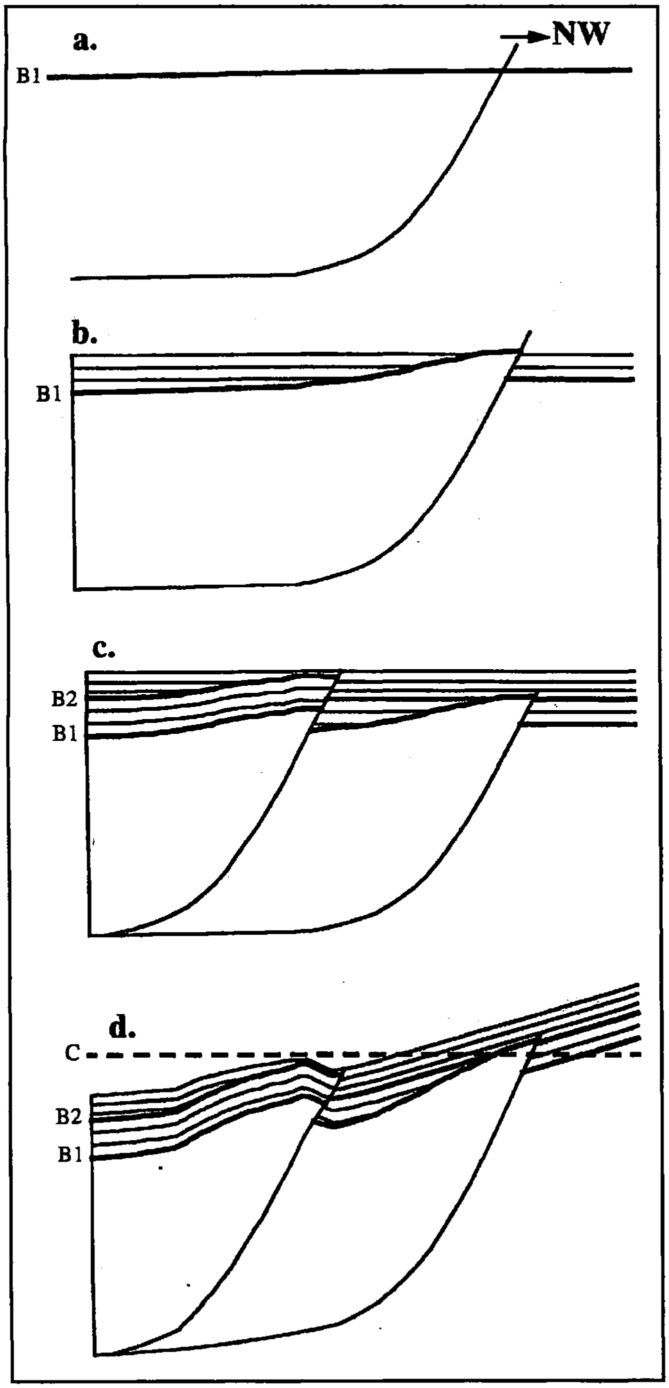

Figure 4. Backward stepping fault model. (a) Undeformed state, a fault was about to develop northwest of the fault in the seismic section (Fig. 2). (b) The fault is moving and a piggyback basin developed in the hanging wall. (c) The fault in the seismic section developed with a similar piggyback basin. (d) Further folding and tilting followed by an erosion period (unconformity C).

For a forward-stepping fault model, the fault in the seismic section developed first with a piggyback basin (Fig. 6a, b). Next, a fault northwest of the seismic section formed with a piggyback basin extending over the previous fault (Fig. 6c). All units were then folded or tilted and the erosional truncation surface C formed (Fig. 6d). When applying this model to the seismic data (Fig. 2b), the onlap surface B in the hanging-wall has to be correlated to a concordant surface below B in the footwall, and the onlap surface B in the footwall has to be unfaulted and extending over the fault to the hanging wall. Apparently this model does not fit the seismic data.

Thrust fault interpretation

The reverse fault interpretation can be validated by sequential restorations through a reasonable correlation scheme. The difficulty in the interpretation is that the reverse fault has a steep dip (70 degrees to horizontal and 55 degrees to bedding). Alternatively, a thrust fault interpretation also fits the seismic data (Figs. 2b, 7a). The deformed state section was restored to the key horizons (Fig. 7b–d). As indicated by these restored-state sections, it requires tremendous bedding shear (67 degrees) toward hinterland during folding (the trailing age in the restored state sections indicates reciprocal shear strain). Bedding shear is not uncommon in fold-thrust belts, but the shear sense is usually toward an anticline hinge. Except the abnormal shear sense, one can argue that the large amount of shear strain could indicate a detachment zone. Although it appears that the fault formed earlier than that in the reverse fault interpretation (Figs 7c, 3c), the main folding and tilting episode occurred approximately at the same time (Figs. 3b, 7b).

Normal fault interpretation

A normal fault dipping to the northwest is another interpretation that also fits the seismic data (Figs. 2b, 8). The interpretation is also viable as indicated by the restorations to the key horizons (Fig. 8b–d). The normal fault formed and accompanied by tilting and folding in both hanging wall and footwall after unconformity B formed (Figs. 8b, c). The folding and tilting event created the basins that the sediments subsequently onlapped on to.

Cross section validation technique can narrow the range of solutions for a problem with limited data, but cannot generate a unique solution. As indicated above, either a reverse fault, a thrust fault, or a normal fault can be a viable interpretation

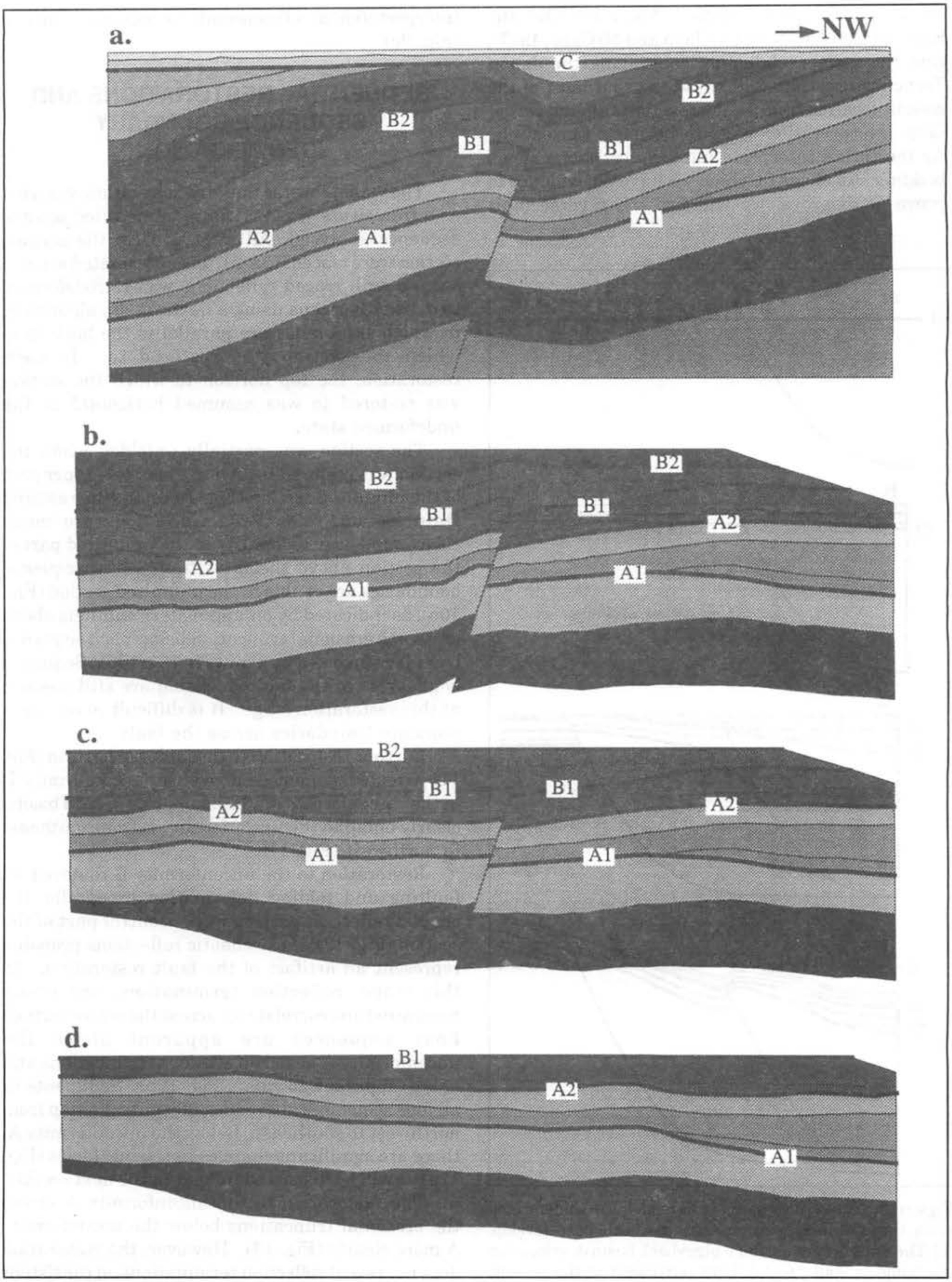

Figure 5. Alternative horizon correlation based on the backward stepping fault model and its restorations. (a) An alternative horizon correlation based on the backward stepping fault model. The two main unconformities in the hanging wall (A2 and B2) are now younger than the two main unconformities in the footwall (A1 and B1). (b) The restoration to the fault-tip horizon. (c) Restoration to B2. (d) The restoration to B1.

based on the seismic data. When consider the regional tectonic setting (Celaya and McCabe, 1987), that the active subduction zone along the Japan Trench is less than 200 km to the southeast of the seismic location (Fig. 1), the reverse fault and thrust fault interpretation seem to be more reasonable. As the thrust interpretation requires tremendous bedding slip shear to which we have no evidence to prove or disprove, we will use the reverse fault interpretation as a framework for sequence analysis (Fig. 2c).

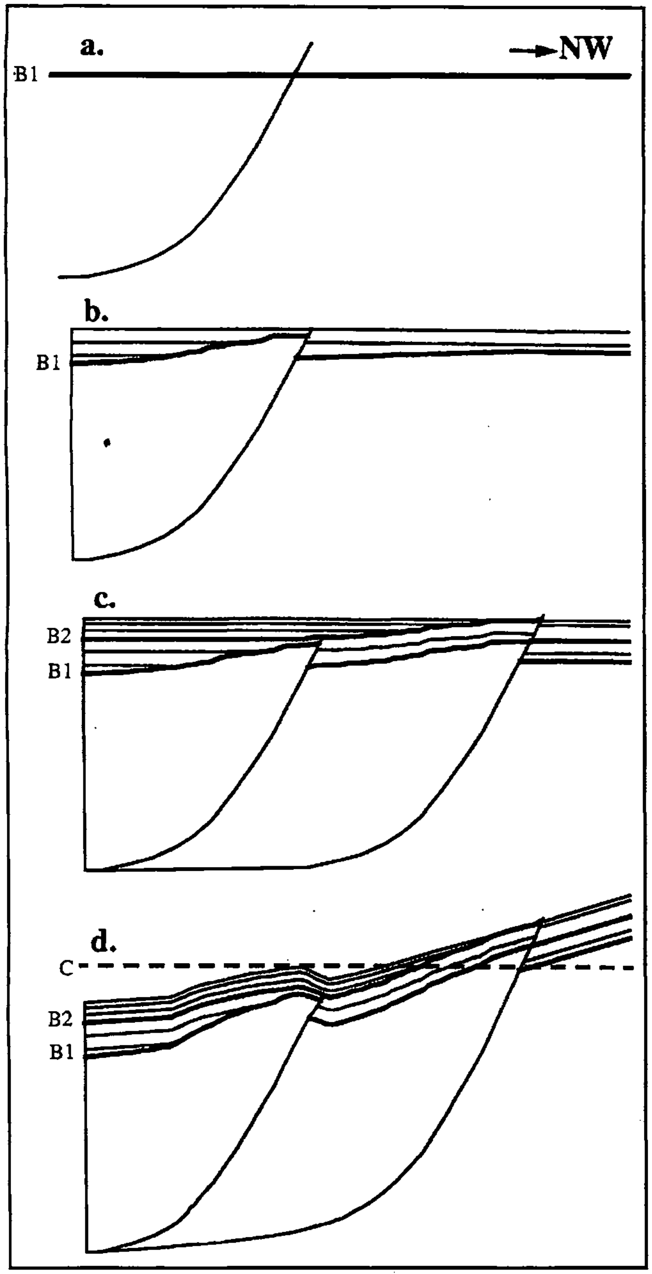

Figure 6. Forward stepping fault model. (a) Undeformed state, the fault in the seismic section was about to develop. (b) The fault is moving and a piggyback basin developed in the hanging wall. (c) A fault northwest of the seismic section developed with a similar piggyback basin. (d) Further folding and tilting followed by a erosion period (unconformity C).

SEQUENTIAL RESTORATIONS AND SEQUENCE BOUNDARY IDENTIFICATION

The viable reverse fault interpretation was used as a framework (Fig. 2c) for more detailed seismic sequence analysis. All reflections in the seismic section were traced (Fig. 9). The interpreted seismic section with traced reflections was retrodeformed to marker horizons using a flexural-slip algorithm, in which slip planes are parallel to the horizon to which the section was restored to. In each restoration, the top horizon to which the section was restored to was assumed horizontal in the undeformed state.

The section was partially unfolded when the section was restored to an horizon in the upper part of the unfaulted section (Fig. 10a). In this restored state section, reflection terminations are much clearer and easy to identify in the unfaulted part of the section above the fault tip. Three sequence boundaries are visible in the unfaulted section (Fig. 10b), as indicated by onlapping terminations above and some erosional truncation below each sequence boundary (marked by arrows in Fig. 10b). Sequence boundaries in the faulted section are still obscure at this restoration stage. It is difficult to correlate sequence boundaries across the fault.

Further restoration to the fault-tip horizon (Fig. 11) revealed sequences above the unconformity B in their undeformed state. Sediments in both basins clearly onlap to the unconformity B from southeast to northwest (Fig. 11b).

Restoration to the unconformity B removed all faulting and folding deformation except for the chaotic reflection pattern in the central part of the section (Fig. 12); these chaotic reflections probably represent an artifact of the fault restoration. At this stage, reflection terminations are easily recognized and correlatable across the entire section. Four sequences are apparent above the unconformity A based on erosional truncations and onlap (apparent downlap, Fig. 12b). Sediments in all four sequences above unconformity A onlap from northwest to southeast. Below the unconformity A, there are significant changes in seismic facies (Fig. 12a) as will be discussed further in the next section.

The restoration to the unconformity A shows the erosional truncations below the unconformity A more clearly (Fig. 13). However, the restoration does not reveal reflection terminations on consistent boundaries for the section below A. Although it is still possible that sequences boundaries exist in

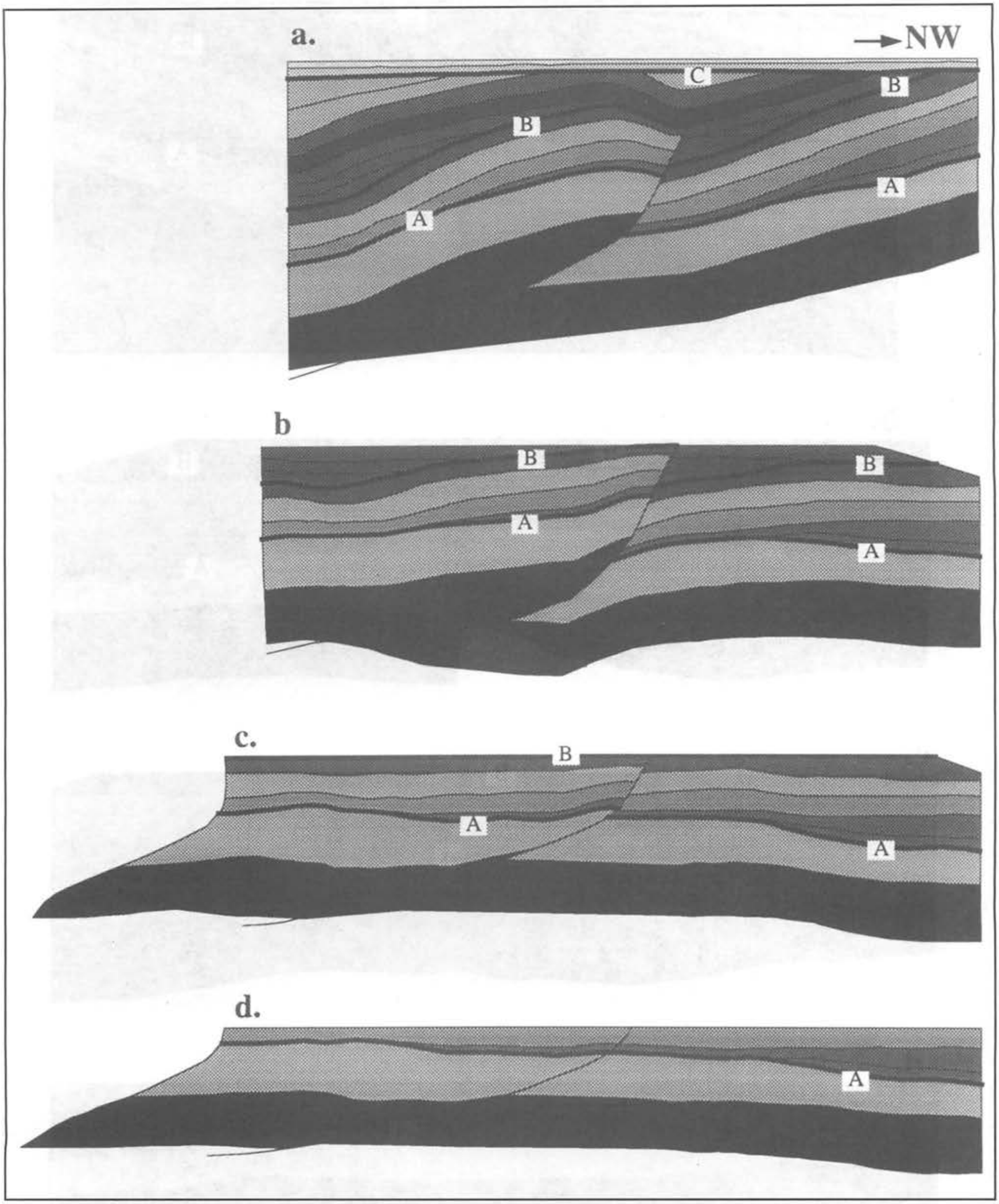

Figure 7. A thrust fault interpretation and its restorations. (a) A thrust fault interpretation with a detachment approximately at the depth of the section. (b) The restoration to the fault-tip horizon. (c) The restoration to unconformity B revealed large bedding shear at the trailing edge. (d) The restoration to a horizon between Unconformities A and B removed faulting and folding effect.

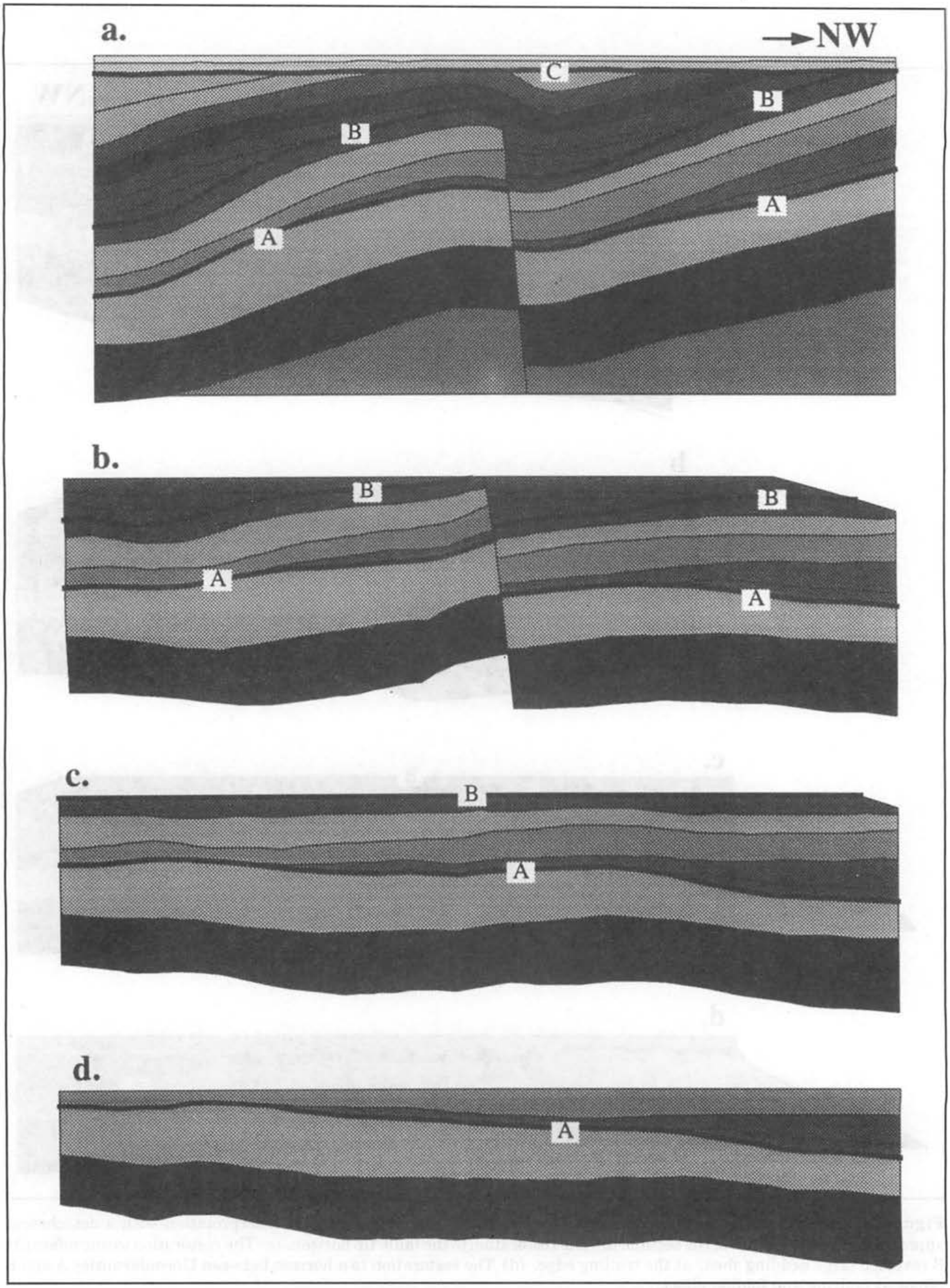

Figure 8. A normal fault interpretation and its restorations. (a) A high-angle normal fault interpretation. (b) The restoration to the fault-tip horizon. (c) The restoration to unconformity B removed faulting and folding effect. (d) The restoration to a horizon between Unconformities A and B.

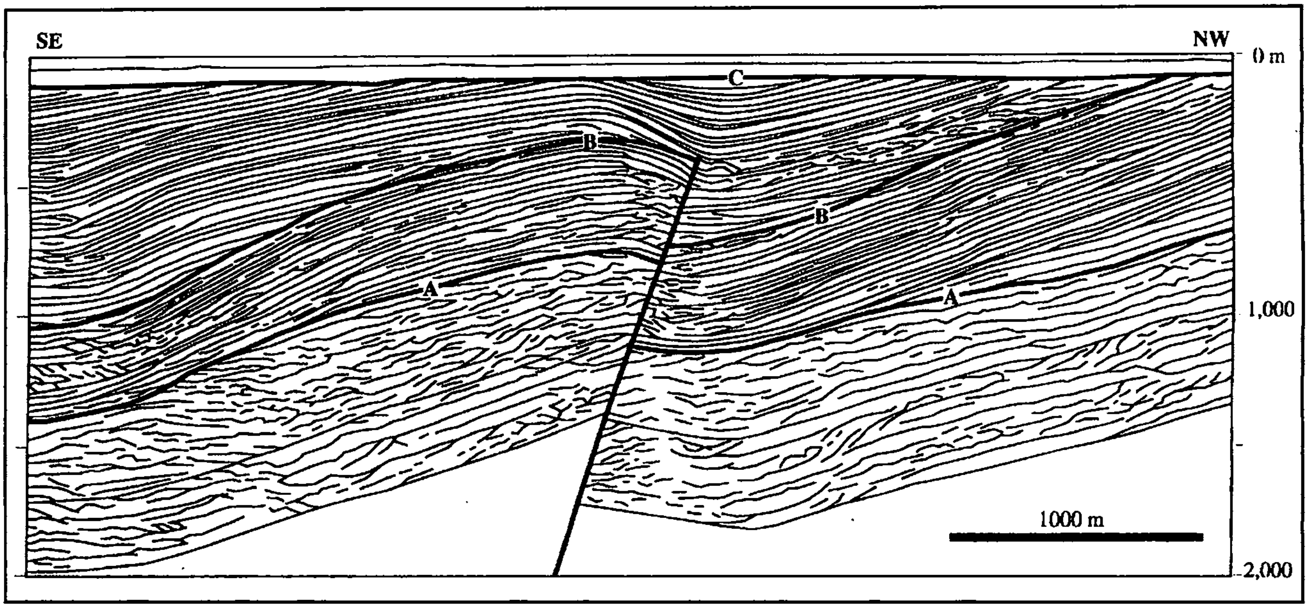

Figure 9. Traced seismic reflections using the reversed fault interpretation. The traced seismic reflections will be retrodeformed to revealed termination boundaries when the section is restored to the correlation horizons sequentially.

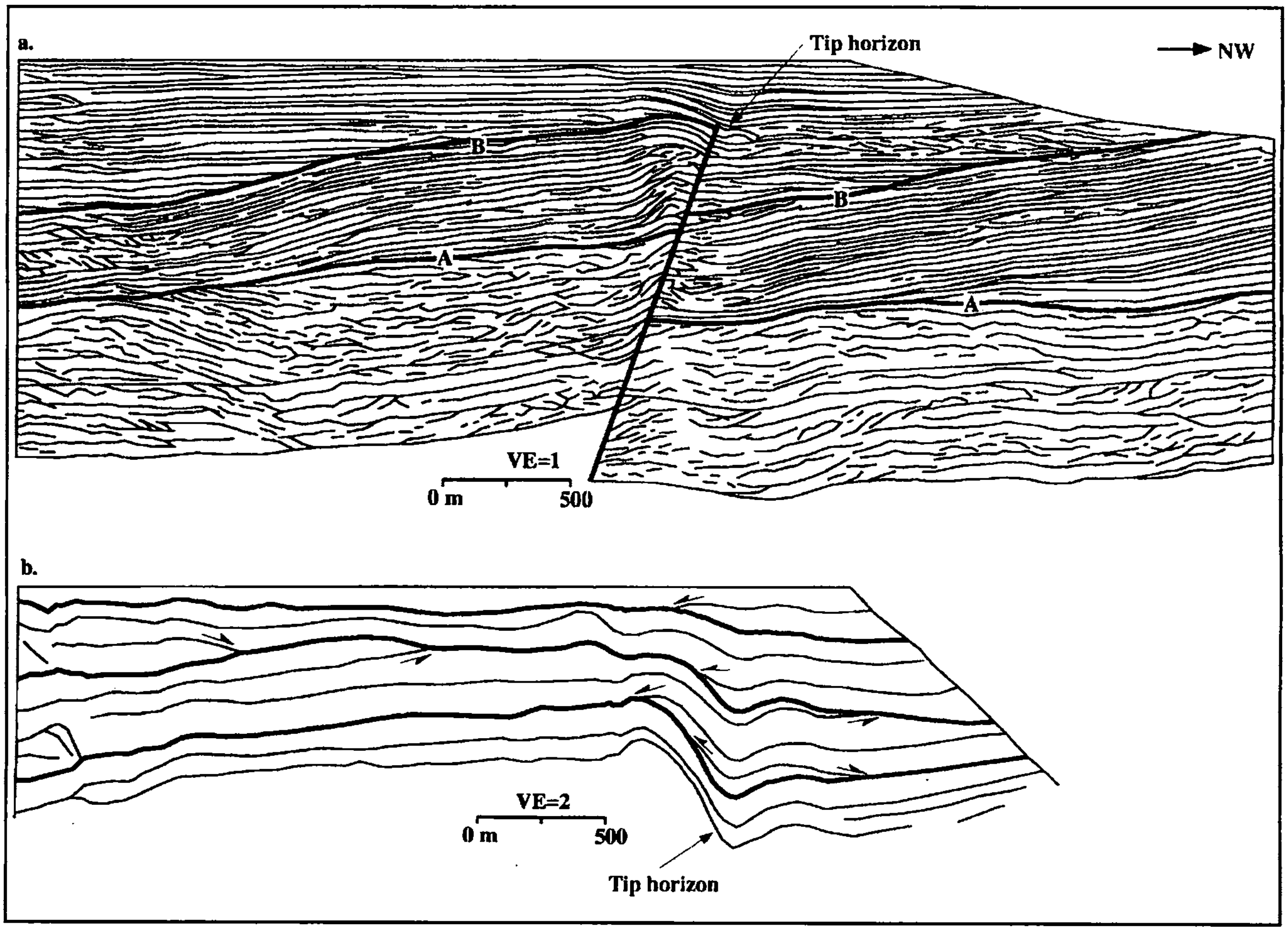

Figure 10. Restoration to a horizon in the upper part of the unfaulted section removed some folding effect and revealed reflection terminations. (a) Shows the whole restored section. (b) Shows unfaulted part of the restored section with VE = 2. Onlaps, downlaps, and truncations are marked by arrows; sequence boundaries are indicated by thick lines.

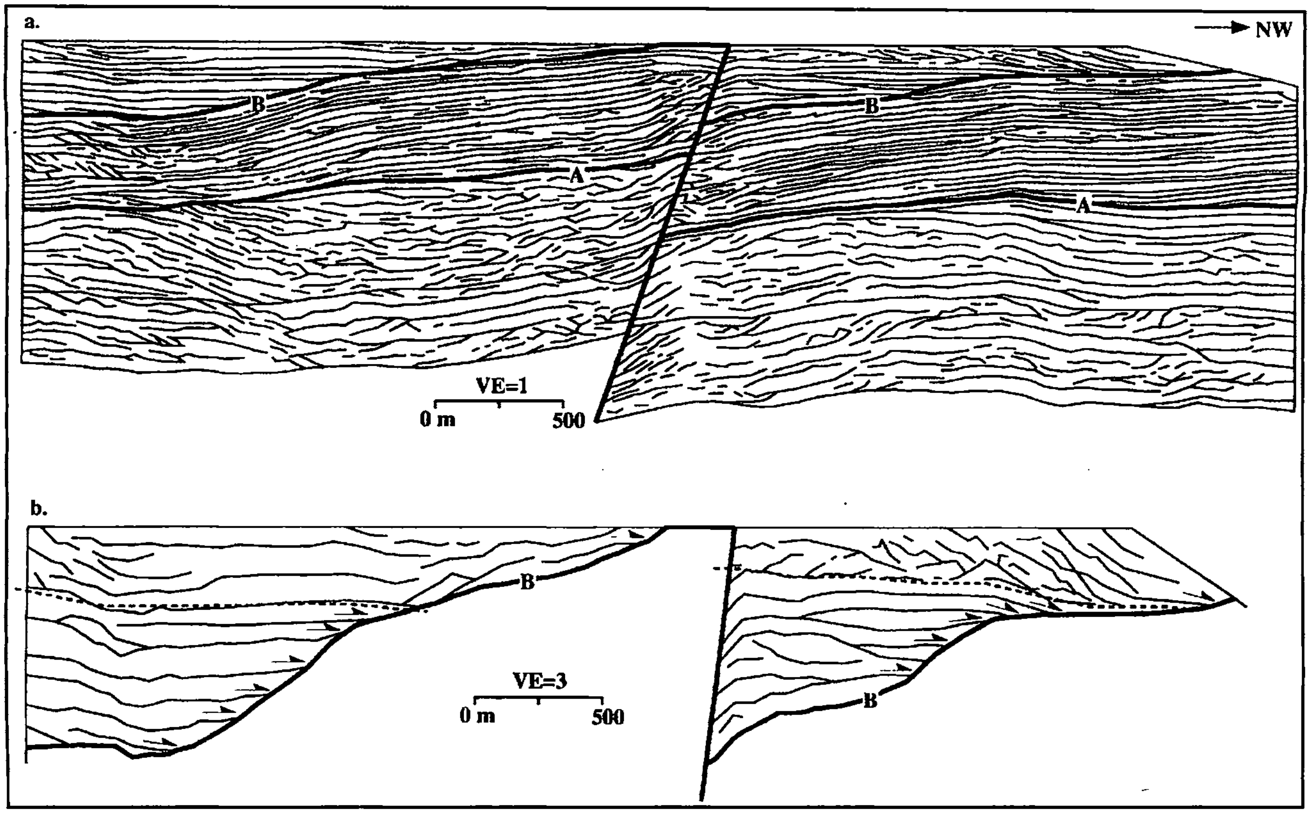

Figure 11. Restoration to the fault-tip horizon revealed sequences in the piggyback basins. (a) Shows the whole restored section. (b) Shows sequences in the piggyback basins with VE = 3. The sequence boundaries are marked by thick lines; dashed lines show possible downlap surfaces.

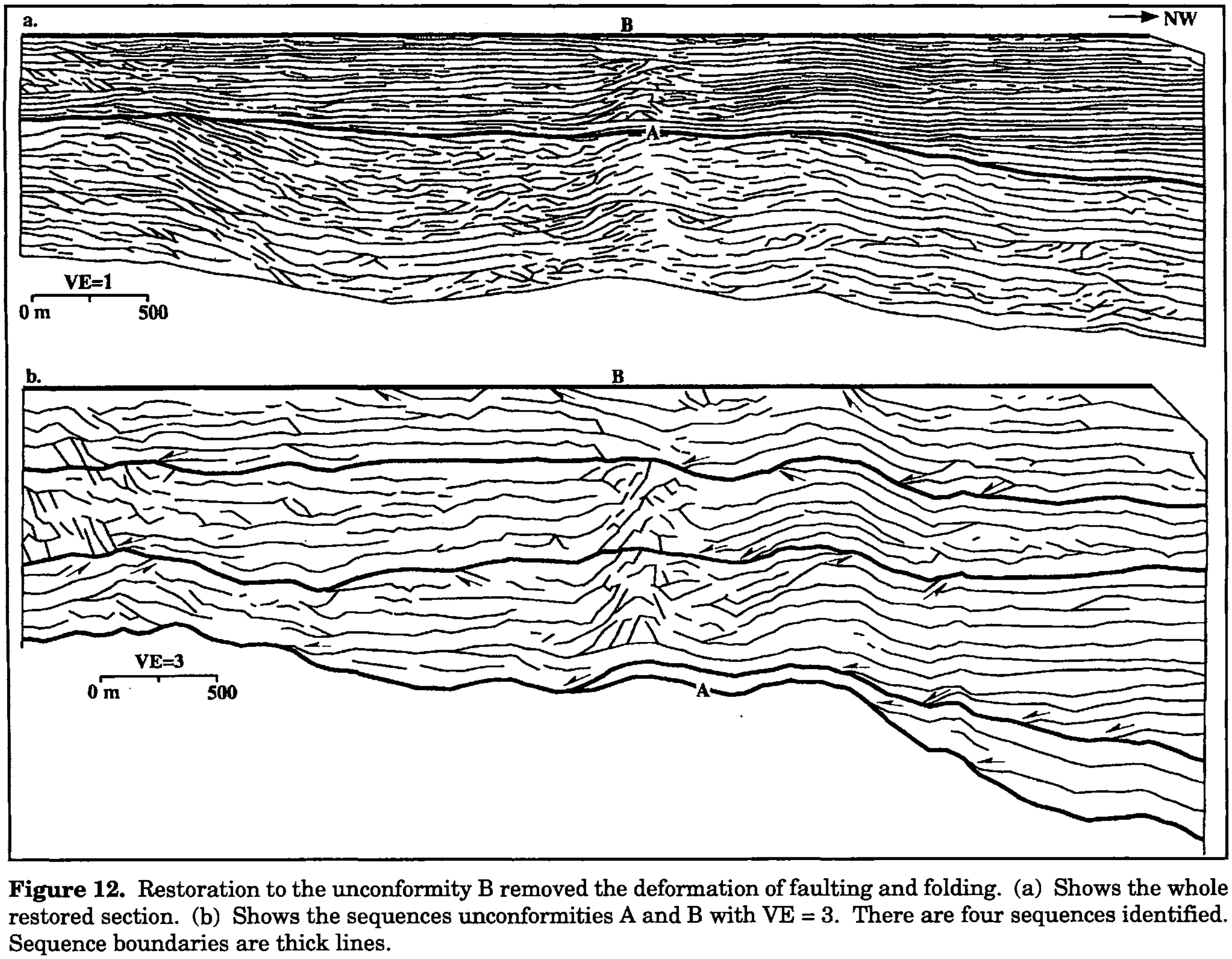

Figure 12. Restoration to the unconformity B removed the deformation of faulting and folding. (a) Shows the whole restored section. (b) Shows the sequences unconformities A and B with VE = 3. There are four sequences identified. Sequence boundaries are thick lines.

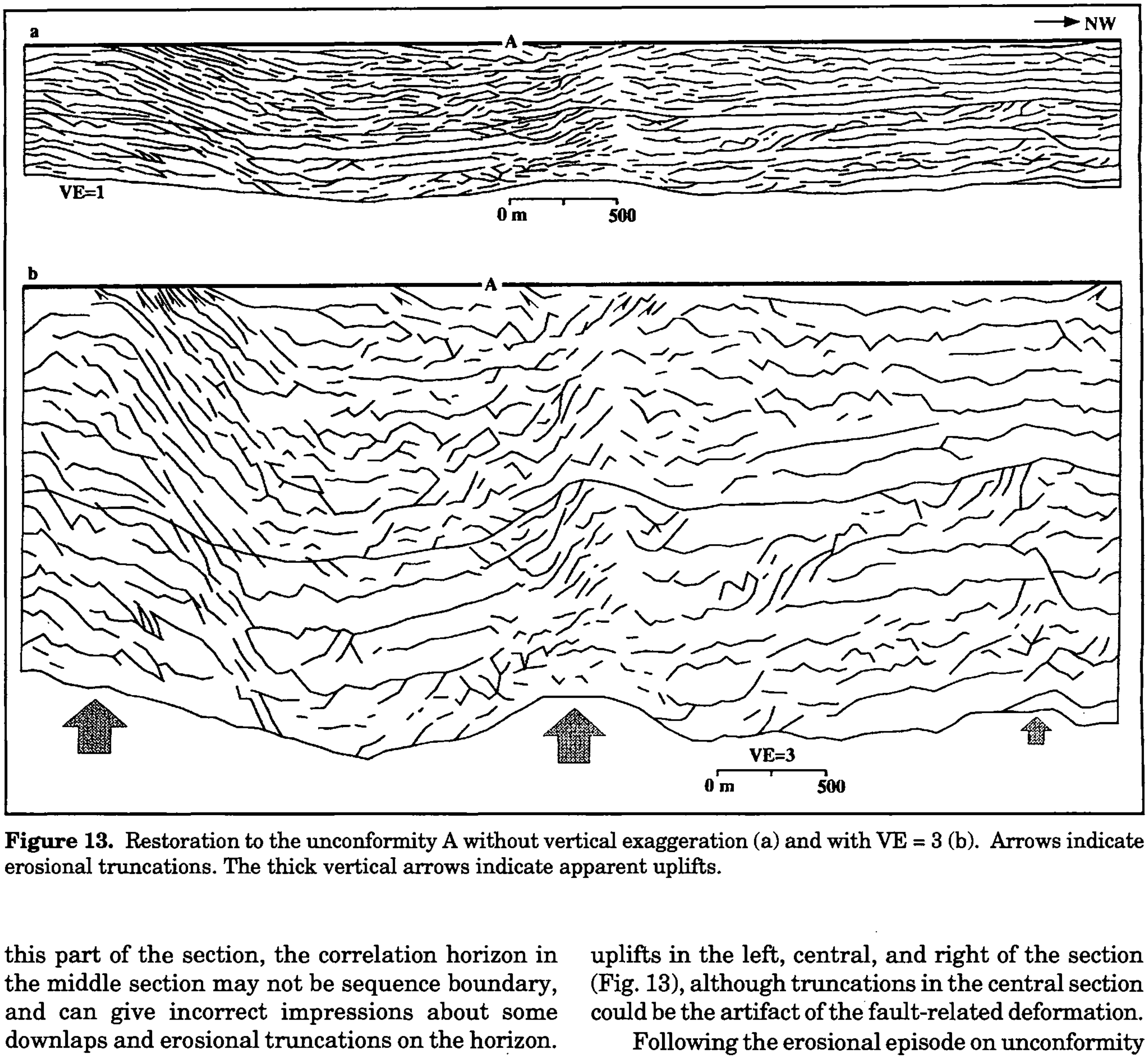

Figure 13. Restoration to the unconformity A without vertical exaggeration (a) and with VE = 3 (b). Arrows indicate erosional truncations. The thick vertical arrows indicate apparent uplifts.

this part of the section, the correlation horizon in the middle section may not be sequence boundary, and can give incorrect impressions about some downlaps and erosional truncations on the horizon.

SEQUENCE DEVELOPMENT AND STRUCTURAL EVOLUTION

According to Fujiwara (1993, personal communication), the Kushiro sedimentary basin contains up to 6,000 meters of seaward dipping Cretaceous to Neogene open marine shales and sandstones. A well drilled to 1,200 m depth on the anticline imaged by the DIA seismic line penetrated Cretaceous siltstones at TD. Based on the well data, it is most likely that all sequences above the unconformity A are Paleogene to Neogene in age. Cretaceous sequences exist in the lower part of the section.

The sequences below unconformity have an overall hummocky to subparallel reflection configuration with poor continuity, moderate amplitude, and lower frequencies. Erosional truncations are seen above the three apparent uplifts in the left, central, and right of the section (Fig. 13), although truncations in the central section could be the artifact of the fault-related deformation.

Following the erosional episode on unconformity A, the section was tilted to the northwest, as indicated by significant truncation at the southeast part of the section and onlap of sediments on the unconformity A from the northwest (Fig. 12). Three sequences development between unconformities A and B. The overall seismic facies are significantly different from those below A. Seismic reflections are parallel to subparallel with good continuity and higher frequencies. Although the northwest-ward tilting could have been caused by regional tectonics, there was no apparent evidence of local structural development. Changes in sea level may have led the sequence development between unconformities A and B.

The next major event was development of the reverse fault which controlled subsequent sedimentation and sequence patterns (Fig. 11). A piggyback basin formed on each side of the fault with sediments onlap to the northwest, a reversal of onlapping direction from that of older sequences between A and B. Also, older units below unconformity B which previously dipped to the northwest now began to dip to the southeast. The faulting and associated deformation clearly had a profound effect on the local sedimentation patterns and sequence development in the piggyback basins. Although the seismic section only shows one fault, the wedge geometry of piggyback basin and tilted beds in the footwall suggest other fault(s) exists to the northwest.

Although fault displacement gradually ceased after the formation and deposition of the two piggyback basins (Fig. 10), the restoration (Fig. 10b) clearly shows the influence on the ongoing folding process to the development of the sequences between the fault-tip horizon and the unconformity C. Another reversal in onlap direction occurred in the three sequences between fault-tip horizon and C, it was from northwest to southeast. During this period, the development of sequences was perhaps effected equally by folding and sea level change.

The folded strata were truncated by the unconformity C and the sequence above is undeformed.

SUMMARY

Restored seismic sections with traced seismic reflections are very useful for sequence boundary identification and correlation and to distinguish the effect of eustasy and structural event on the development of sequences. Sequential restorations to sequence boundaries (or condensed sections) are appropriate for constraining the depositional history and structural evolution.

Approximately eight sequences have been recognized and correlated between unconformities A and C in the seismic section from offshore Kushiro, Hokkaido, Japan. The onlap direction reversed twice during the depositional history. For the four sequences between unconformities A and B, the main effect was eustasy and sediments onlap to from northwest to the southeast. The development of the sequences in the piggyback basins was effected mainly by the faulting and folding process. The onlap direction during this period was from southeast to northwest. The three post-faulting sequences between the fault-tip horizon and unconformity C were perhaps effected equally by a folding process and eustasy. The onlap direction, reversed again, was from northwest to southeast.

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