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Styles of folding within thrust sheets: examples from the Appalachian and Rocky Mountains of the U.S.A. and Canada

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Abstract—Folds in a single thrust sheet can be classified as trailing edge (formed over footwall ramps), intraplate (due to shortening within the body of the sheet) and leading edge. Leading edge folds are usually removed by erosion at the front of a thrust sheet, but their unfaulted equivalents can be examined at the lateral termination of the thrusts. Most folds of these various classes possess a kink-band geometry with sharp hinges and long, planar limbs. The orderly nature of kink-band folds breaks down when thin incompetent units separate thicker competent members. The resulting fold geometry, ranging from simple disharmonic to hinge-collapse, is controlled by the thickness of interbedded incompetent materials. The Appalachian and Rocky Mountain thrust belts provide examples of these various classes and styles of folds.

INTRODUCTION

IN THE recent past, folds in thrust and fold belts were modelled as being cylindrical and concentric (Dahlstrom 1969, p. 220, fig. 3); that is, the fold axes lie in the plane of bedding and bedding units maintain constant thickness about the folds. Folds were drawn as sinusoidal and projected to depth from surface data using the methods of Busk (1929). However, Faill (1969, 1973), Laubscher (1976, 1977) and Roeder *et al.* (1978) have shown that folds in most fold and thrust belts possess kink-band geometries, with narrow hinges and long planar limbs. Since folds are rarely concentric, the Busk method cannot be applied to the construction of cross sections in kink-folded terranes (Faill 1973, p. 1291).

Nevertheless, many geologists persist in the use of concentric fold models. Therefore, I have chosen to demonstrate the kink-band nature of thrust-belt folds by presenting maps, cross-sections, field photos and sketches, well data, and seismic interpretations drawn primarily from the Rocky Mountains of the western United States (Fig. 1). Additional examples have come from the Canadian Rocky Mountains and the central and southern Appalachians of the eastern United States. The following discussion deals primarily with folds in two-dimensional cross-sections and does not attempt to describe complexities which occur in the third dimension.

TRAILING EDGE RAMP ANTICLINES

Folds in a single thrust sheet fall into three classes: trailing edge, intraplate, and leading edge (Fig. 2), all of which possess kink-band geometries.

Trailing-edge folds develop over footwall ramps in the thrust surface (Fig. 4a), and contain two kink-bands, one caused by the footwall ramp itself and the other resulting from the cutoff of hangingwall units against the upper thrust surface. Kink planes in the hangingwall units originate from the base of the ramp (1 in Figs. 4a & b), the top of the ramp (2 in Figs. 4a & c), and bound the hangingwall cutoffs (3 in Figs. 4a & d).

Not all ramp anticlines are as simple as the ones in Fig. 4. Late in the movement of a thrust sheet, imbricate

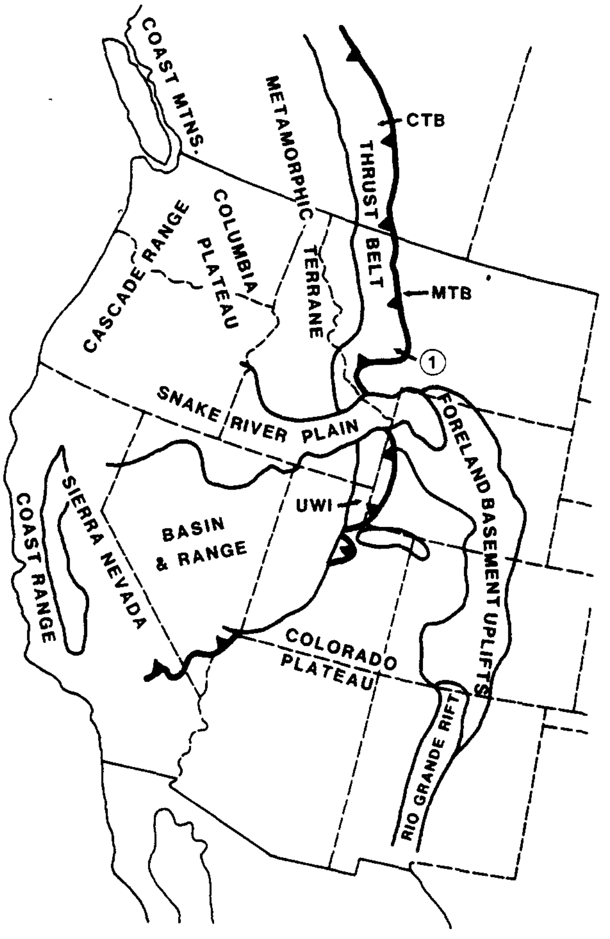

Fig. 1. Tectonic sketch map of western North America showing the Canadian thrust belt of Alberta and British Columbia (CTB), the Montana thrust belt (MTB) and the Utah–Wyoming–Idaho thrust belt (UWI).

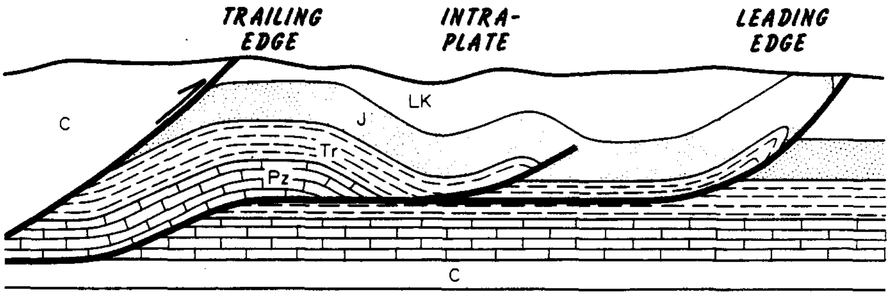

Fig. 2. Thrust anticlines are related to footwall ramps (trailing edge), shortening within the body of the sheet (intraplate), or fault propagation at the leading edge of a thrust (leading edge).

faults may initiate at the footwall ramp (Fig. 5a), resulting in a compound anticline. A cross-section through Carter Creek Field (Fig. 5b) by Lamerson (1982) shows an example of a compound ramp-anticline from the Utah–Wyoming thrust belt (location 1 in Fig. 3). The late imbrication on the Absaroka ramp may have occurred during propagation and movement on the lower and younger Darby thrust to the east.

INTRAPLATE FOLDS

Intraplate folds accommodate shortening strain within the body of a thrust sheet and are commonly cored by imbricate faults which propagate from the basal thrust (Fig. 2). Figure 6(a) shows, in simplified form, a typical fault-cored intraplate fold. Note that fold form is a function of position within the fold. The fold has a box-like configuration with two distinct kink planes at higher levels, but with depth the fold becomes a chevron as the two kink-bands merge. A thrust-cored kink fold from the Appalachians (Fig. 6b), lacks the upper box-like form but demonstrates thrust displacement decreasing upward as it is replaced by shortening in the chevron fold.

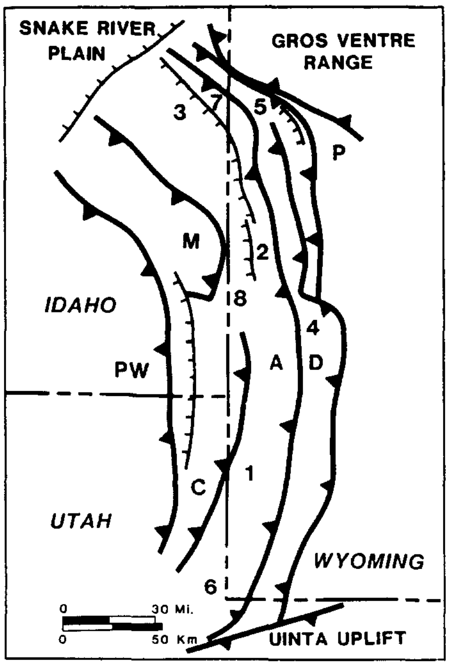

Fig. 3. Six major thrust sheets comprise the Utah–Wyoming–Idaho thrust belt: the Paris/Willard (PW), Meade (M), Crawford (C), Absaroka (A), Darby (D) and the Prospect (P). The Gros Ventre and Uinta uplifts, cored by Precambrian basement, were coincident with movement on the Prospect thrust and post-dated movement on the Darby thrust. Numbers are locations referred to in the text.

Elk Horn anticline (Fig. 7) in the Montana thrust belt (Fig. 1, location 1) is a large version of an intraplate fold possessing a box-like geometry. It presumably tightens with depth, and seismic data and surface mapping suggest that folds of this type in this portion of the thrust belt are cored by imbricate faults above a basal thrust.

Bear Creek anticline in southeast Idaho (location 3 in Fig. 3) has been breached by erosion to reveal an imbricate fault and chevron fold of lower Paleozoic carbonate rocks in its core (Fig. 8a). At the Triassic level the enveloping fold has a kink-band geometry and plunges toward the south (Fig. 8b). The imbricate fault and fold are due to shortening within the Absaroka thrust sheet and the imbricate fault presumably joins the Absaroka thrust at depth.

As shown by Faill (1973, p. 1291), kink-band folds in the Pennsylvania Valley and Ridge Province have planar limbs and narrow hinges, a geometry which holds for fold wavelengths of a few centimeters to eighteen kilometers. An anticline 6 km northeast of Afton, Wyoming (Fig. 9a; location 2 in Fig. 3), developed in thick-bedded Paleozoic carbonates, and a small chevron fold in Cambrian shales and siltstones from the Appalachians (Fig. 9b) further demonstrate that kink-band folding occurs on all scales.

LEADING-EDGE FOLDS

Elliott (1976) suggested that folding precedes thrusting. A thrust propagates laterally and up-section with a fold at its tip. The forelimb of the advancing fold front is continuously being cut by the propagating thrust. Such 'fault-propagation folds' (Suppe & Medwedeff 1984) appear at the emergent edge of thrust sheets as 'leading-edge folds' (Fig. 2).

The Darby thrust in Wyoming (Fig. 3) clearly demonstrates the relationship between thrusting and leading-edge folds. From south to north, Darby thrust displacement at the Mississippian level decreases from >26 km (location 4 in Fig. 3) to 3 km (location 5) over a distance of 100 km, and at its northern surface termination

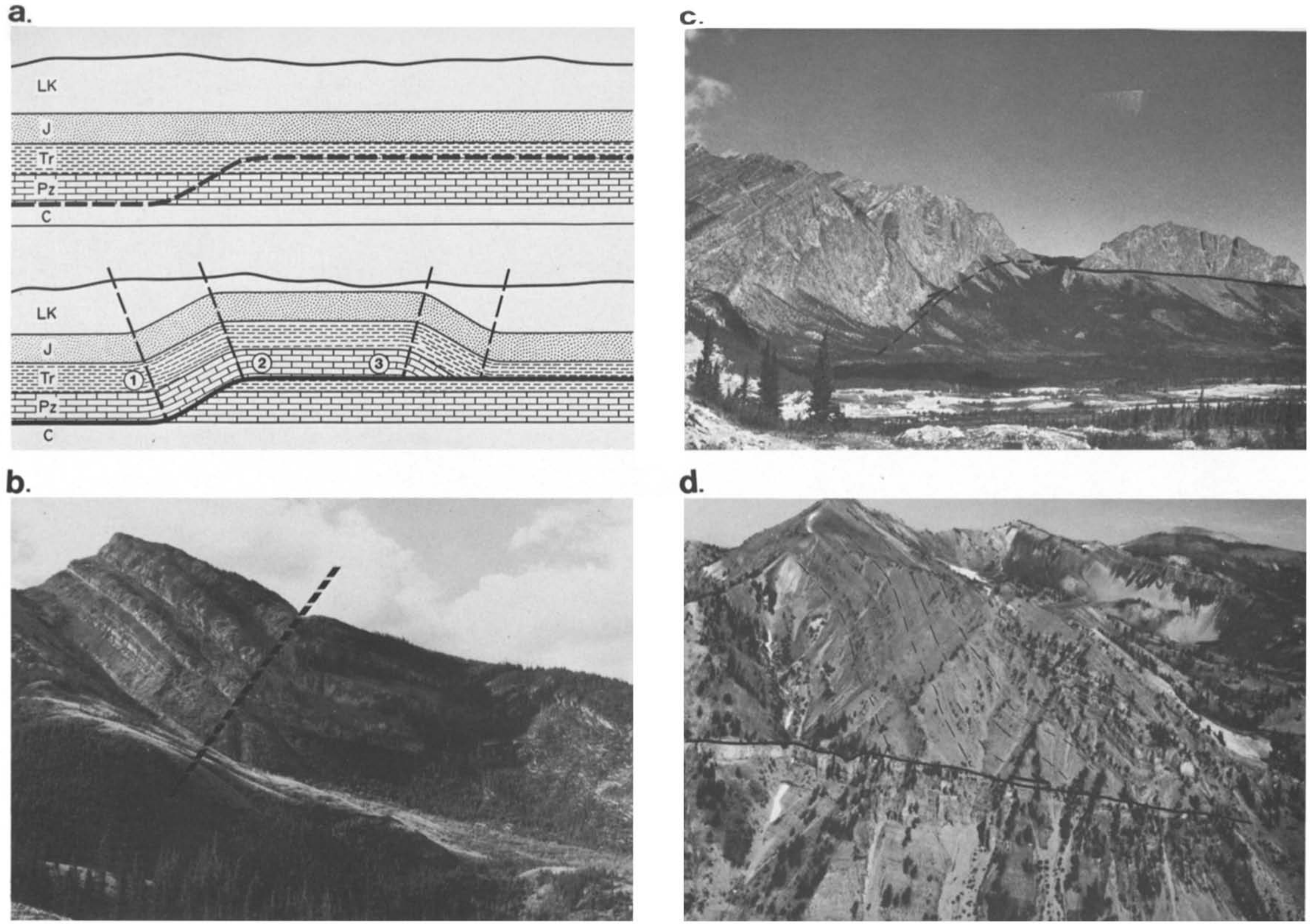

Fig. 4. (a) The trailing-edge or ramp-anticline model as developed by Rich (1934). Kink bands result from footwall ramp geometry (1 and 2) and hangingwall cutoffs (3). Kink axial planes are dashed. (b) Geometry in these Devonian and Mississippian carbonate rocks has resulted from ramp geometry of the underlying Rundle thrust. Monoclinal flexure corresponds to base of ramp (1 in the above Rich model). Photographed along Kananaskis Highway in Alberta, Canada. View toward the south. (c) Ramp in the McConnell thrust corresponds to 2 in (a). Lower Paleozoic carbonate rocks have been thrust over Cretaceous synorogenic clastic sediments (Price *et al.* 1972, fig. 5, p. 17). (d) Frontal kink-band of a hangingwall anticline corresponding to 3 in (a). North side of Little Elk Canyon in the Snake River Range of western Wyoming (location 2 in Fig. 3). Cambrian through Mississippian carbonate rocks thrust on Mississippian (Woodward 1981).

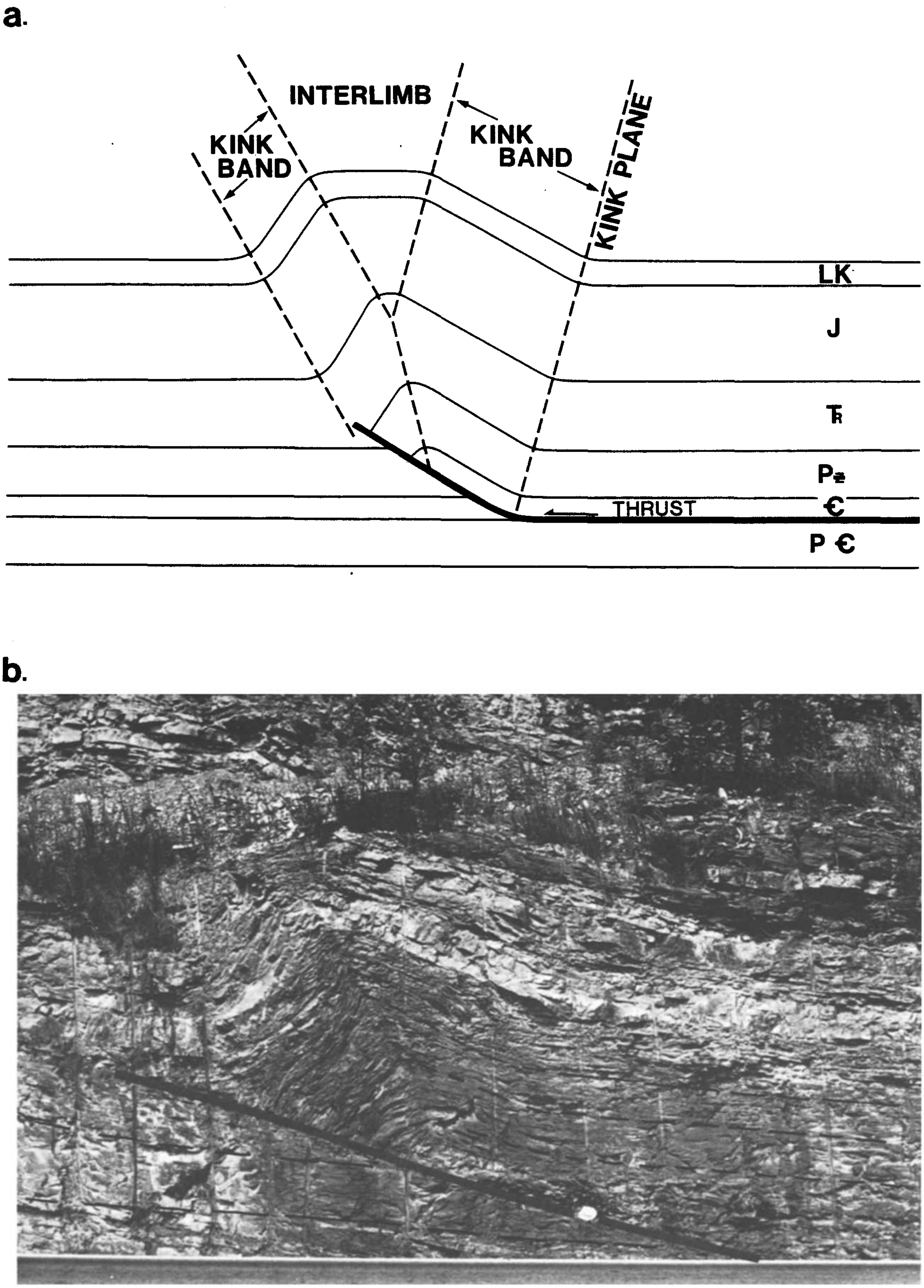

Fig. 6. (a) In a thrust-cored kink anticline, fold shortening in the upper layers is balanced by faulting at lower levels. Fault displacement decreases upward as faulting gives way to folding. The lengths of all stratigraphic horizons are equal (adapted from figs. 6 and 9 of Faill 1973). (b) Minor thrust losing displacement into a kink fold. Upper Carboniferous Gizzard Group. Along Tennessee route 8 near Dunlap, Tennessee, in the Valley and Ridge Province. View towards the north.

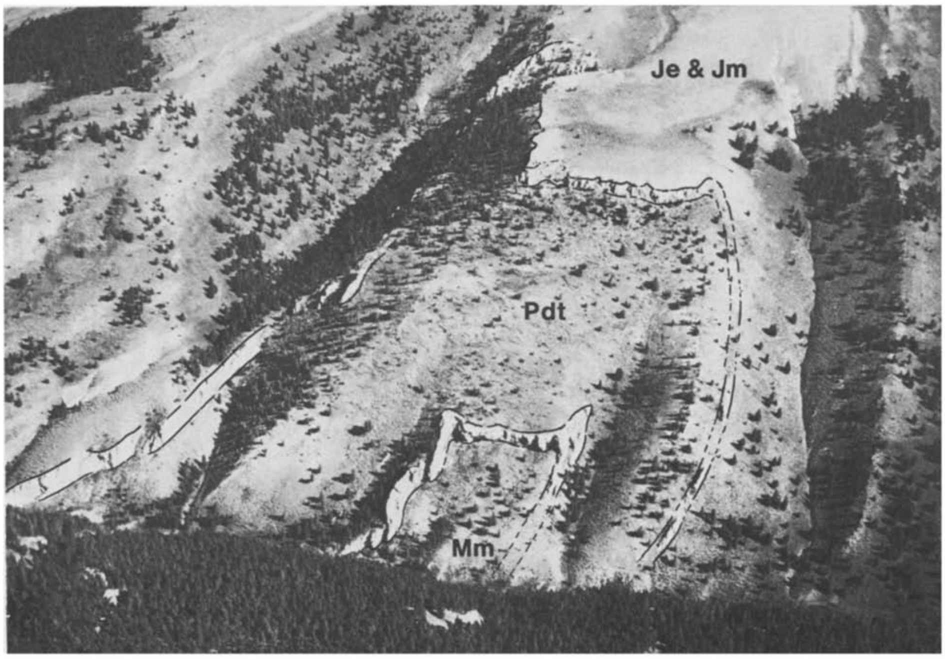

Fig. 7. Elkhorn Anticline, viewed from the south. North side of Coal Gulch; Sections 15 and 16, Township 4 North, Range 7 East, Montana (Skipp 1977) (location 1 in Fig. 1). Mm, Mission Canyon Limestone; Pdt, Devils Pocket (dolomite) and Tyler (mudstone and siltstone with interbedded carbonates) Formations; Je, Ellis Group (sandstone, shale, and limestone); Jm, Morrison Formation (mudstone and shale interbedded with siltstone and sandstone).

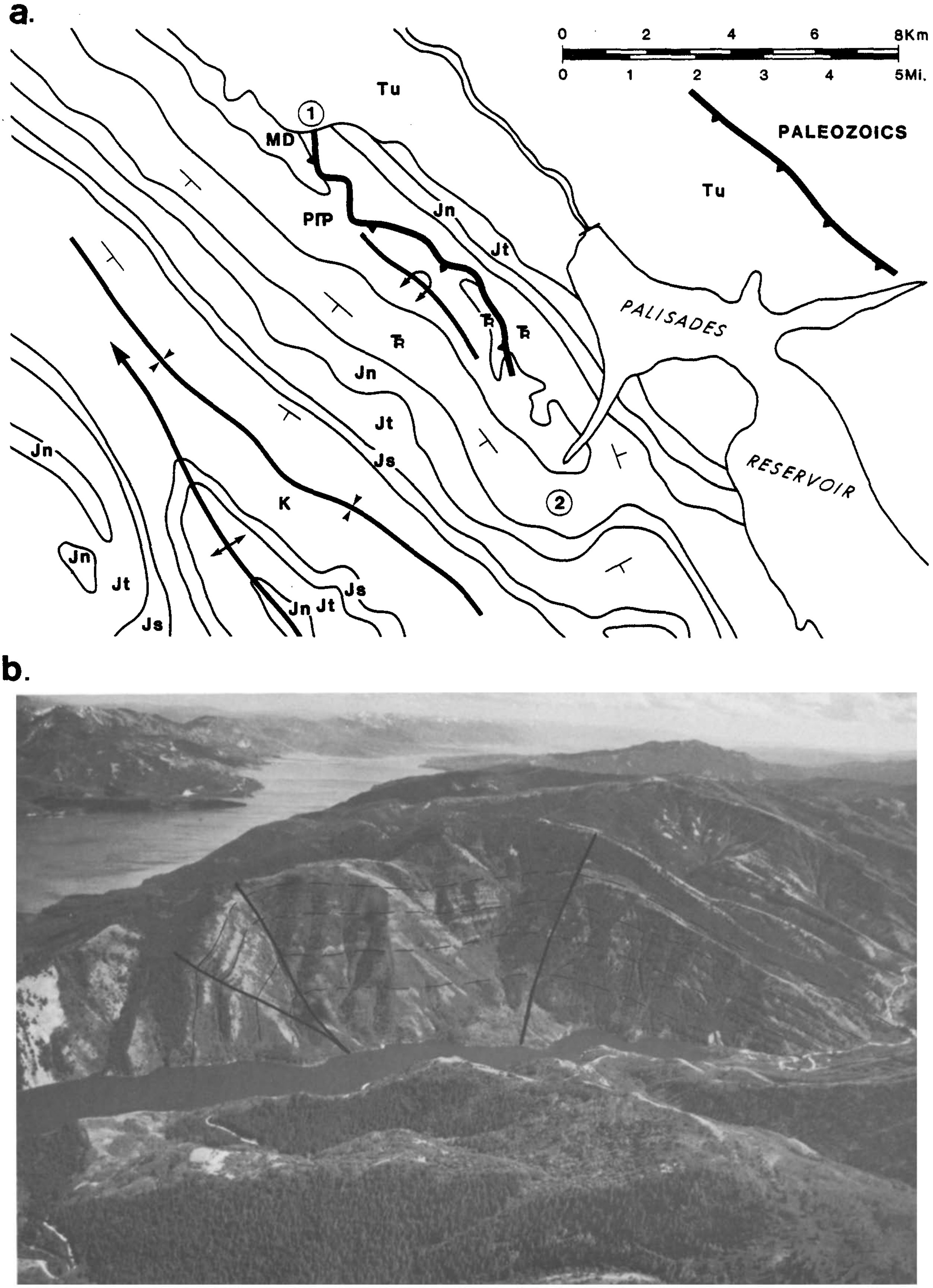

Fig. 8. (a) Map of box fold (2), cored by unnamed thrust (1) (location 3 in Fig. 3). MD, Paleozoic carbonates; PP, Paleozoic clastics and carbonates; Tr, undifferentiated Triassic red-beds and carbonates; Jn, eolian sandstones (Nugget Formation); Jt, carbonates (Twin Creek Formation); Js, siltstones, shale, and sandstone (Preuss and Stump Formations); and K, Cretaceous clastics with minor carbonates (Gardner 1961). (b) Aerial photograph of box fold (2 in Fig. 8a) in Triassic red-beds. View towards the south.

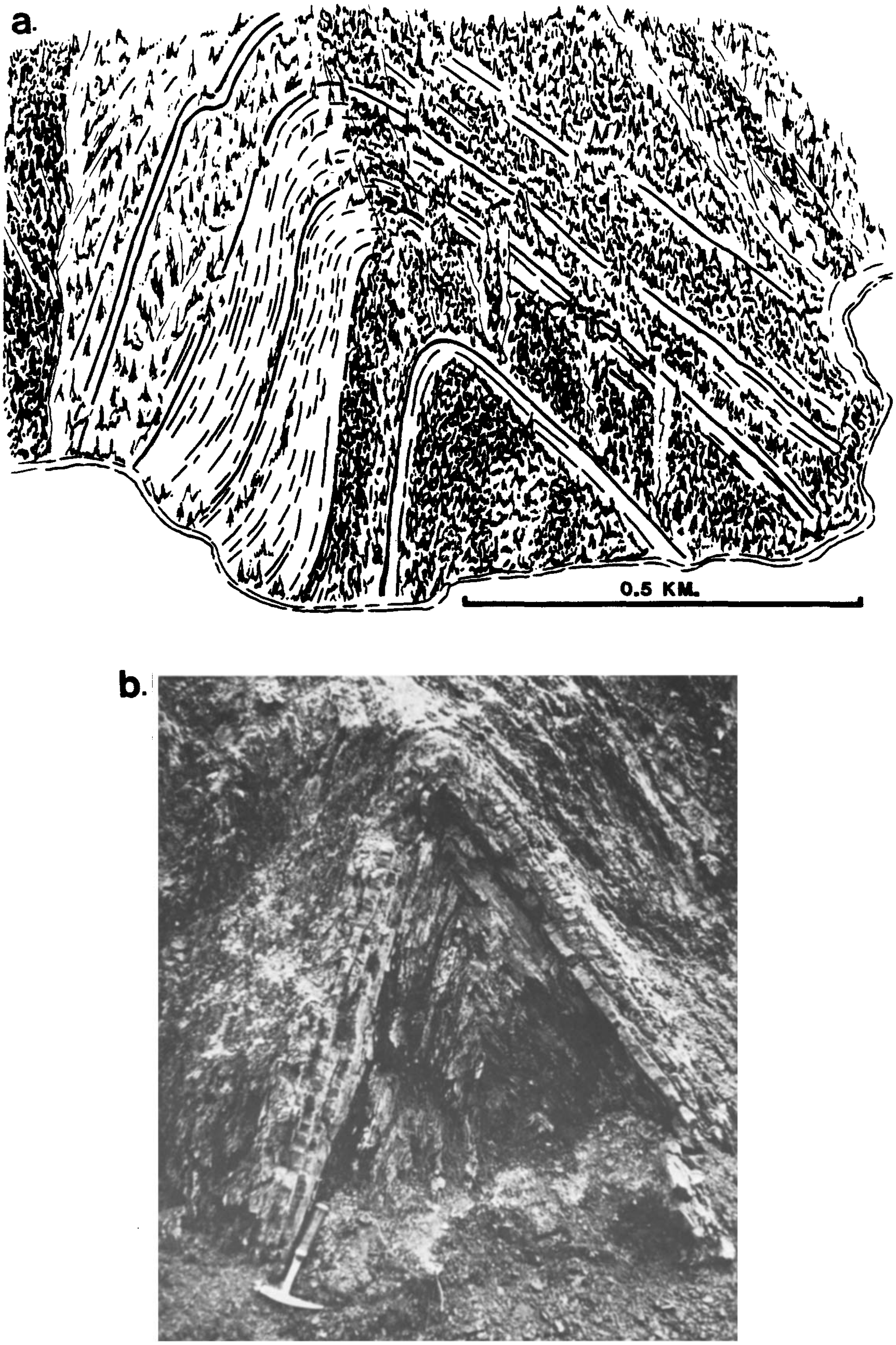

Fig. 9. (a) Chevron fold in Paleozoic carbonates. Northeast of Afton, Wyoming (Rubey 1973, location 2 in Fig. 3). Viewed from the north. Drawn from an aerial photograph. (b) Chevron fold in Cambrian shale and siltstone. Valley and Ridge Province of southwest Virginia.

Fig. 11. Chevron folds at the northern termination of the Lewis thrust. View towards the north. Photographed from the Kananaski's Highway, Alberta, Canada.

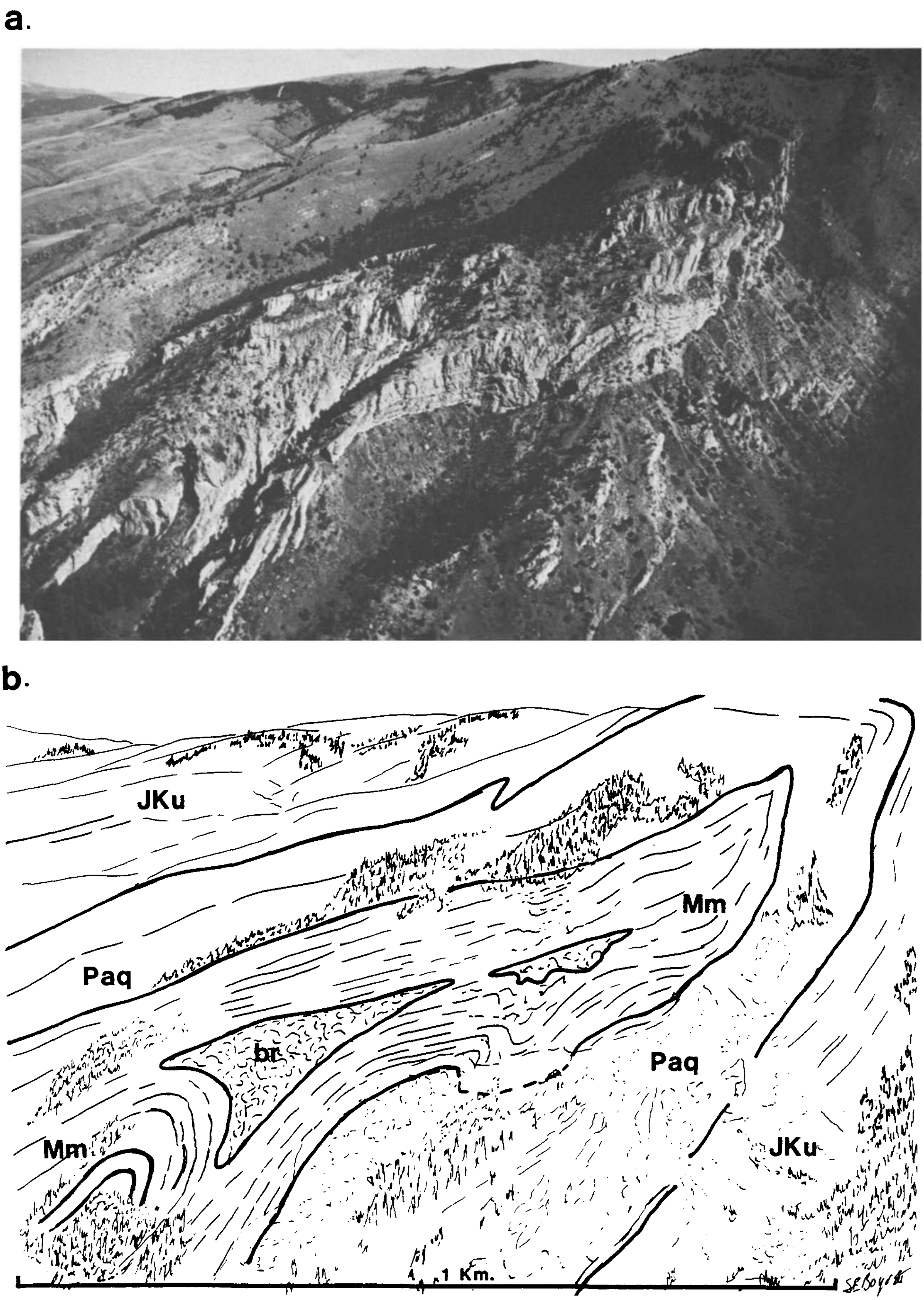

Fig. 15. (a) Aerial photograph of Middle Fork Anticline (Skipp & Hepp 1968), a collapse fold cored by Paleozoic carbonates. View toward the north-west. Location 1 in Fig. 1. (b) Sketch of Middle Fork Anticline as viewed from the south. Mm, Mission Canyon limestone; Paq, Quadrant sandstone and Amsden dolomite and claystone; JKu, undifferentiated limestone and clastics.

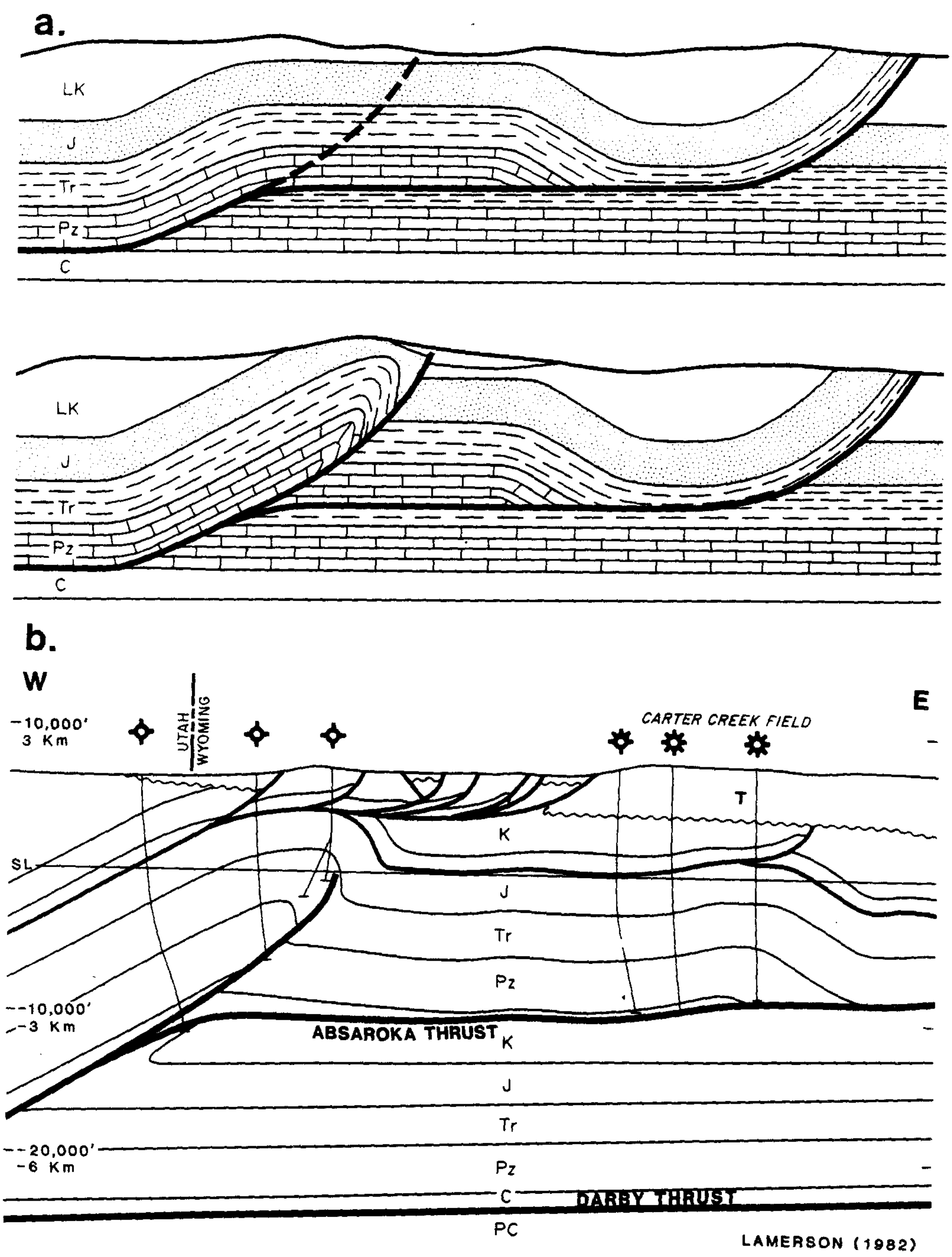

Fig. 5. (a) An out-of-sequence thrust imbricate (dashed) may initiate at a pre-existing thrust ramp. Movement on the later imbricate results in a compound ramp anticline. (b) Compound ramp anticline from the Wyoming thrust belt (location 1 in Fig. 3) (after Lamerson 1982).

(location 5) the Darby thrust passes into a box fold (Fig. 10a). A cross-section, constructed using seismic control and down-plunge projections of map data, shows that the thrust is dying up-section, as well as along strike, into a kink anticline (Fig. 10b). The Darby termination box fold, with its NW- and NE-plunging fold axes, demonstrates that such folds are usually non-cylindrical. As a result, leading-edge folds can be expected to exhibit complex variations in geometry along a thrust trace.

Another example of a major thrust dying along strike into a fold or fold complex is the Lewis thrust of the Canadian and Montana thrust belts (Mudge & Earhart 1980, Price *et al.* 1972, p. 122 and fig. 72, p. 123, Stockmal 1979). At Mt. Kidd the northern surface termination of the Lewis thrust is expressed as a series of chevron folds (Fig. 11).

DISHARMONIC FOLDING

The folds discussed up to this point have had orderly kink-band geometries with sharp hinges and planar limbs. Formational thicknesses are relatively constant in the limbs of these folds; but, as Ramsay (1974) has demonstrated, in chevron folds (a subset of kink-band folds) there may be a marked variation of thickness in hinge areas.

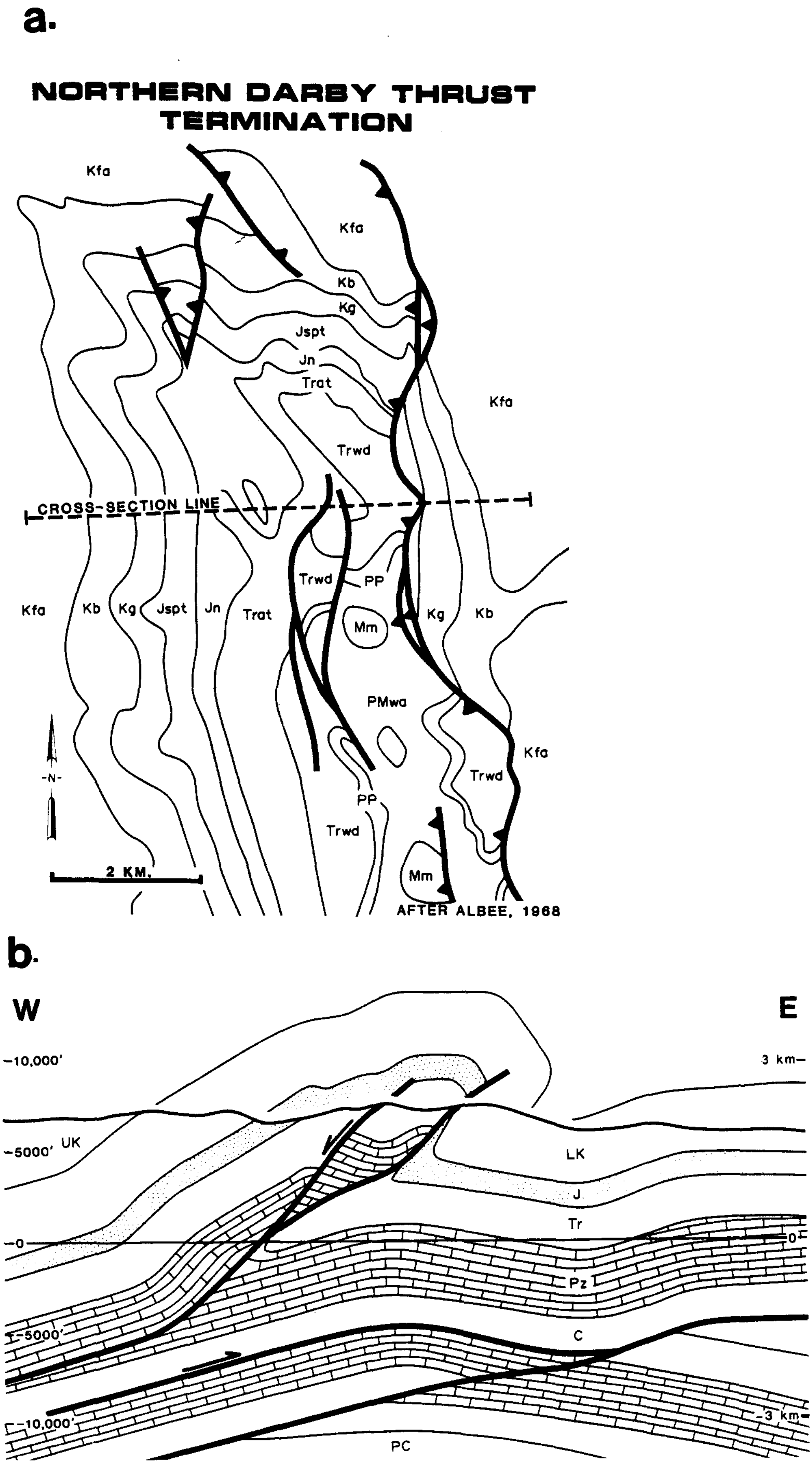

Fig. 10. (a) Map of the northern termination of the Darby thrust at Munger Mountain. Vicinity of location 5 in Fig. 3. Modified from Albee (1968). (b) Darby thrust dying upsection into fold. Thrust shortening in the Paleozoic and lower Mesozoic is balanced by fold shortening in the Upper Mesozoic.

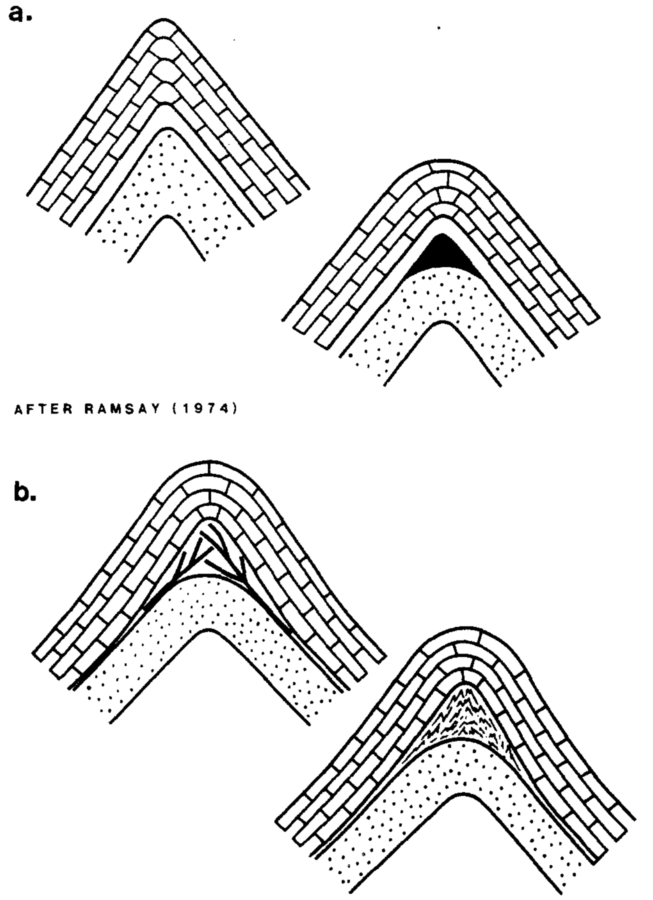

Fig. 12. (a) At left is a simple chevron model with uniform crestal thickening. In a real chevron fold (at right), with interbedded competent members (limestone and sandstone patterns) and incompetent shale or evaporites (unpatterned), competent units will maintain constant thickness and a void (black) will result. (b) This void may be filled by flowage, wedging or mineralization (not shown). After Ramsay (1974).

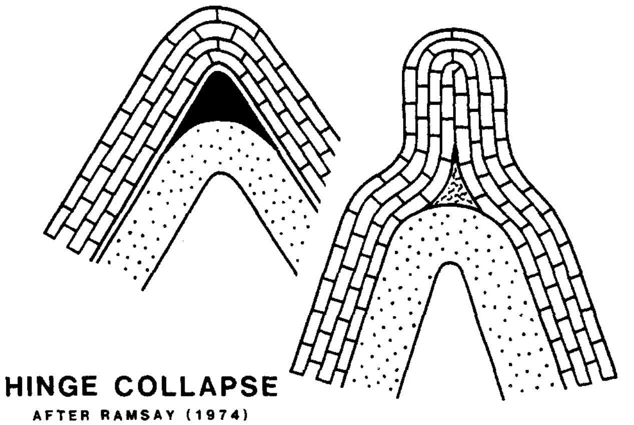

Fig. 14. When an insufficient volume of incompetent material is available to fill void in the hinge area of a chevron fold, hinge collapse results (after Ramsay 1974).

In a simple chevron model all units maintain constant thickness in the limbs and undergo uniform thickening in the hinges (Fig. 12a). For interbedded sequences of competent and incompetent rocks, this model is unrealistic. Competent units will maintain constant thickness about the fold resulting in a void (Fig. 12a; Ramsay 1974, fig. 4, p. 1744). Such crestal voids become filled by (1) crystallization of mineral species which are mobile during deformation (Ramsay 1974, fig. 12, p. 1746), (2) flow of incompetent material from the limbs (Fig. 12b; Ramsay 1974, p. 1746 and fig. 14, p. 1747) or (3) wedging and flowage of interbedded competent and incompetent materials (Fig. 12b; Cloos 1961, fig. 12, p. 113).

When the incompetent material is of sufficient thickness extreme disharmonic folding results (Nickelsen

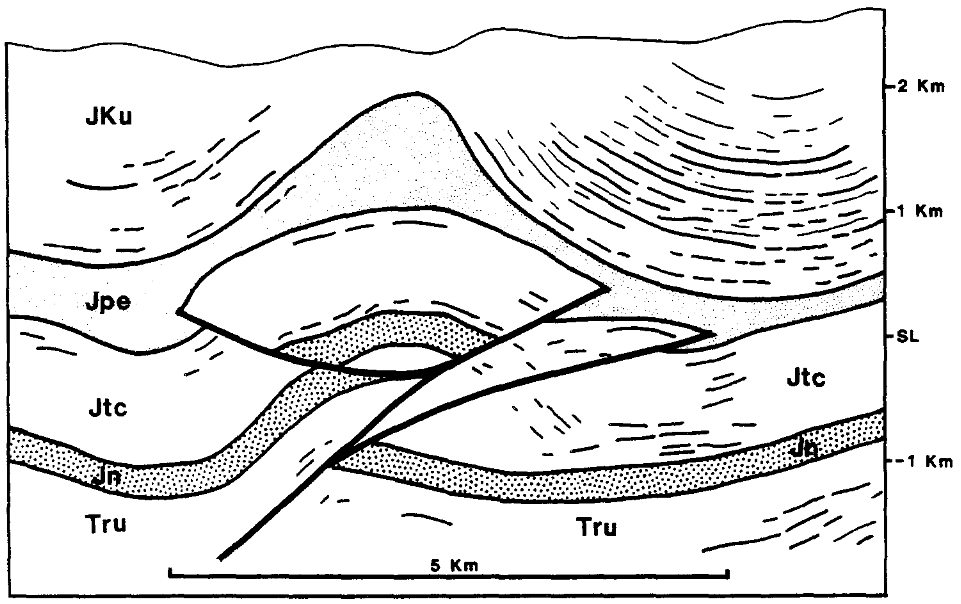

Fig. 13. Disharmonic folding in Mesozoic clastics and carbonates. Drawn from a seismic profile (location 8 in Fig. 3). JKu, Cretaceous synorogenic and Jurassic marine clastics; Jpe, Preuss evaporites; Jtc, Twin Creek argillaceous limestone; Jn, Nugget eolian sandstone; Tr, red-beds and carbonates. Traced from a seismic line.

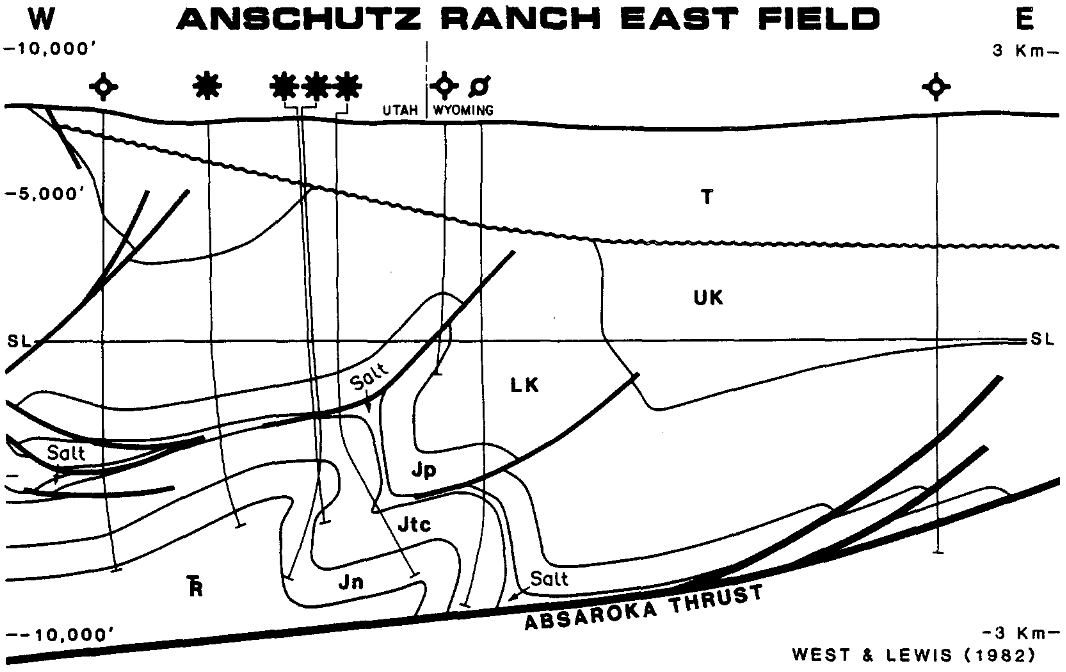

Fig. 16. Cross section through Anschutz Ranch East Field in the Utah–Wyoming thrust belt (location 6 in Fig. 3). Collapse fold has resulted from flowage of evaporites which separate Jurassic Twin Creek Limestone (Jtc) from Jurassic Preuss/Stump fine-grained clastics (Jp). Jn, Nugget sandstone; Tr, red-beds and carbonates; LK and UK, undifferentiated Upper and Lower Cretaceous synorogenic clastic sediments (after West & Lewis 1982).

1979, Nickelsen & Cotter 1983, p. 128 and fig. III-2, p. 130). In the Utah–Wyoming–Idaho thrust belt (Fig. 2) evaporites at the base of the Jurassic Preuss marine clastics are responsible for much of the disharmonic folding. The lower Mesozoic section is often folded into tight synclines and broad faulted anticlines, whereas the upper Mesozoic rocks above the evaporitic unit are independently folded into tight anticlines and broad synclines (Fig. 13).

As stated previously the crestal void between competent units can be filled by flowage or imbrication of interbedded incompetent materials (Fig. 12b). However, when there is insufficient incompetent material to fill the void, hinge collapse results (Fig. 14; Ramsay 1974, pp. 1746–7, fig. 13, p. 1747, and fig. 15, p. 1748).

Middle Fork anticline (Skipp & Hepp 1868) provides an excellent example of a large-scale hinge-collapse fold (Fig. 15). The fold, located northeast of the Bridger Mountains of Montana (1 in Fig. 1), is composed of the Mission Canyon Limestone of the Mississippian Madison Group. In Montana an anhydrite/gypsum unit, measuring 8–15 m in thickness, is located in the middle of the Mission Canyon Limestone. The evaporite zone provided a glide zone for disharmonic folding between the upper and lower Madison Group. However, the amount of slip was so great that the thin evaporite zone could not fill the resulting void in the hinge zone, leading to hinge collapse.

Drilling at the Anschutz Ranch East field in the Utah–Wyoming thrust belt (location 6 in Fig. 3) has revealed another collapse feature (Fig. 16). As in Fig. 13, the cause of the disharmony is an evaporite unit within the Jurassic sequence.

CONCLUSIONS

Most thrust-belt folds, including trailing-edge, intraplate, and leading-edge folds, and folds at the lateral terminations of major thrusts, possess kink-band geometries. The positions of kink-bands in trailing-edge ramp-anticlines are controlled by the geometry of the underlying thrust. Intraplate folds are due to bulk shortening within the body of a thrust sheet and are cored by imbricate faults which splay from the basal thrust. Leading edge anticlines form as the frontal part of a thrust as a result of thrust propagation. These frontal anticlines are often removed by erosion, but analogous folds can be observed at the lateral terminations of major thrusts.

Not all kink-band folds are orderly. Varying degrees of disharmonic folding may result from the presence of varying quantities of interbedded incompetent units. Hinge-collapse folds, an extreme case of disharmonic folding, result when the incompetent material is too thin to fill crestal voids, but is of sufficient thickness to allow interbed slip.

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