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Relationship of spaced cleavage to folds and thrusts in the Idaho–Utah–Wyoming thrust belt

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Abstract—The Idaho–Utah–Wyoming thrust belt of the Rocky Mountain Cordillera preserves structures that developed at very shallow levels of the crust ($T < 200°C$). The geometry of major structures is well documented and synorogenic conglomerates record the timing of movement on major thrusts. Spaced cleavage and pencil fracturing are developed within micrites of the Jurassic Twin Creek Formation.

The cleavage developed dominantly by pressure-solution early in the deformation history of each thrust sheet, aided by elevated temperatures and pressures in areas where increased overburden resulted from emplacement of earlier, overriding sheets. Cleavage within any sheet is well developed in the area covered by the pre-erosional extent of the previous sheet; forelandward from this area cleavage intensity decreases drastically. Thermal modelling of the sheets agrees well with temperature estimates from illite crystallinity studies on material from the cleavage planes.

Cleavage is axial planar to small folds and formed concurrently with small-scale buckle folds and contraction faults during the early history of movement on each thrust. However, cleavage strongly fans about large-scale folds formed later during movement, suggesting passive rotation of cleavage with bedding during the later stages of thrust history. The rotated cleavage may also be folded and overprinted by a second weaker cleavage during a second ramping, or during movement on a later, lower thrust. Cross-folding may also develop as a result of lateral ramping. Thus, complex patterns of interfering folds, multiple cleavages, and associated fiber-filled fractures may be produced during motion on a single thrust fault, and so magnify the problem of correlating cleavages and deciphering multiple deformations.

INTRODUCTION

THE IDAHO–UTAH–WYOMING thrust belt is part of the eastern fold and thrust belt of the North American Cordillera. It forms a broad salient, convex to the east, with several major thrust faults that transported a thick sequence of Paleozoic and Mesozoic sediments eastward. The thrust belt is not very deeply eroded, and preserves structures that developed at very shallow depths. The deeper structure, particularly in the frontal thrust sheets, is fairly well known on the basis of seismic profiling and well data (Dixon 1982, Lamerson 1982).

The geometry of major structures is well documented (Royse *et al.* 1975, Dixon 1982, Lamerson 1982) and is typified by 'foothills family of structures' (Dahlstrom 1970, Boyer & Elliott 1982). Thrusts dip westward, are listric in shape, and cut up section in the direction of transport in a stair-step fashion. The major thrusts, from west to east, are the Willard, Paris, Meade, Crawford, Absaroka, Darby and Prospect (Fig. 1). There are also numerous smaller thrust faults, listric normal faults, tear faults and parallel folds (with concentric or kink geometries). In addition, the movement on major faults is recorded by synorogenic conglomerates (Fig. 1), giving perhaps the most complete and refined record of timing of thrust faults of any thrust belt in the world (Wiltschko & Dorr 1983).

Spaced cleavages developed at low to medium metamorphic grades have been previously described from other mountain chains (Gray 1981, Alvarez *et al.* 1978, Ramsay 1981). The exposed rocks in the thrust belt were deformed at low metamorphic grades ($P < 5$ kb, $T < 200°C$) and show the development of a spaced cleavage in the Jurassic Twin Creek Formation. The cleavage is best developed in the Rich and Leeds Creek Members (Imlay 1967) which are dominantly micrites having 10–20% clay, quartz and feldspar. Also, tectonic stylolites are developed in sparry limestones, and siltstones locally have an incipient slaty cleavage. The Jurassic section is preserved in all the major thrust sheets except the Paris–Willard sheet, and in each sheet the Twin Creek Formation shows the development of a spaced cleavage and pencil fracturing. Twin Creek pebbles within the synorogenic conglomerates are also cut by a spaced cleavage.

Timing of cleavage development can be determined by studying synorogenic conglomerate pebbles and detailed structural geometries within thrust sheets. Palinspastic restorations combined with thermal modelling are used to estimate the pressure–temperature history of the thrust sheets. Thus, relationships can be studied between cleavage development and P-T histories as successive thrust sheets are emplaced.

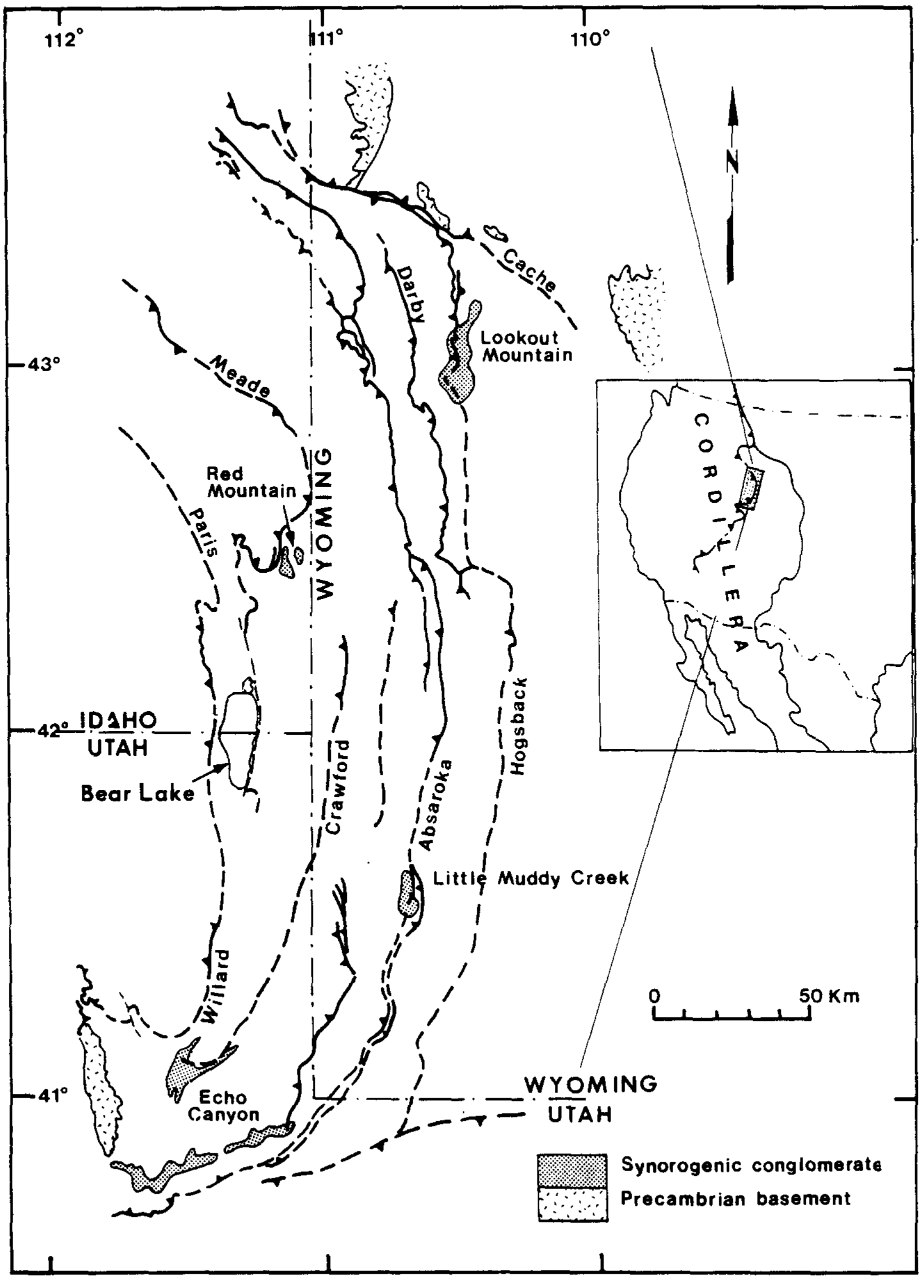

Fig. 1. Map showing location of the Idaho–Utah–Wyoming thrust belt. Major thrusts and synorogenic conglomerates are shown. Modified after Lamerson (1982).

CLEAVAGE MORPHOLOGY

Cleavage in micrites of the Twin Creek Formation is characteristically a close-spaced, parallel parting that is generally at high angles to bedding (Fig. 2a). The parting is defined by zones of clay-rich insolubles left behind by pressure solution that removed the calcite. The zones of insolubles range from thin, diffuse layers to spaced, thick seams that bound otherwise undeformed micrite lithons (Fig. 2b). Within the seams, the phyllosilicates tend to be dimensionally aligned parallel to seam boundaries and anastomose around slightly corroded quartz grains. The seams truncate fossil fragments and ooids, and offset bedding planes and calcite-filled fractures that are oblique to the seams. Material dissolved along the seams is reprecipitated in pressure-shadows behind large grains of calcite or quartz or pyrite framboids, or as fibrous calcite in fractures. All these features are characteristic associates of cleavage formed by pressure solution (Durney 1972).

TIMING AND CONDITIONS OF CLEAVAGE FORMATION

The timing of thrusting in the Iadho–Utah–Wyoming thrust belt is well established on the basis of structural and stratigraphic data (Armstrong & Oriel 1965, Royse *et al.* 1975, Dorr *et al.* 1977, Jordan 1981, Wiltschko & Dorr 1983). Cross-cutting relationships and overlapping of the fault traces by younger beds have been used to bracket the timing of motion on individual faults (Wiltschko & Dorr 1983) (Fig. 3). The time of major motion on each fault is given by the age of the synorogenic conglomerate shed off that thrust sheet; for

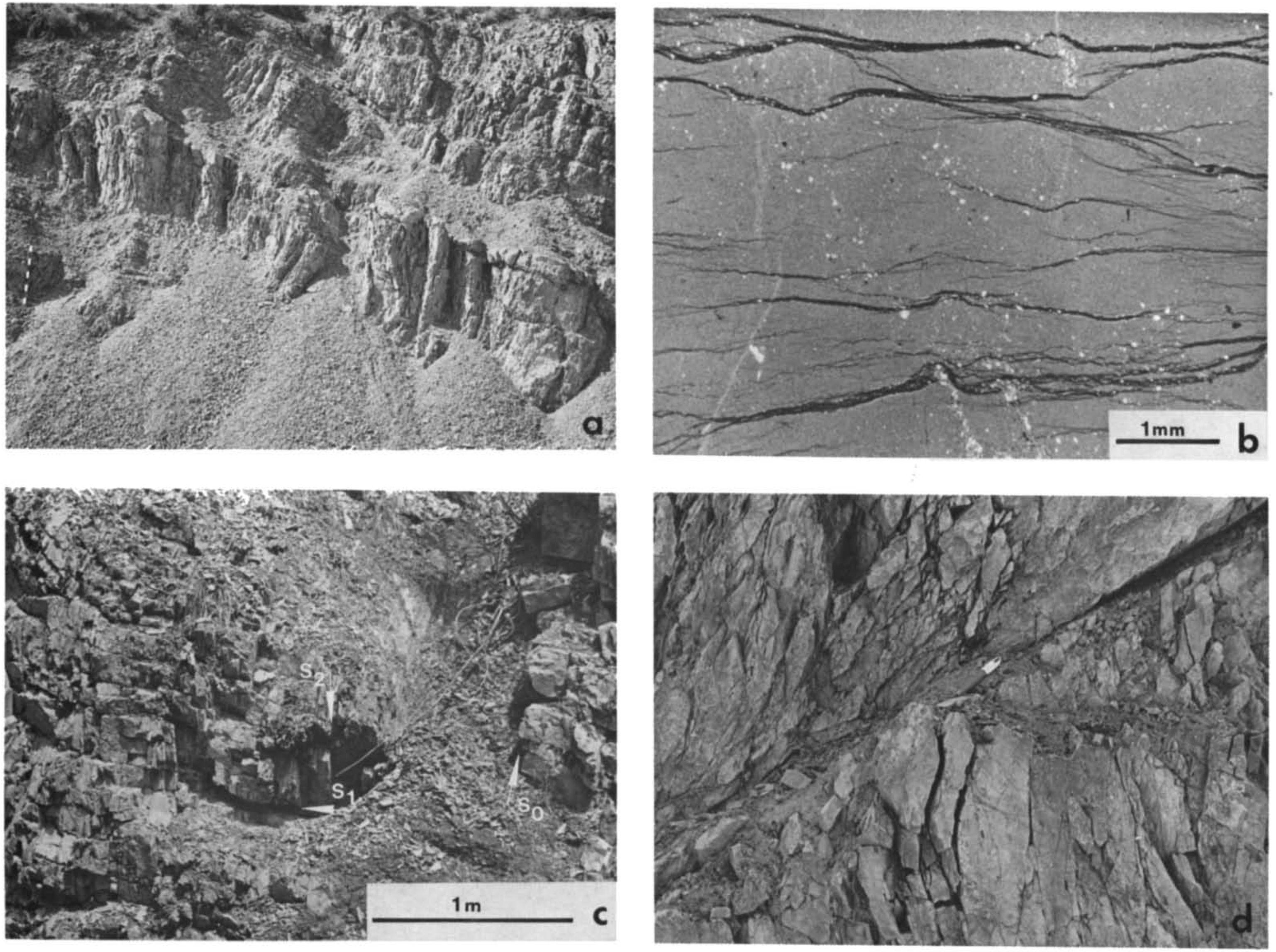

Fig. 2. (a) Outcrop showing cleavage in micrites of the Jurassic Twin Creek Formation. Cleavage is steeply dipping and approximately perpendicular to bedding. Rock weathers to pencil fragments seen in scree. Metre stick for scale. (b) Photomicrograph showing cleavage defined by spaced seams of dark residue bounding otherwise undeformed micrite lithons. Thin seams join to form thicker seams, and the seams show anastomosing pattern. (c) Gently dipping cleavage (S_1) refolded into upright folds along Swift Creek (Fig. 7, section YY′Y″) in the Absaroka thrust sheet. A second cleavage (S_2) is developed parallel to the axial planes of the folds. Bedding (S_0) is steeply dipping. The east limb of the fold has been displaced by a reactivated fault. (d) Small fault in section along Dry Creek (Fig. 7, section ZZ′Z″) showing cleavage asymptotic to the fault plane. Pen for scale.

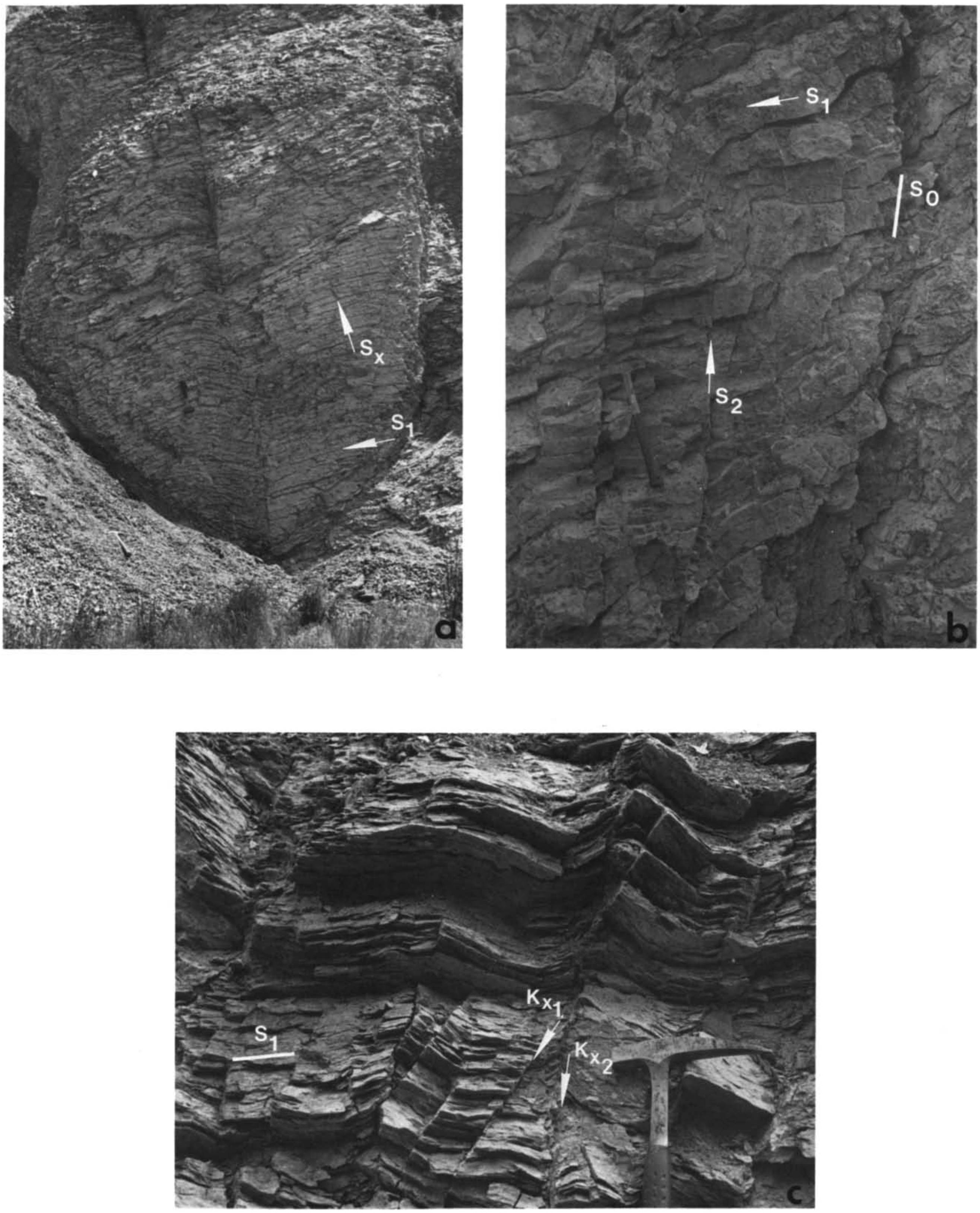

Fig. 9. (a) Cleavage (S_1) folded into cross-kink at Cokeville in the Crawford thrust sheet. Stylolites (S_x) were formed parallel to the axial plane, and the axial plane is fractured. (b) Cleavage (S_1) folded into upright folds along Montpelier Canyon in the Crawford sheet. A steep second cleavage (S_2) was formed approximately parallel to bedding. There was some shearing along the spaced second cleavage planes late in the deformation history. (c) Cleavage (S_1) folded into cross-kinks (Kx_1 & Kx_2) along Montpelier Canyon in the Crawford sheet. This kinking also affects bedding planes. A weak cleavage may form parallel to the axial surfaces of the kinks.

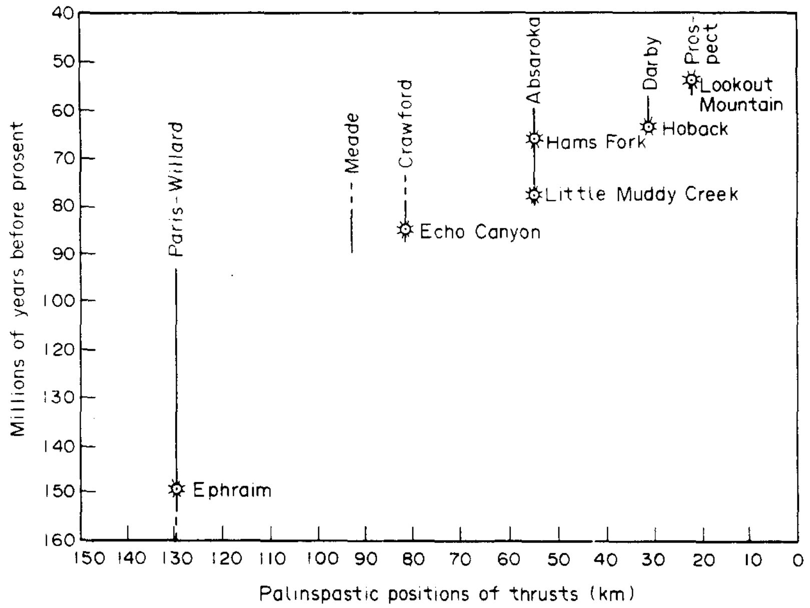

Fig. 3. Timing of motion on various thrusts versus their palinspastic position along 42°N latitude (based on palinspastic maps in Wiltschko & Dorr [1983]).

example, the Aptian Ephraim conglomerate was shed off the Paris sheet (Eyer 1969), the middle Coniacian Echo Canyon conglomerate from the Crawford sheet (Nichols 1979), the late Santonian Little Muddy Creek conglomerate from the Absaroka sheet (Nichols 1979), and the early Graybullian Lookout Mountain conglomerate from the Prospect sheet (Dorr *et al.* 1977). Thrusts developed sequentially from west to east in a forelandward progression. The Paris–Willard sheet was emplaced first, and was followed successively by the Meade, Crawford, Absaroka, Darby and Prospect thrusts. Within each of these thrust sheets cleavage developed in the Jurassic Twin Creek Formation, although this unit is no longer preserved in the deeply eroded Paris–Willard sheet.

The synorogenic conglomerates contain pebbles and boulders of Jurassic Twin Creek Formation that show solution cleavage. The cleavage is generally at high angles to bedding within the clasts. However, the cleavage shows no systematic orientation with respect to the local structure and is absent in the matrix of the conglomerates. In the source thrust sheets, on the other hand, cleavage shows systematic patterns related to the major structures. This indicates that the cleavage developed before the synorogenic conglomerates were shed off their respective sheets.

The temperatures at which deformation took place in each of the sheets were estimated using the crystallinity of illite as an index (Kübler 1967). Illite crystallinity was determined from X-ray diffractograms of the <2 μm clay fraction of both the micrite and the cleavage-seam materials. The breadths of the illite (001) peaks were measured at one-half of their height in degrees $\Delta 2\theta$ following Kisch (1980). Illite breadth is proportional to the illite crystallinity of Kübler (1967) and decreases systematically with increasing temperature (Dunnoyer de Segonzac 1970, Frey *et al.* 1980). Details of this method are discussed elsewhere (Yonkee 1983). This gives fairly reliable relative temperatures, although absolute temperature estimates from this method may not always be completely correct. As we might expect, pebbles from synorogenic conglomerates give the same estimated temperatures as samples from the corresponding thrust sheets from which the pebbles were derived (Fig. 4) (Gentry 1983).

It should be pointed out that the conglomerate temperature estimates are based on a limited number of samples, since pebbles with cleavage are very likely to break up during transport and deposition and hence are rarely preserved.

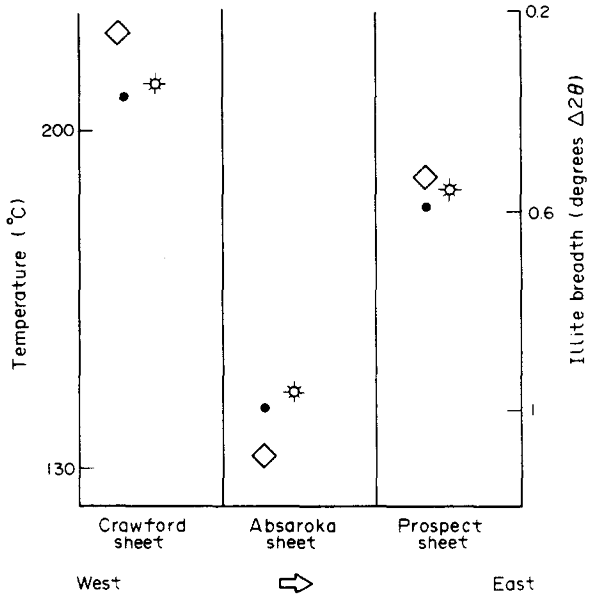

Fig. 4. Illite breadth values for cleavage seam materials from conglomerate clasts (stars) and corresponding source thrust sheets (filled circles), indicating similar temperatures for each pair. Note that there is no continuous temperature gradient across the thrust belt. Estimates of maximum temperatures experienced by the rocks in each of these areas, based on thermal modelling, are shown by diamond symbols.

Different temperatures are obtained for the conglomerate source areas of each of the thrust sheets, and there appears to be no continuous temperature gradient across the thrust belt. The Absaroka sheet was deformed at lower temperatures than both the Prospect sheet (which lies closer to the foreland) and the Crawford sheet (which lies closer to the hinterland). The differences in temperature cannot be explained in terms of differences in stratigraphic thickness of preorogenic or synorogenic units above the Twin Creek Formation in the different thrust sheets. However, the relatively high deformation temperatures could be related to the emplacement of overriding thrust sheets that resulted in an overburden greater than the normal stratigraphic thickness. In order to test this hypothesis, we constructed thermal models from pre-erosion thrust geometries based on balanced cross-sections (Royse *et al.* 1975, Sections XX′ and YY′).

THERMAL MODEL

The emplacement of a thrust sheet juxtaposes relatively hot material from deeper levels against cooler material at shallower levels. Time-averaged thrust slip rates vary from 0.1 to 0.5 cm a^{-1} (Elliott 1976, Mitra 1984), although instantaneous rates may be significantly higher. Assuming typical thrust slip rates of 10 km Ma^{-1} (1 cm a^{-1}), typical thrust sheet thickness of 5–8 km, and typical thermal diffusivity for earth materials of 32 km^2 Ma^{-1} (Oxburgh & Turcotte 1974), the heat transfer is dominantly convective (Peclet number >1). So, we can view thrust emplacement as a form of solid-state convection.

Following the emplacement of the relatively hot hangingwall, the disturbed thermal regime is assumed to equilibrate by one-dimensional heat conduction through material of uniform thermal diffusivity (Oxburgh & Turcotte 1974, Brewer 1981, Furlong & Edman 1984). This simplified model assumes that there is no change between the initial and final equilibrium thermal gradients, no frictional heating [a fairly reasonable assumption for thrust faults (Elliott 1976, Bird 1978)], no convective transfer of heat after thrusting (i.e. neglects fluid circulation through the rocks), and no change in thermal gradients due to erosion.

Using a graphical approach, and assuming a constant geothermal gradient, initial isotherms are drawn on a time–temperature plot (Fig. 5a). During thrusting the increased overburden results in rapid depression of the thermal gradient. Following this sudden change, the isotherms gradually return to their equilibrium positions as heat flows from the hot hangingwall into the cooler footwall. Using a Lopatin-type plot (Waples 1980) the position of the Twin Creek Formation is superimposed on the time–depth plot allowing the thermal history to be followed through time.

For example (Fig. 5a), the Jurassic Twin Creek Formation of the Prospect sheet from which the Lookout Mountain conglomerate would be derived was initially buried slowly under synorogenic deposits from the Paris, Meade and Absaroka sheets. The depth of burial increased rapidly as the future Prospect sheet was overridden by the Darby sheet, and began to decrease as the Darby sheet was eroded. The rocks were finally brought rapidly to the surface when the Prospect sheet was emplaced and eroded. The rocks reached their highest temperatures about 5–10 Ma after the emplacement of the preceding sheet, and presumably by this time, shortening within the new sheet had already started. The maximum temperatures derived from the thermal model agree well with those from the illite breadths determined from the Lookout Mountain conglomerate and its source rocks (Fig. 4).

Good agreement between the thermal models (Figs. 5b & c) and illite breadths is also obtained for the Little Muddy Creek conglomerate derived from the Absaroka thrust and for the Echo Canyon conglomerate derived from the Crawford thrust (Fig. 4).

This agreement between the thermal model and measured temperatures from synorogenic conglomerates and their source rocks supports the idea that the emplacement of a thrust sheet could create the right pressure–temperature conditions for the development of cleavage in the next (lower) thrust sheet. However, these measurements are only valid for one area within each thrust sheet. We, therefore, decided to do more detailed measurements and thermal modelling within a single thrust sheet.

Thermal modelling for the Crawford sheet

The Crawford thrust sheet, exposed in southeastern Idaho and westernmost Wyoming, shows the best developed spaced cleavage of any of the thrust sheets in the thrust belt. There are also several spectacular canyon exposures through different parts of the sheet along approximately one line of section in the direction of tectonic transport. Detailed studies of these exposures (Fig. 8) through Georgetown Canyon (Section AA′), Montpelier Canyon (Section CC′), Salt Canyon (Section BB′), and the Cokeville area (Section DD′) makes it possible to draw a composite picture of deformation patterns and cleavage formation from the trailing edge to the leading edge of the sheet.

Thermal models for the different parts of the sheet, based on pre-erosional restored sections, give estimated maximum temperatures that are consistent with temperature estimates from measured illite breadth values from those areas (Table 1). According to the model, the

Table 1. Estimated temperatures from thermal models, and illite breadth values for different sections of the Crawford thrust sheet

		Temperature estimates from thermal models	Illite breadth (°$\Delta 2\theta$)
Trailing edge	Georgetown Canyon	180°C	0.61
↓	Montpelier Canyon	—	0.64
	Salt Canyon	155°C	0.68
Leading edge	Cokeville	—	0.71

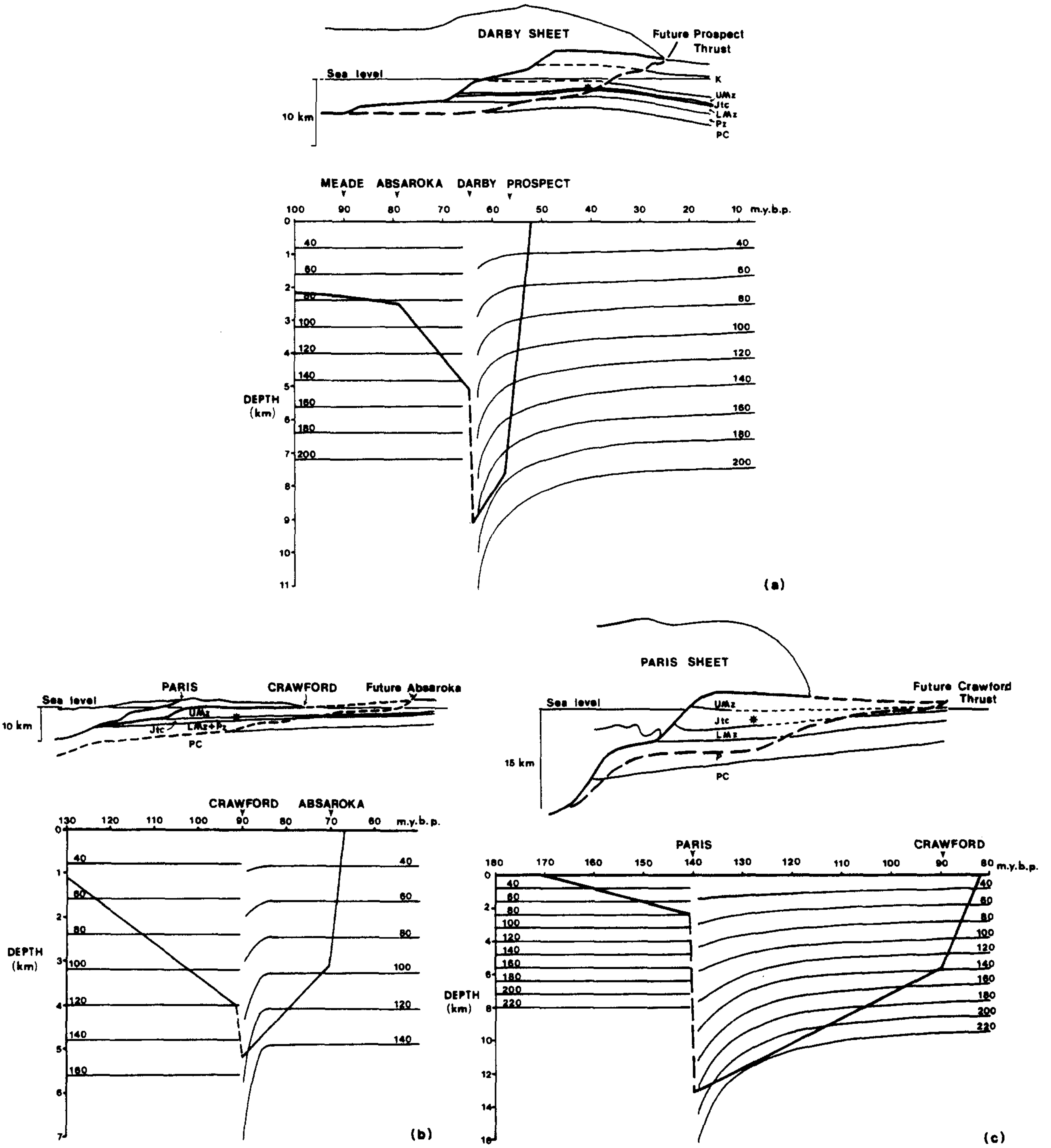

Fig. 5. (a) Restored cross-section (based on Royse *et al.* 1975, section XX′) showing pre-erosional extent of the Darby sheet over rocks from which the Lookout Mountain conglomerate would be derived (star). Time–temperature plot shows depression of isotherms immediately after the Darby sheet is emplaced. Lopatin type plot for the Twin Creek rocks shows that they reach their maximum temperature (*c.* 190°C) a short time after they are overridden by the Darby sheet. (b) Restored cross-section (based on Royse *et al.* 1975, section YY′) showing pre-erosional extent of the Crawford sheet over rocks from which the Little Muddy Creek conglomerate would be derived (star). The thermal model predicts that these rocks reached a maximum temperature of 130°C shortly after the Crawford sheet was emplaced. (c) Restored cross-section (based on Royse *et al.* 1975, section YY′) showing pre-erosional extent of the Paris–Willard sheet over rocks from which the Echo Canyon conglomerate would be derived (star). According to the thermal model these rocks reached a maximum temperature of about 220° approximately 10 Ma after the Paris sheet was emplaced.

highest temperatures and pressures within the Crawford sheet were reached soon after emplacement of the preceding Meade sheet. The development of cleavage is controlled by pressure solution. The strain rate for pressure solution is proportional to diffusivity and to the solubility of calcite (Rutter 1976, Durney 1972). Diffusivity increases exponentially with increasing temperature. Calcite solubility increases with increasing pressure, but decreases with increasing temperature. Immediately after emplacement of the Meade sheet, a

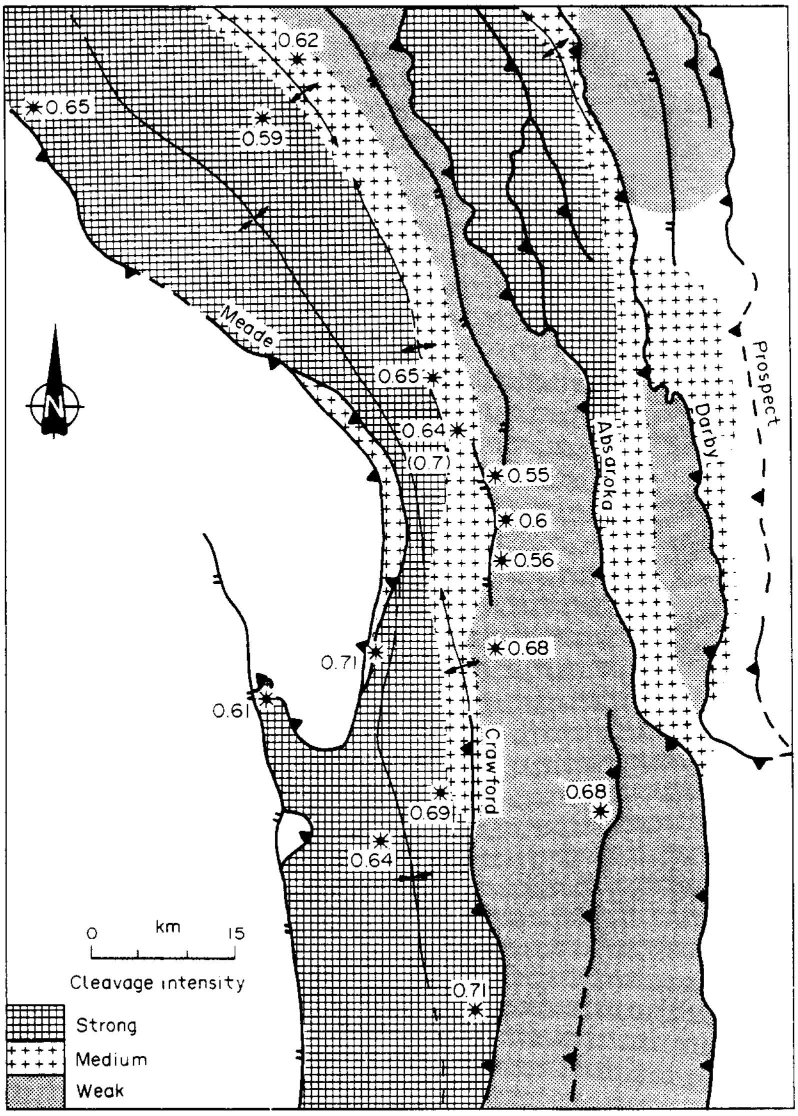

Fig. 6. Map showing degree of cleavage development, and illite breadth values from cleavage seam materials, based on reconnaissance studies for part of the Idaho–Utah–Wyoming thrust belt.

combination of reduced thermal gradients and increased pressure favored calcite solubility and hence pressure solution. At the same time, rising temperature in the footwall from deeper burial increased diffusivity and favored cleavage development. Thus, cleavage probably developed very early in the deformation history of the Crawford sheet, before the isotherms had time to re-equilibrate (Yonkee 1983).

If the emplacement of a thrust sheet does favor pressure solution in the next lower sheet, as suggested by this model along one line of section, then the cleavage should be best developed behind the pre-erosional extent of the preceding thrust sheet. Emplacement of the Meade sheet should therefore have created a cleavage front in the sheets that lie immediately below and in front of it, including the Absaroka sheet in the northern part of the thrust belt, and the Crawford sheet in the southern part of the thrust belt. Regional reconnaissance studies show that cleavage is well developed in a broad area in front of the present Meade thrust-fault trace (Fig. 6). The cleavage front extends close to the estimated pre-erosional extent of the Meade sheet based on balanced cross-sections (Royse *et al.* 1975, pocket cross-section XX′). East of this line, cleavage intensity drops off abruptly.

Initial studies on the section lying in front of the Absaroka and the Darby sheets in the northern part of the Wyoming salient of the thrust belt indicate the same broad patterns. In each thrust sheet well-developed cleavage extends as far as the best estimates of pre-erosional extent of the preceding thrust sheet. Other factors, such as lithology and stresses high enough to start pressure solution, will also influence cleavage development (Marshak & Engelder 1985). North of the Crawford tip, cleavage intensity decreases along with shortening from small-scale folding; these lower strains may reflect lower deviatoric stresses in the area beyond the thrust tip.

Temporal relationships between thrust movement and cleavage development

There is usually not a large time lag between major motion on one fault and start of deformation in the next sheet (Wiltschko & Dorr 1983, fig. 3). Thus, even though the earlier sheet may have been partially eroded, the depressed isotherms may not have fully re-equilibrated by the time the new sheet starts to deform. For the development of strong cleavage a sheet should start deforming soon after the preceding sheet is emplaced while the thermal gradient is still depressed.

Although the best available stratigraphic evidence suggests that the Meade and Crawford thrusts were contemporaneous (Wiltschko & Dorr 1983), structural evidence indicates that the Meade thrust probably preceded the Crawford thrust. The movement on the Crawford thrust can be dated definitely as Middle Coniacian on the basis of the synorogenic Echo Canyon conglomerate. The Meade thrust, on the other hand, has no known synorogenic deposits and can only be dated by cross-cutting relationships as post-Lower Turonian (Wiltschko & Dorr 1983); hence, it may have started to move as much as 5 Ma before the Crawford thrust. In the area east of Bear Lake, Idaho, the southern termination of the Meade thrust lies west of the northern termination of the Crawford thrust in a broad transfer zone (Fig. 1). The geometry of the Meade thrust appers to have been affected by the underlying Crawford thrust (Cressman 1964, Valenti 1980, Wolberg 1983) suggesting that the Meade thrust was emplaced somewhat earlier. The closeness in timing between the Meade and the Crawford thrusts may account for the excellent cleavage development in this part of the Crawford sheet. None of the other major faults studied show such a close association in time.

During progressive deformation, the early formed cleavage may be passively reoriented as the thrust sheet climbs over ramps, or as a result of ramping on underlying sheets. Under certain circumstances, the rotated cleavage may itself be folded and a second, weaker cleavage developed. This is observed in both the Crawford and northern Absaroka thrust sheets and is discussed further in the section on cleavage geometry. A second cleavage can form only if the pressure, temperature and thermal gradient conditions remain favorable for pressure solution of calcite. Thus, the second cleavage may form at any time early in the deformation, perhaps related to ramping of the thrust sheet or to formation of imbricates in its hangingwall. Because no data exist on the exact timing of such events, it is not possible to determine when the second cleavage formed. Perhaps the main synorogenic conglomerates related to the thrusts formed at the time when each sheet ramped up from the basal décollement surface, since this would result in rapid uplift and erosion rates at the toe. If development of the second cleavage was related to such ramping, these conglomerates may give some idea of the time at which the second cleavage formed.

Thrusts may also climb over lateral ramps during their deformation history. This gives rise to cross-folds in the thrust sheet, and a weak cross-cleavage may develop. The Crawford sheet shows excellent examples of cross-folds and cross-kinks that have folded the first cleavage, and have a weak second cleavage parallel to their axial surfaces; these will be discussed further in the section on cleavage geometry.

CLEAVAGE GEOMETRY AND STRUCTURAL RELATIONSHIPS

Cleavage in the Jurassic Twin Creek Formation formed by pressure solution, and therefore developed perpendicular to maximum finite shortening during an increment of deformation. If the overall deformation in a thrust sheet is assumed to take place by inhomogeneous simple shear (with most of the shearing close to the base of the sheet) we might expect cleavage to be asymptotic to the thrust plane. Asymptotic cleavage is observed on small faults (Fig. 2d), but rarely on major faults. The change in orientation of cleavage may take place over a narrow zone above a major fault, and this zone is usually highly deformed and rarely preserved. Thus, in general, cleavage is observed only at a high angle to the major thrusts.

Cleavage is best developed in the Crawford sheet, and in the part of the Absaroka sheet that lies directly east of the Meade thrust. We have studied several excellent sections through these sheets, and these are very instructive in understanding the relationships between cleavage and other structures.

Absaroka sheet

The subsurface geometry of the Absaroka thrust (Dixon 1982) (Fig. 7) on the east side of Star Valley shows that the thrust ramps up from the basal décollement plane to a glide horizon in the Lower Cretaceous rocks before ramping to the surface. The sections described here are presently located above the eastern margin of the first ramp, and were therefore transported over the ramp during major motion on the thrust.

The Swift Creek (Fig. 7, section YY′Y″) and Dry Creek (Fig. 7, section ZZ′Z″) canyon sections near Afton, Wyoming, expose the eastern, steep limb of a synform that is overturned westward; the fold may originally have been upright or overturned to the east, but was passively rotated during ramping and back-thrusting (Royse *et al.* 1975, section XX′). A weak cleavage, extension faults and contraction faults have all been passively rotated. The cleavage is asymptotic to these early faults (Fig. 2d), but is otherwise generally perpendicular to bedding. Locally, the cleavage is refolded into upright folds, with a weak second cleavage formed parallel to the axial plane. Such folds have new contraction and extension faults associated with them (Fig. 2c).

Roadcuts along Salt River (Fig. 7, section XX′) immediately north of Grover, Wyoming, give an oblique section through an inclined synformal kink with a faulted-out axial plane. The east limb dips gently westward and shows refracted cleavage which appears to have resulted from flexural slip during folding. The west limb dips steeply eastward and shows the development

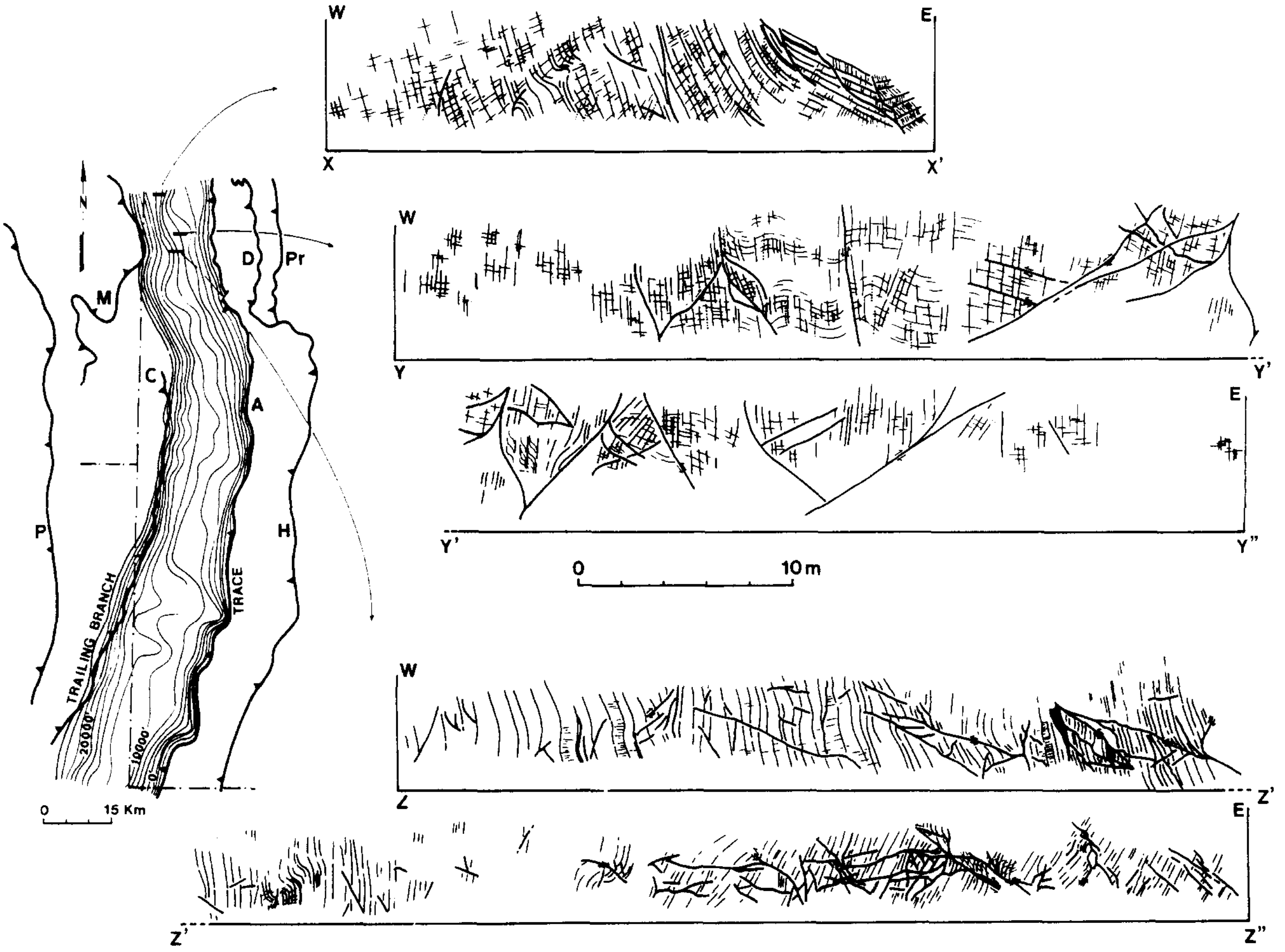

Fig. 7. Structure contour map (left) of part of the Absaroka thrust plane (after Dixon 1982) superposed on a surface map of thrust traces showing locations of detailed sections. The Salt River (XX'), Swift Creek (YY'Y") and Dry Creek (ZZ'Z") sections show details of fault (thick lines)–bedding (medium lines)–cleavage (fine lines) interactions. Folding of cleavage, development of a second cleavage (dotted lines) and reactivation of faults is seen along section YY'. Section ZZ'Z" is presented as a mirror-reflection of the actual roadcut to allow direct comparison of symmetry of structures with sections XX' and YY'Y".

of two cleavages that are perpendicular to bedding but have different trends. Illite breadth values for the two cleavages are different ($\Delta 2\theta = 0.64°$ for the first cleavage, $\Delta 2\theta = 0.7°$ for the weaker second cleavage), indicating that the second cleavage formed at lower temperatures. Both cleavages are strongly fanned about the synform, and may represent successive increments of shortening in slightly different directions during the early deformation of the sheet.

Crawford sheet

The subsurface geometry of the Crawford thrust fault is shown in Fig. 8, derived from a series of cross-sections presented in Dixon (1982). Although the construction of the cross-sections west of the Crawford thrust is highly subjective (Dixon 1982), they are useful for identifying broad structural trends such as major ramps and flats. The Crawford ramps up from the basal décollement plane to the Upper Jurassic or Lower Cretaceous rocks and may glide in these horizons for long distances (up to 20 km) before ramping to the surface. A major lateral ramp can be observed in the northern part of the fault. The sections described here range from those close to the tip line of the fault to those close to the trailing branch line.

A large hangingwall ramp anticline is exposed along Salt Canyon (Fig. 8, section BB'). The fold approximates a double kink, with cleavage that is strongly fanned remaining subperpendicular to bedding at all bedding dips (Yonkee 1983, Mitra *et al.* 1984). Calcite-filled fractures are subparallel to bedding. Cleavage is asymptotic to early, small-scale contraction faults. Mesoscopic and microscopic buckle folds have convergent and divergent cleavage fans in alternate micrite and siltstone layers. Cleavage formed during early shortening concurrently with the small-scale faults and folds. During major motion on the Crawford thrust, this part of the sheet only went over one ramp and the small-scale early formed structures underwent passive rotation.

Immediately north of Cokeville, Wyoming (Fig. 8, section DD'), an upright, N-plunging, isoclinal anticline is exposed (Yonkee 1983). This fold is located somewhat further from the tip line than the Salt Canyon fold. The oolitic Sliderock and Boundary Ridge Members define a single chevron fold with steep limbs, constant bed thick-

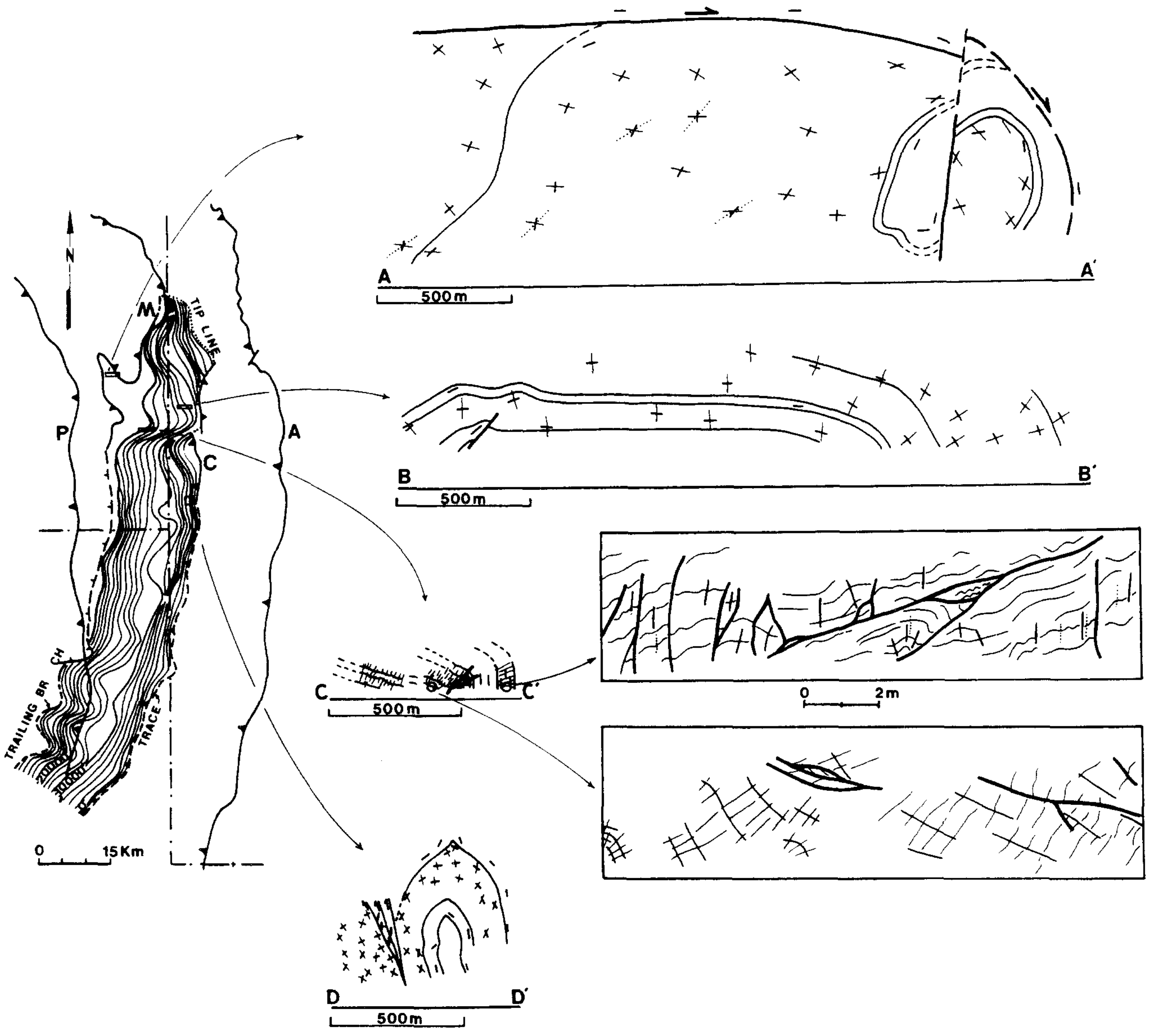

Fig. 8. Structure contour map (left) of the Crawford thrust plane (derived from cross-sections presented in Dixon 1982), superposed on a surface map of thrust traces showing locations of down-plunge projections. The Georgetown Canyon (AA'), Salt Canyon (BB'), Montpelier Canyon (CC'), and Cokeville (DD') sections show relationships between faults (thick lines), bedding (medium lines), cleavage (fine lines) and second cleavage (dotted lines). Details of folding of cleavage in the west and east limbs of the Montpelier Canyon anticline (CC') are also shown.

ness and rare stylolites perpendicular to bedding. The micritic Rich Member defines a fold with class 1C geometry, which shows a partial cleavage fan. The overall fold geometry probably resulted from flexural-slip folding, followed by flattening (Yonkee 1983); during this later flattening, cleavage may have been passively rotated. There is local folding of cleavage that is coaxial with the first fold. There are also cross-kinks developed with prominent stylolites and fracture zones along the axial planes (Fig. 9a).

Sections both parallel to the direction of tectonic transport (E–W) and parallel to strike (N–S) are exposed along Montpelier Canyon, Idaho. The major structure is an overturned kink anticline with a gently dipping west limb and a steep to overturned east limb (Fig. 8, section CC'). Numerous small-scale contraction and extension faults are present. Cleavage is well developed and strongly fanned, always remaining subperpendicular to bedding. In the eastern limb of the fold where cleavage is subhorizontal, the cleavage is folded into upright second folds, and a second cleavage is developed approximately parallel to bedding (Figs. 8 [section CC'] and 9b). On the western limb where cleavage dips steeply and bedding is gently dipping, the second folding has refolded the bedding. A N–S section of the road through this limb illustrates well the cross-folding geometry. There are cross-kink folds with steep E–W trending axial surfaces that affect both the bedding and the first cleavage; a weak second cleavage may form parallel to the axial planes (Fig. 9c). This part of the Crawford sheet was probably folded along early imbricates, and cleavage may have developed very early in the history of movement on the Crawford thrust. The second folds with their associated cleavages probably formed as the thrust sheet ramped up to the Lower Cretaceous glide horizon. The rocks in this area also lie directly above a prominent lateral ramp in the Crawford thrust and motion over this ramp probably produced the cross-folds.

The overturned limb and core of a complex footwall synform that developed during movement on the overlying Meade thrust is exposed along Georgetown Canyon (Fig. 8, section AA′). Here, the Meade thrusts glides through Mississippian limestones in the hangingwall and cuts up through the Jurassic Twin Creek and Preuss formations in the footwall. Cleavage-bedding angles vary from 90° at the syncline hinge to 20° near the thrust where cleavage is better developed. The cleavage was forming and rotating to gentle dips during early simple shear along the Meade thrust. Both the footwall syncline and the thrust were kinked, and cleavage was passively rotated during movement on early imbricates of the Crawford thrust. Such reoriented cleavage may be folded into open folds and conjugate kinks during subsequent shortening of the sheet. A weak second cleavage may also develop and has a very consistent orientation cutting across pre-existing structures.

Summary

The detailed sections through the Crawford and Absaroka sheets show that cleavage developed early in the deformation history of each sheet, soon after the preceding sheet was emplaced. The cleavage formed at high angles to bedding and accommodated early layer-parallel shortening. It may be asymptotic to the thrust plane in a narrow zone immediately above the fault. The cleavage is contemporaneous with small-scale buckle folds and early contraction faults.

During major ramping of the thrust sheet, large-scale ramp folds formed in the hangingwall. This folding passively rotated cleavage into large fans, which are especially well preserved near the tip line of the fault where the hangingwall rocks have undergone a fairly simple motion history (e.g. Fig. 8, BB′). The fan angle may have been somewhat modified by flattening of the folds during later deformation (Fig. 8, DD′).

The hangingwall rocks nearer the trailing branch of the fault (Figs. 7 and 8, CC′) may have moved over more than one ramp, and show evidence of a more complicated deformation history. Cleavage that is suitably reoriented by early folding, may be refolded and a second cleavage may form (Fig. 2c, Fig, 7, YY′, Fig. 8, CC′, Fig. 9b). If the cleaved rocks moved over a lateral ramp (Fig. 8), the cleavage was cross-folded in places, and conjugate fractures and a weak cross-cleavage developed (Fig. 9c). This cross folding may also affect bedding. The trailing edge of a thrust sheet may therefore show complicated structural patterns with several periods of folding, each with its own associated spaced cleavage.

CONCLUSIONS

Detailed studies of structural geometry, combined with palinspastic restorations and thermal modelling, allow us to reach certain conclusions regarding the structural history of thrust sheets and their internal deformation.

Internal shortening of a thrust sheet starts very early in its history, soon after the preceding thrust sheet is emplaced. This shortening is recorded by a spaced cleavage that is formed by pressure solution under pressure–temperature conditions resulting from the emplacement of the overriding hotter sheet.

As the thrust fracture forms and propagates and the thrust sheet starts to move, the deviatoric stresses may decline and pressure solution may stop. As the sheet moves over a ramp, the cleavage may be passively reoriented into the shortening field as bedding gets folded. If the deviatoric stresses build up again during ramping, the reoriented cleavage may become folded, and a second cleavage may develop provided the pressure–temperature conditions are still appropriate. The folding of cleavage may take place on both longitudinal and transverse ramps. Thus, more than one cleavage may develop and successive cleavages may undergo complex reorientation during the emplacement of a single thrust sheet.

On a regional scale, cleavage is developed progressively toward the foreland as successive thrust sheets are emplaced. This sequence of events may not always be recognizable in other thrust belts. If a thrust belt is deeply eroded, 'cleavages' developed in successive thrust sheets may all appear to be one cleavage close to the level of the lowest décollement plane where they are all asymptotic to the sole thrust (Mitra & Elliott 1980). Fanning of spaced cleavage is observed in other thrust belts such as the Appalachians (Gray 1981) and the Alps (Siddans 1977); such passive rotation of pressure solution cleavage may record emplacement of earlier overriding sheets, as shown here for the Idaho–Utah–Wyoming thrust belt.

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