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A cross-section through the Scandinavian Caledonides constructed with the aid of branch-line maps

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Abstract—Fault surfaces have a finite area enclosed by branch- and tip-lines. A tip-line separates the slipped from the unslipped region. A branch-line forms where one fault splays off another and occurs at the trailing or leading ends of thrust sheets and along frontal, oblique and lateral ramps. Hence potentially complicated patterns of branch- and tip-lines outline or surround the fault surface. The branch-lines determine which parts of the fault geometry, off a line of section, can be projected on to the section; help to define the fault movement direction; and identify horses or fragments left behind by the faulting. The technique of analysing branch- and tip-lines is demonstrated on the thrusts of the Trondheim area to derive a more rigorous section which is also constrained by gravimetric, aeromagnetic and metamorphic data. Lateral branch-lines, parallel to the thrust slip-direction, suggest slip vectors between 155 and 165° (SE) for three of the thrusts. Horses, left behind by the thrusts, suggest minimum displacements of 50 and 100 km for two of these thrusts.

INTRODUCTION

THRUST faults are surfaces of finite extent which are bounded or framed by a line that can be described as a branch-line, a tip-line or a combination of both. These lines may intersect the ground surface to produce characteristic outcrop patterns which can be recognized on a geological map. Once identified, they are useful to the geologist constructing a cross-section because they allow a more rigorous approach to be taken. The outcrop of the fault can be used to position the fault on the section but the tip- and branch-lines can be used to position the fault in the air or underground in the section. Hence, a more complete description of fault attitude and length of fault trace in the section is possible. Moreover the branch-line pattern will determine whether a particular thrust or thrust sheet can be projected along-strike into the line of the cross-section. I have found that branch-lines are particularly valuable in section construction in the Scandinavian Caledonides, and in this paper their use in a cross-section through the Trondheim nappes, originally drawn by Roberts & Wolff (1981) is demonstrated.

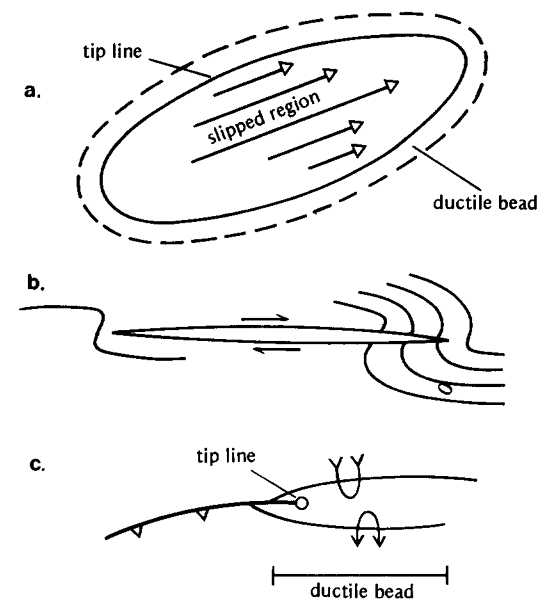

Fig. 1. (a) A Somigliana dislocation surrounded by a tip-line and a ductile bead. The slipped region of the fault is contained within the tip-line. (b) Cross-section through a Somigliana dislocation with an anticline–syncline pair forming a ductile bead beyond the tip-line. (c) Outcrop pattern of a tip-line in the Canadian Rockies (after Elliott 1976).

TIP-LINES

Isolated faults can be described mathematically as Somigliana dislocations (Eshelby 1972) and are similar to crystal dislocations. The fault can be conceived as a penny-shaped crack within a closed boundary line. Elliott (1976) described the geometric form of the boundary line, equivalent to the edge of a Somigliana dislocation, which occurs at the ends of thrust faults, and subsequently he named it a tip-line (Boyer & Elliott 1982). Within a closed tip-line, both sides of the dislocation or fault have slipped relative to one another but outside the tip-line the material retains its cohesion and has not slipped (Fig. 1). The fault is generated at a point and grows by increasing its area within the tip-line. Hence, the tip-line lengthens and migrates through the deforming rock. Across the tip-line the slip on the fault has to decrease to zero but it is likely that strain compatibility requires the loss of slip to be smeared out across a zone which may extend beyond the tip. Elliott (1976) showed that a ductile zone of non-cylindrical folding lies ahead of the tip-line in thrust faults in the Canadian Rockies (Figs. 1b & c), and Cooper *et al.* (1982, 1983) showed that a ductile zone of layer-parallel shortening may have moved ahead of thrusts in the Hercynian inlier of the Boulonnais. Hence it is suggested (Fig. 1), that an isolated thrust fault is bounded by a tip-line with a ductile bead outside it, which has been propagating ahead of the thrust. If the tip-line intersects the ground surface or is breached by later erosion it will result in an outcrop pattern such at that illustrated in Fig. 1(c), but the underground portions of the line will be more difficult to identify.

However, isolated thrust faults of this type are either rare or non-existent in nature. In reality, thrust faults form a branching or imbricate network (Bally *et al.* 1966, Boyer & Elliott 1982) within which the faults divide and splay. Hence another possible boundary around part or all of a fault is the line of merger between the faults called a branch-line (Boyer & Elliott 1982).

BRANCH-LINES

The simplest branch-line is formed in an imbricate stack where a younger thrust splays off the footwall of a higher and older thrust (Fig. 2). The origin of these splays is controlled by the timing of thrusting and the step-like character of thrusts (Rich 1934, Dahlstrom 1970). Thrusts can climb up steps or ramps in the direction of motion and in most mountain belts it is an axiom that the higher thrusts are older. Younger thrusts then form by branching off the footwall ramp of a higher thrust (Fig. 2b). Because the branch-line forms at the trailing end of the lower thrust sheet (Dahlstrom 1970) it is called in this account a trailing branch-line. Such lines follow closely the shape of the original footwall ramp and mark a line that originally lay in the ramp. Figure 2 has been drawn so that the younger splay dies out upwards into a tip-line. Hence, in this instance part of the Somigliana boundary is a tip-line and part is a branch-line. Depending on the erosion level, the splay thrust will be seen to be completely separate or joined to the higher thrust at one or both ends (the isolated splay, the diverging splay and the rejoining splay, respectively, Boyer & Elliott 1982). The point on the map where the two thrusts merge is where a branch-line intersects the ground surface.

Thrust ramp structures, however, can display more complicated patterns than the simple example illustrated in Fig. 2, and will produce more complicated trailing branch-line geometries. Thrusts can climb up-section along-strike as well as in the movement direction to form frontal, lateral and oblique ramps (Elliott pers. comm.) (Fig. 3). A frontal ramp is normal to the movement direction, a lateral ramp is parallel to the movement, and an oblique ramp is in an oblique direction. If a younger, lower splay thrust branches off a footwall ramp with a complicated structure (Fig. 3), the trailing branch-line will have a zigzag map pattern (Fig. 3b). In this example the rest of the Somigliana dislocation boundary has again been defined by a tip-line.

Finally, it is possible for splay thrusts to rejoin the higher thrust at their leading end to form a leading branch-line (Fig. 4). Such rejoining faults form 'horses' (Elliott & Johnson 1980) and the Somigliana boundary of the horse is completely outlined by leading and trailing branch-lines. The tip-line of the Somigliana geometry has finally disappeared. It is also possible for the leading branch-line to have a zigzag map pattern because of frontal, lateral and oblique ramps.

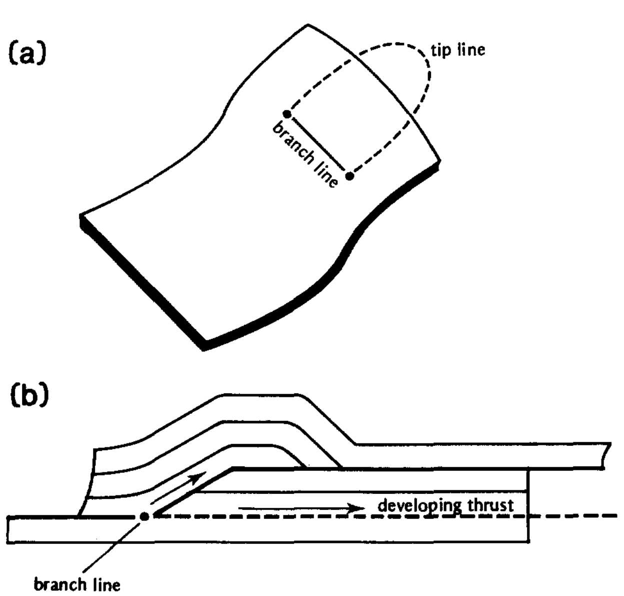

Fig. 2. (a) Splay thrust with a trailing branch-line and a leading tip-line. (b) Cross-section through a branch-line (after Dahlstrom 1970).

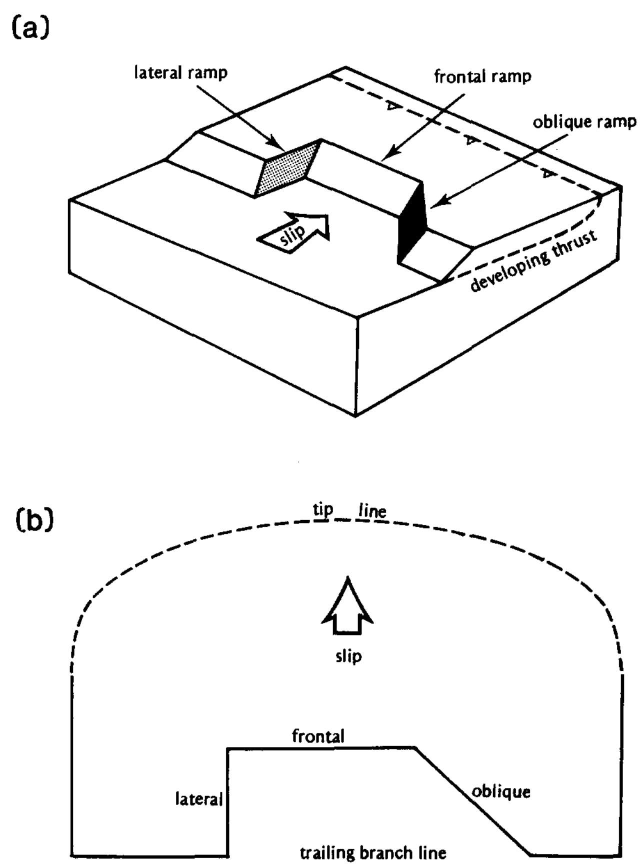

Fig. 3. (a) Footwall ramp with lateral, oblique and frontal ramps in different orientations relative to the slip direction. (b) Plan view of a Somigliana boundary around a thrust with a trailing branch-line formed from lateral, oblique and frontal ramps.

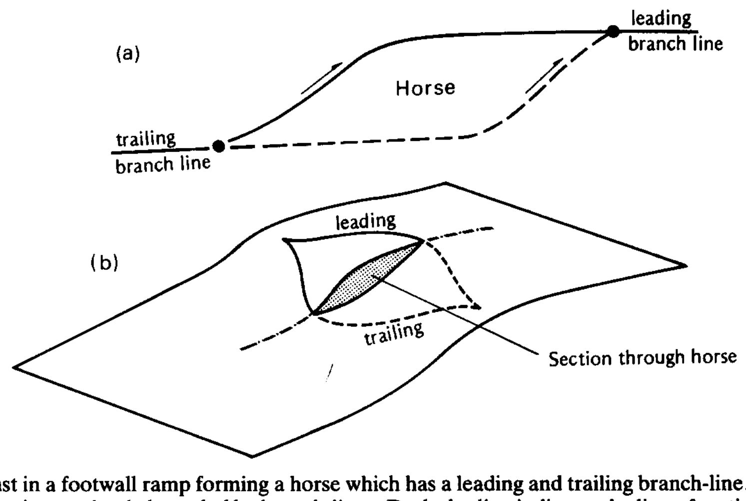

Fig. 4. (a) Rejoining splay thrust in a footwall ramp forming a horse which has a leading and trailing branch-line. (b) The Somigliana boundary of the splay thrust is completely bounded by branch-lines. Dash-dot line indicates the line of section shown in (a).

BRANCH-LINE MAPS IN THE SCANDINAVIAN CALEDONIDES

I have not yet found any map patterns of exposed tip-lines in the Scandinavian Caledonides. However, there are many examples of maps which display merging thrusts or branch-lines and I have found these lines useful when constructing geological cross-sections. Firstly, points are marked on the map where the thrust at the base of any reference sheet meets or joins a higher thrust. These points represent the intersection of the reference branch-line with the ground surface. Then a line is drawn through these points so that it encloses any outcrops of the reference thrust sheet in klippen or windows. Elliott & Johnson (1980) were the first authors to formally draw branch-line maps and made a useful distinction between areas where the branch-lines have been eroded, and hence are now up-in-the-air, from areas containing lines which are buried. The technique of drawing branch-line maps is identical to the construction of subcrop maps beneath unconformities. The branch-line is the structural equivalent of a zero isopath, and within the line the reference thrust sheet either occurs in sub- or outcrop. I have found it convenient to mark the outcrop side of the branch-line with a tick. The reference thrust sheet will not occur on any cross-section on the other side of the line. Hence, if any branch-line lies completely outside the line of a cross-section and does not intersect it, the thrust sheet within the branch-line cannot appear in the section. A branch-line map should always be prepared before a cross-section is constructed and balanced, because this map provides the information from which it is possible to decide if the geology can be projected along-strike on to the section.

Zachrisson (1973) anticipated the construction of such maps (Fig. 5). He illustrated a trailing branch-line to the Seve thrust sheet and differentiated the exposed and buried portions of the sheet and the western limit (or trailing branch-line) of the Seve thrust. He was able to use the presence or absence of the Seve thrust sheet in a series of windows to define closely the the subcrop

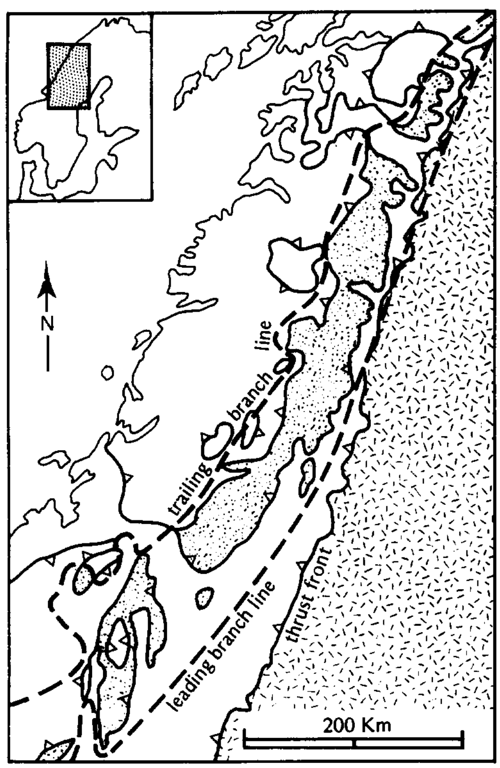

Fig. 5. Map of branch-lines of the Seve thrust, mainly after Zachrisson (1973). Inset-location map. Stipple, Seve thrust sheet; random dashes, Precambrian basement.

portion of the sheet. This branch-line is an enormous structure which extends for over 800 km from northeast to southwest through the Scandinavian Caledonides, and outlines an original footwall ramp of identical dimensions.

A more detailed map (Fig. 6) shows the continuation of the Seve trailing branch-line through the Trondheim nappes. To construct this map I used the geological map of Roberts & Wolff (1981) and extended it into Sweden to the thrust front (Fig. 7), using the preliminary copy of the 1:1,000,000 I.G.C.P. Tectonostratigraphic Map of Scandinavia (Roberts *et al.* in prep.). The interested

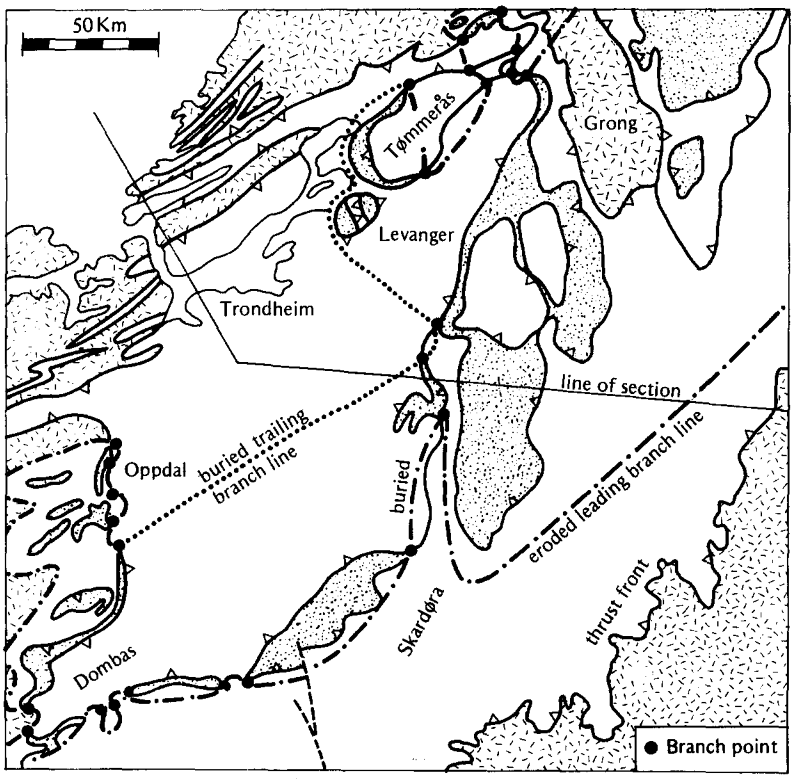

Fig. 6. Detailed map of the Seve branch-lines in the Trondheim area. The buried and eroded portions are distinguished and the outcrop of the Seve thrust sheet is shown by stippling. Precambrian basement is shown by random dashes.

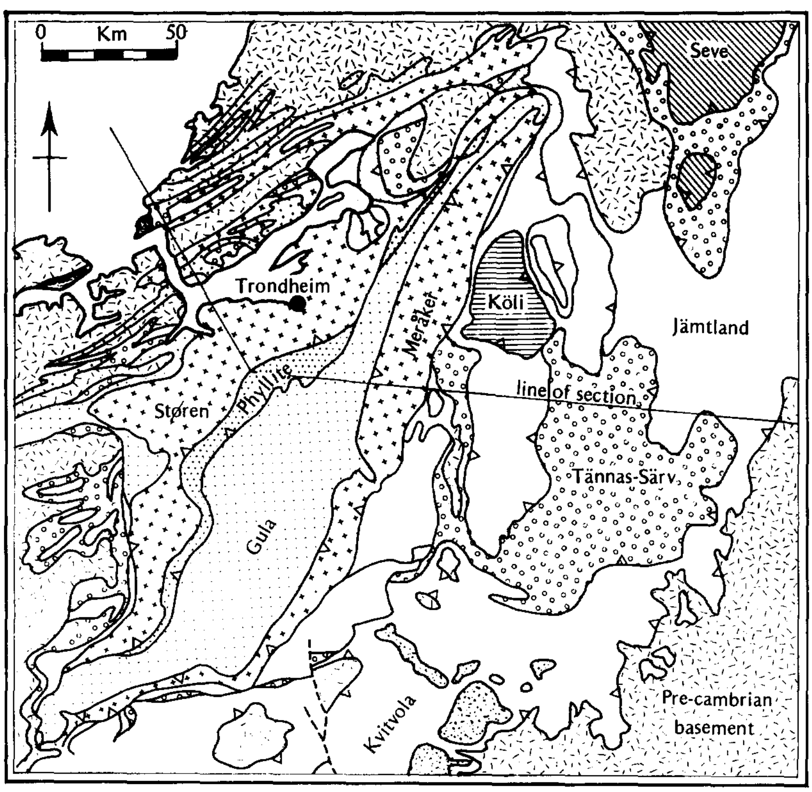

Fig. 7. Geological map of the area between the thrust front and Trondheim (Roberts & Wolff 1981, Roberts *et al.* in prep.). The line of section shown in Fig. 10 is indicated.

reader can find descriptions of the rock units in each of the thrust sheets in Gee (1975) and Roberts & Wolff (1981).

The trailing branch-line of the Seve thrust (Fig. 6) is drawn with a complicated salient pattern on the southwest side of the Grong window to pass through nine very closely spaced branch points. It then continues to the south of the Tømmerås window and cuts back across the window following a lateral branch-line to form another salient in the southwest of that window. From there the line is buried around the Levanger window but it must trend to the south to pass through two branch points at the north end of the Skardøra window (H. Sjöstrom in prep.), formerly the Sylarna or Riksgrensen anticline. To the southwest there is another buried portion of the line as far as Oppdal where it bends northwards into a salient defined by five points. The eroded portion on the other side of the salient cannot be fixed properly, but is known to be folded about the Oppdal folds (Krill 1980) before it reaches the two trailing branch points at Dombås.

There is a leading branch-line to the Seve thrust making the Seve sheet, at least at its southwest end, an enormous horse. The line is defined by a few points to the southeast of Dombås (Fig. 6), and it then continues northeastwards in and out of the Skardøra window to pass into an undefined, eroded leading branch-line between the Seve thrust and the thrust front (Figs. 5 and 6).

Branch-line maps are also presented for the other thrusts shown in Fig. 7. The Jämtland thrust (Fig. 8a) is the lowest in the section and forms the main thrust front. It has a simple trailing branch-line formed from a footwall ramp which has an offset on a possible lateral branch-line on the southwest side of the Grong window. This line trends 165° (SE) and may define the slip direction for the thrust. The Tännas–Särv thrust sheet lies above (Fig. 8b). This sheet is identical to the middle allochthon of Gee (1978) and includes the Tännas Nappe, the Särv Nappe and the Offerdal Nappe. However, published maps make no clear separation between the Tännas and the Offerdal Nappes so I have combined them. Also the Särv Nappe, consisting of late Precambrian sediments, is separated from older Tännas gneisses beneath it by a thick mylonite zone. This zone clearly poses a problem because younger rocks have glided above older. Either the mylonites represent a décollement or detachment zone following an original unconformity, or out-of-sequence thrusting has occurred. Because I cannot distinguish between these two possibilities, I have simplified the map pattern and included all three nappes in a single thrust sheet (Fig. 8b). Hence, the derived branch-line pattern must be considered as an interim statement until more detailed maps are available.

The Tännas–Särv thrust sheet is enclosed between trailing and leading branch-lines, forming a huge horse. Between Grong and Tømmerås there is a large square re-entrant in the trailing branch-line made up of two mirror-image lateral ramps connected by a frontal ramp. Following the rules of Elliott & Johnson (1980) that the thrust slip vector must always cut up-section across a thrust ramp and can never cut down-section, the slip vector is uniquely defined. It must be parallel to the two mirror-image lateral ramps or branch-lines. In any other direction it would cut down-section across one or other of the ramps. The slip vector defined by this method is towards 155° (SE): this direction was measured from the detailed map of Peacey (1964) which shows the best defined part of the southern lateral branch-line in the Tømmeras window.

A small isolated lens of Tännas–Särv occurs at Turtbakktjørna (T in Fig. 8b and see Fig. 9) (Kautsky 1978). This structure has been interpreted as a megaboudin produced by stretching of the thrust sheets after their emplacement (Gee 1978, 1982, Andreasson *et al.* 1978). These authors describe major changes in thickness across strike which they interpret as pinch-and-swell structures. They believe that in extreme cases of stretching, thrust sheets can be disrupted into separate lenses. However, this pinch-and-swell appearance could also be produced by drawing cross-sections which cut across lateral and oblique ramps so that the apparent changes in thickness of the thrust sheets are due to the basal thrust climbing up and down section along strike (Dahlstrom 1970). These ramps could appear in oblique view in the cross-section.

The Turtbakktjørna lens (Fig. 9a) can be interpreted in several ways. It could be a megaboudin (Gee 1982), a horse (Elliott & Johnson 1980) or an emergent imbricate fan (Boyer & Elliott 1982). Unfortunately, the branch-line pattern of the lens cannot distinguish between these three models and other structural criteria have to be used. However, at Turtbakktjørna there is an internal strain grid in the form of intersecting dykes and bedding which in plan view does not appear to have suffered much internal deformation. Hence, I believe that an origin by boudinage is unlikely. Because of the tectonic depth of burial and the observation that there are several higher thrusts, the emergent imbricate fan model is unlikely. I prefer to view the structure as a horse, that is a lens-like block plucked from a footwall ramp during thrusting and carried along by the overlying thrust (Elliott & Johnson 1980). The Turtbakktjørna lens lies 100 km behind the trailing branch-line of the square re-entrant (Fig. 8b) and, if it is a horse, this value is the minimum displacement distance for the Tännas–Särv thrust.

Andreasson *et al.* (1978) described the lunate outcrop of the Tännas–Särv rocks at the southwest end of the Tømmerås window (Figs. 7 and 8) as another megaboudin. I have chosen to include it within the main part of the Tännas–Särv thrust sheet and explain its sudden truncation on both sides of the window by a lateral branch-line crossing the window, rather than as a boudin.

The Seve trailing branch-line with its re-entrants and salients formed by lateral and frontal ramps has already been described (Figs. 6 and 8c). Because the lateral ramps are mirror-image structures on each side of the

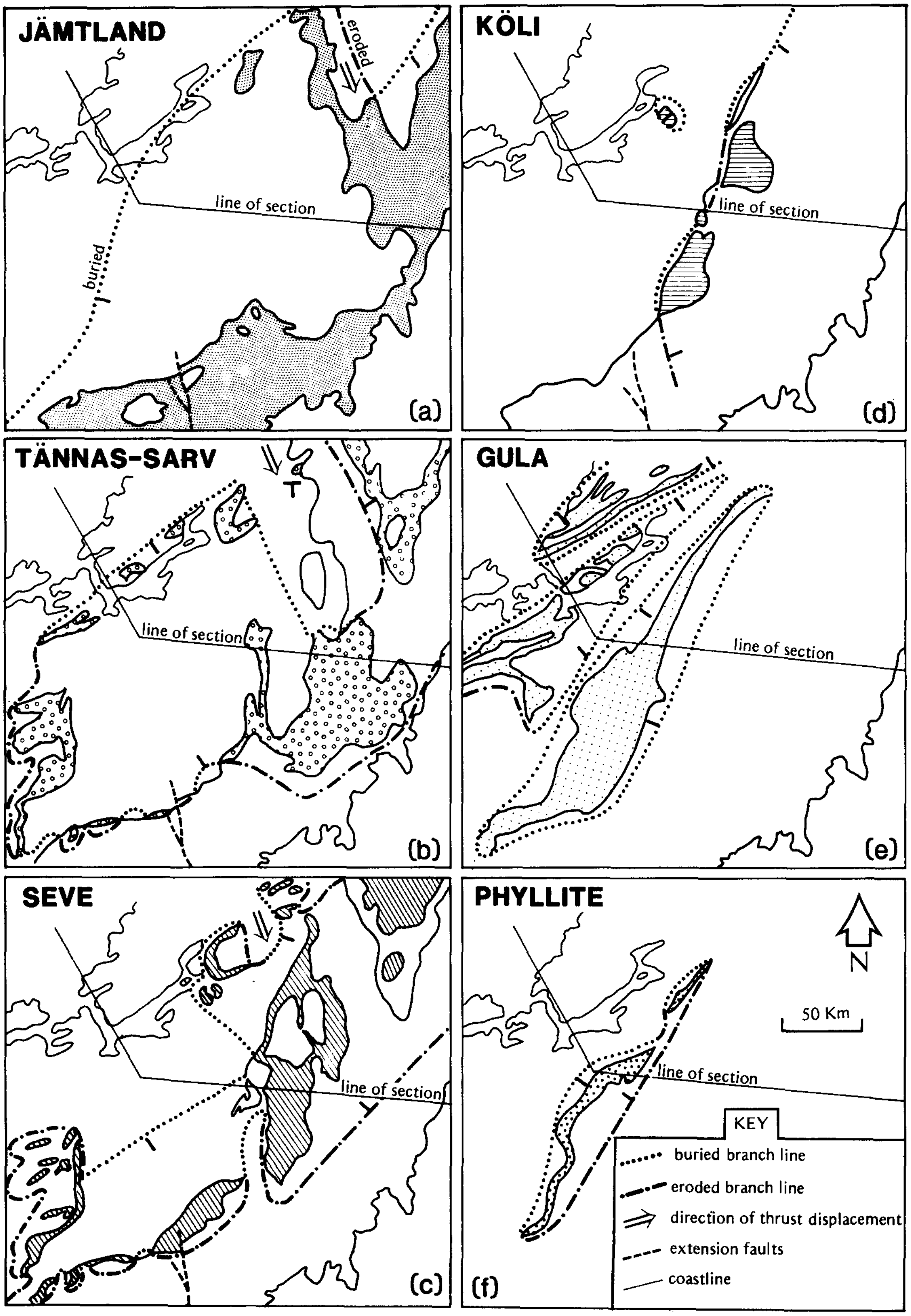

Fig. 8. (a–f) Branch-line maps. The outcrop of each reference thrust sheet is stippled. The ticks mark the outcrop-subcrop side of the branch-line Double arrow, thrust slip direction; T, Turtbakktjørna.

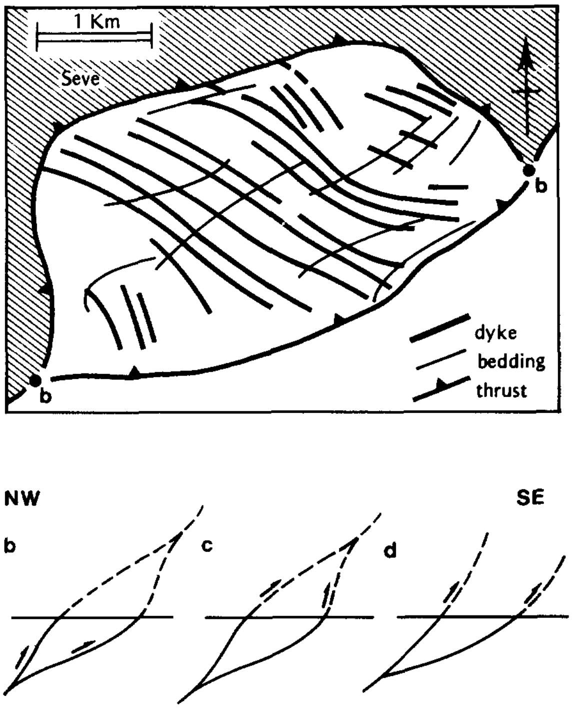

Fig. 9. (a) Map of the Turtbakktjørna lens of Tännas–Särv rocks showing form lines of dykes and bedding (after Kautsky 1978). b and b′ are the branch-points of the enclosing boundary. (b)–(d)—Sketch NW–SE sections through the lens showing structural interpretations of the lens as a megaboudin, a horse and an emergent imbricate fan.

re-entrant, a slip direction is closely defined for the thrust using the rules of Elliott & Johnson (1980). A vector of 160° (SE) seems appropriate.

The Köli thrust (Fig. 8d) has a simple trailing branch-line. However, there is one complication. There is an isolated lens of Köli rocks in the Levanger window which I also interpret as a horse separated from the main thrust. This horse is 50 km behind the trailing branch-line suggesting that this is the minimum displacement on the Köli thrust.

The Gula Schist Group (Roberts & Wolff 1981) lies within three isolated closed branch-lines in the form of three separate horses (Fig. 8a). The southeastern branch-line forms the core of the mushroom structure described by Roberts & Wolff (1981). But there are two closed branch-line loops containing Gula rocks between the mushroom core and the west coast of Norway. If the stratigraphic correlations are correct and these are all one rock sequence, then the original geometry must have been severely disrupted during thrusting.

The Phyllite outcrop (Fig. 8f) has previously been interpreted as part of the Støren thrust sheet (Roberts 1980, Wolff 1976, 1979). However, Horne (1979) interprets the phyllites as a mélange which is distinct from all the other thrust sheets and this geometry is followed here. The unit has a simple enclosed branch-line in the form of a horse.

The Støren and Meråker thrust sheets (Fig. 7), which contain fossils of American affinity, are composed of sea-floor volcanic and sedimentary rocks. They have been correlated stratigraphically and structurally (Roberts & Wolff 1981) and combined into the Støren–Meråker Nappe whereas other authors (Gee 1975) consider them to be two separate thrust sheets. I prefer the latter view. Although they are composed of the same rocks and might have been originally adjacent to each other, they are now separated by a branch-line (seen as two branch points at the north and south ends of the Gula Schist Group) (Fig. 7). Hence, they are drawn on the subsequent section as two different thrust sheets. I continue to use the terminology of Roberts & Wolff (1981) and refer to them as the Støren and Meråker thrust sheets. It is not possible to draw any branch-lines for the Støren thrust because there are no higher thrusts preserved in the section.

THE GEOLOGICAL CROSS-SECTION

Roberts & Wolff (1981) presented several cross-sections through the Trondheim thrust sheets. They were able to use aeromagnetic and Bouguer anomalies to model the depth to basement in the sections. They found that the thrusts are disposed in a large synclinal structure (Fig. 10a) which extends down to 12 km below sea-level in the centre of the region. The underlying Precambrian basement rises to both the east to crop out in the foreland and to the west to crop out in the coastal region of Norway. The sole thrust has been folded in the west so that basement gneisses are exposed in the anticlinal cores. I have used the same line of section (B–B′ in fig. 1, Roberts & Wolff 1981) so that I can follow the constraints of their aeromagnetic and Bouguer anomaly modelling. Unfortunately, because this section crosses lateral ramps and the slip direction, it is not capable of being balanced.

The branch-lines were laid off on the new section (Fig. 10b) along with the surface outcrops of the thrusts. At any one branch-line position on the section, the reference thrust sheet will exist on one side of the line but not on the other. Also at that position the reference thrust will merge with the thrust above. Both buried and eroded branch-lines were used so that a more rigorous estimate of the length of thrust trace in the section could be made. The new pattern leads to a different cross-section (Fig. 10b). For instance, I have had to extend the Jämtland and Tännas–Särv thrusts much farther to the west. I have followed a different interpretation for the structure of the Gula Schists. Guezou (1978) has described the southwestern area of the Trondheim thrust sheets around Dombås. There he has mapped four major thrust sheets within the Gula outcrop. I suggest that the Gula Schists form a major hinterland-dipping duplex (the term hindward for the sense of direction towards a hinterland was introduced by Boyer & Elliott 1982) at depth. The imbricate thrusts of Guezou probably splay off a sole thrust at the base of the Gula Schists and meet a roof thrust beneath the Støren and Meråker thrust sheets. This roof thrust corresponds to the major obduction surface that carried the oceanic crust of the Støren and Meråker sheets over the thrust sheets of the

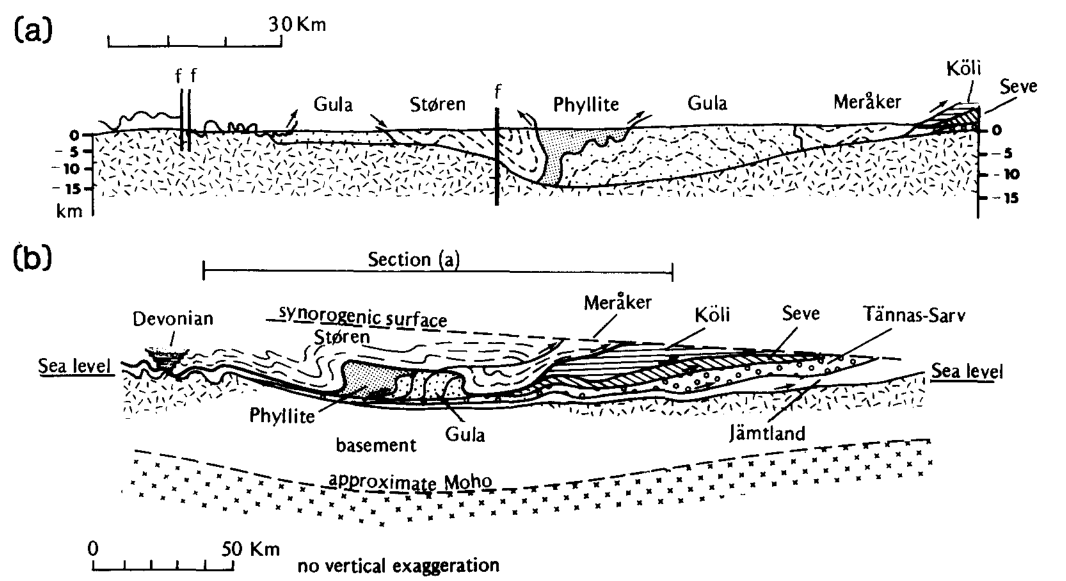

Fig. 10. (a) Section B–B′ (fig. 2, Roberts & Wolff 1981). Depth to basement modelled by aeromagnetic and Bouguer anomalies. (b) New cross-section along the same line constructed from branch-lines. The syn-orogenic surface is modelled on the metamorphic data of Andreasson & Gorbatschev (1980) and Bergstrom (1980), and the depth to the *Moho* is from Sellevoll (1973). Scale of section (b) twice that of section (a).

Baltic shield (Gale & Roberts 1974). I also utilized the metamorphic data (Andreasson & Gorbatschev 1980, Bergström 1980) to reconstruct a syn-orogenic surface in the section (Fig. 10b). It was assumed that most of the major thrusts reached this surface. However, the Seve and the Tännas–Särv thrusts have to meet the Köli thrust in leading branch-lines near the foreland (Fig. 8). Finally, I have drawn an approximate depth to the *Moho* using the data of Sellevoll (1973). The *Moho* is deepest beneath the centre of the Tronheim thrust sheets and rises towards the coastal area of Norway. On the coast at Hitra and Ørland (Siedlecka & Siedlecki 1972) Downtonian post-orogenic sediments rest directly on Precambrian basement beneath the folded sole thrust (Fig. 10b). There is an obvious relationshhip between the position of the Devonian basins and the depth to the *Moho*. Over 20 km of cover thrust sheets must have existed at one time over the sole thrust at this position, and have been removed between the end of orogenesis in the mid-Silurian–Downtonian. This represents an average uplift rate of 1 mm year^{-1} and was probably caused by crustal stretching and mantle uplift at the trailing ends of the Caledonian thrust sheets This uplift continued in the Mesozoic and Tertiary during the formation of the off-shore Viking graben (Ziegler 1981).

CONCLUSIONS

Branch-line maps are an important tool for geologists constructing cross-sections in areas with extension and contraction faults. Although I have demonstrated their use in a thrust belt, similar geometric relations must exist in the branch-lines of extension faults. They allow surface geology to be transferred more rigorously on to a cross-section. However, the branch-line patterns obtained are dependent on the fault and lithotectonic correlations made on the map. If the correlations change, so will the branch-line patterns. The branch-lines presented here for the thrusts of the Trondheim area are based on the map of Roberts & Wolff (1981). Gee (1975, 1978, pers. comm.) presents some different correlations and obviously there is still no complete agreement on correlations through the Trondheim section. It is likely that because of future work and changes in correlations the branch-line geometry may have to be revised and changed.

These branch-lines also give useful information on the amount and direction of fault slip. Branch-lines forming beneath thrust sheets composed of major alternations of competent and incompetent strata are likely to have complicated map patterns. These arise from the stratigraphic control on the position of frontal, lateral and oblique footwall ramps. Mirror image lateral branch-lines facing each other are particularly useful because they identify the slip direction. Small lenses or horses of a reference thrust sheet lying behind the trailing branch-line of the same sheet can give minimum estimates of amount of slip because they have effectively been left behind during thrust emplacement. Three of the thrusts of the Trondheim area, the Jämtland, the Tännas–Särv and Seve, respectively, have lateral branch-lines suggesting a slip direction towards 155–165° (SE). The Tännas–Särv has moved at least 100 km in this direction and the Köli thrust by at least 50 km.

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