INDIRECT EVIDENCE FOR TRANSCURRENT FAULTING AND SOME EXAMPLES FROM NEW ZEALAND AND THE NETHERLANDS

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INTRODUCTION

Normally only lateral offset of a reference line or surface is regarded as evidence of transcurrent faulting. Subsequent abrading, aggradation, volcanic activity or rapid erosion of a loose cover of ash or pumice can destroy or mask this direct evidence so that other features must be evaluated as evidence for transcurrent faulting.

One of the authors (LENSEN, 1958 d) explained the formation of horsts and grabens associated with dominantly transcurrent faulting. The present paper gives an extension of the mechanism already proposed. Several features, which can be regarded as indirect evidences for transcurrent faulting, are dealt with and examples are given, mainly from New Zealand and the Netherlands.

The theory of horst and graben formation, as treated in the above-mentioned paper of the second author, is summarised below.

HORST AND GRABEN FORMATION

ANDERSON (1942) considered faults to be controlled by stress in the earth's crust and defined the type of fault in relation to one of the three stress components, the Principal Horizontal Stress (P.H.S.). It is considered that any transcurrent fault at an angle other than 45° to the P.H.S. possesses a normal or reverse component if it strikes at angles less or greater, respectively, than 45° to the P.H.S. (LENSEN, 1958 a, b, c).

The theory of transcurrent fault grabens is based on the assumption that the friction along the plane of a reverse fault (compressional) is greater than that along the plane of a normal fault (tensional). Within the same stress system the friction decreases in magnitude from reverse faults through transcurrent faults to normal faults.

MECHANICS

The clockwise (dextral) transcurrent fault in figure 1 strikes at 60° to the P.H.S. direction and has a reverse component (a reverse component is not necessary; it is used here only to simplify the explanation). This fault bifurcates, the transcurrent branch fault strikes at 30° to the P.H.S. direction and has a normal component.

The fault system divides the area into three blocks, A, B and C, as shown in figure 1. Consider clockwise lateral movement of block A relative to block B. The friction between blocks A and C (reverse component) will be greater than that between blocks C and B (normal component), so that blocks A and C move together relative to block B

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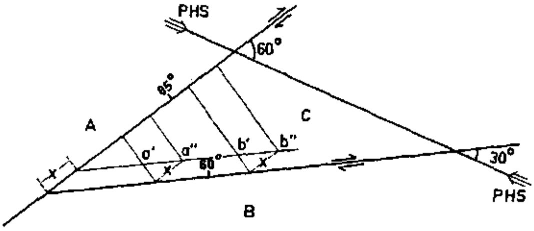


Fig. 1. Displacement mechanism for graben (in plan)

over a distance x. Two reference lines of lengths a and b in block C will be displaced from positions a′ and b′ to a″ and b″ relative to block B. Theoretically, a gap between blocks C and B would result.

Vertical cross sections through the reference lines a and b in block C (fig. 2) show the position of the wedges a′ and b′ after lateral displacement. As the distances across block C at a″ and b″ are greater than at positions a′ and b′, the wedge (block C) will subside.

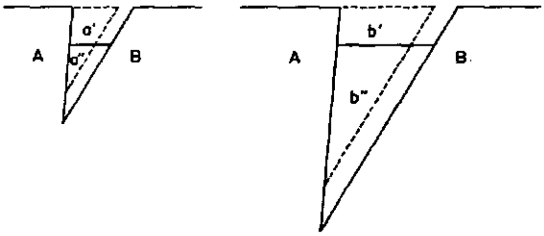


Fig. 2. Displacement mechanism for graben (in section across faults)

A cross section through the line of intersection of both fault planes (fig. 3) shows the position of the block between the two reference lines a and b before and after lateral displacement and subsidence took place.

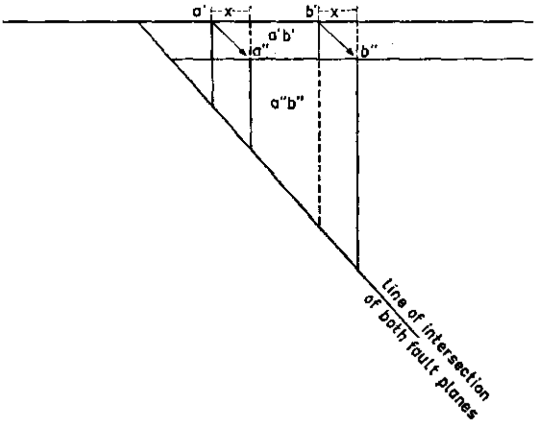


Fig. 3. Displacement mechanism for graben (in section along faults)

Repeated lateral displacement will cause repeated subsidence, resulting in a pronounced graben. The same mechanics can be applied to show that lateral displace-

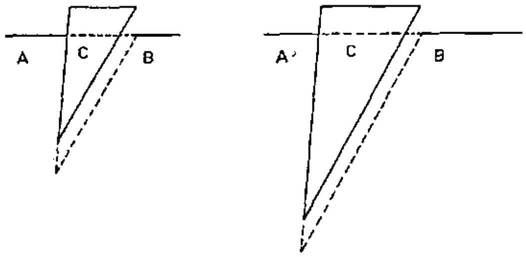


Fig. 4. Displacement mechanism for horst (in section)

ment can result in elevation and horsts. By reversing the sense of lateral displacement in figure 1, the wedge C will rise (fig. 4).

A transcurrent fault which bifurcates and joins again (fig. 5 and 6) results in a graben and a horst linked by a stable block.

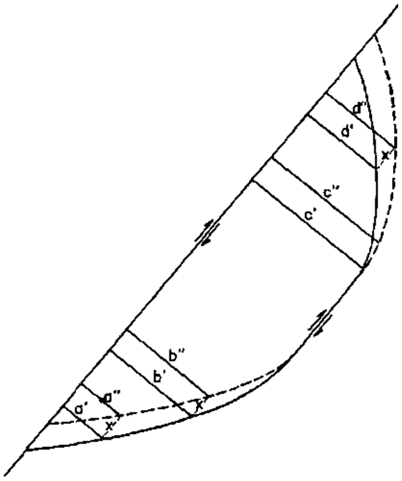


Fig. 5. Displacement mechanism for horst and graben (in plan)

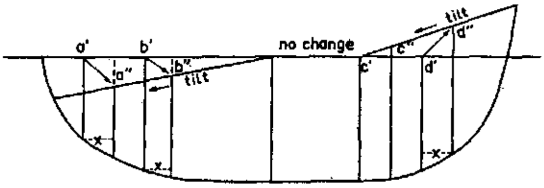


Fig. 6. Displacement mechanism for horst and graben (in section)

An example is shown in figure 7, which is part of the geological map of the Eglinton Valley in the southwest of the South Island of New Zealand (after Grindley, 1958).

The Hollyford Fault bifurcates into the Mackay and Countess Faults which join again further south. The northern part of the enclosed wedge is a graben filled with sediments of Arnold (Eocene) age, while the rock bounding this graben is Permian in age. The southern part of this wedge forms a horst consisting of rocks of Permian age, flanked by sediments of Arnold and Landon (Oligocene) age outside the wedge.

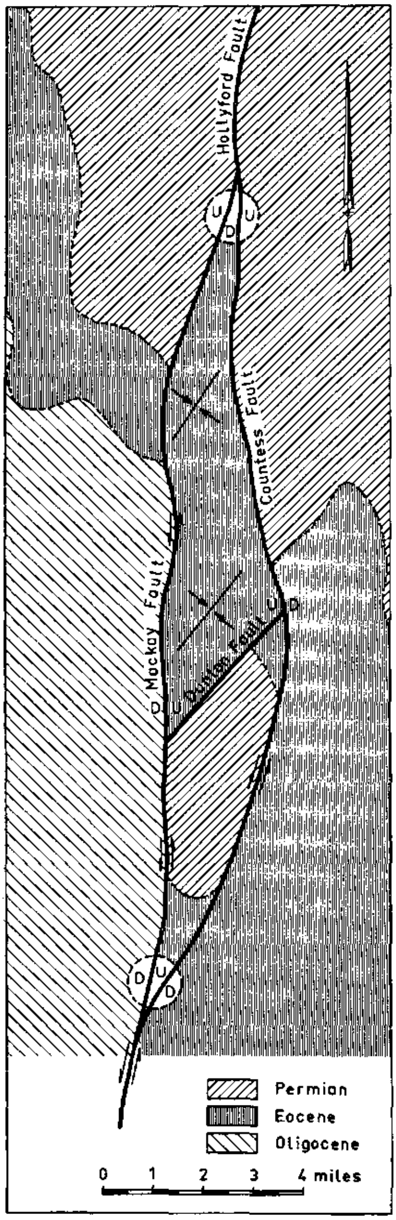


FIG. 7. GEOLOGICAL MAP OF THE EGLINTON VALLEY, SOUTH ISLAND, NEW ZEALAND (after Grindley, 1958)

The faults are anti-clockwise transcurrent and for part of their length have been active since Last Glaciation. Synclinal folds in the Eocene sediments suggest a NW-SE Principal Horizontal Stress (P.H.S.) direction in accordance with the anticlock-wise character of the faults.

Another example is shown in figure 8, which is part of the fracture pattern of the Peel region in the southeastern Netherlands, as published recently by one of the authors (De RIDDER, 1959). The map has been brought up to date in accordance with some additional data.

The fault system of the Peel region forms part of the extensive fault system of the Lower-Rhine embayment and is dissected by several SE-NW striking faults. This fault system probably originated at the end of the Permian and had a period of maximum activity during the Late Cimerian (between the Lower Jurassic and the Cretaceous) and another period of activity in the Upper Tertiary (DE SITTER, 1949). Some of the major faults of the Peel region have even been active during the Quaternary, as has been demonstrated by ZONNEVELD (1947) and DE RIDDER (1959).

One of the most striking features of the fault pattern are the bifurcations. The Peel-boundary Fault can be cited as an exemple of this bifurcation.

Near the village of Neer the Meyel Fault bifurcates from the Peel-boundary Fault and joins the main fault again near Meyel, further to the northwest. Bifurcations from this fault are also known near Deurne (Milheeze Fault) and in the south (Meinweg Fault). In comparing the fracture pattern of the Peel region with that of New Zealand (Geological map of New Zealand, 1:63,360, Sheet N 85, Waiotapu, GRINDLEY, 1959; and figures 7 and 11), a striking similarity appears to exist.

The Meyel horst, enclosed between the Meyel Fault and the Peel-boundary Fault, forms a small horst consisting of sediments of Miocene age, overlain by the Veghel formation (Upper Pleistocene). Outside this horst, these sediments occur at greater to much greater depth (DE RIDDER, 1959, section B).

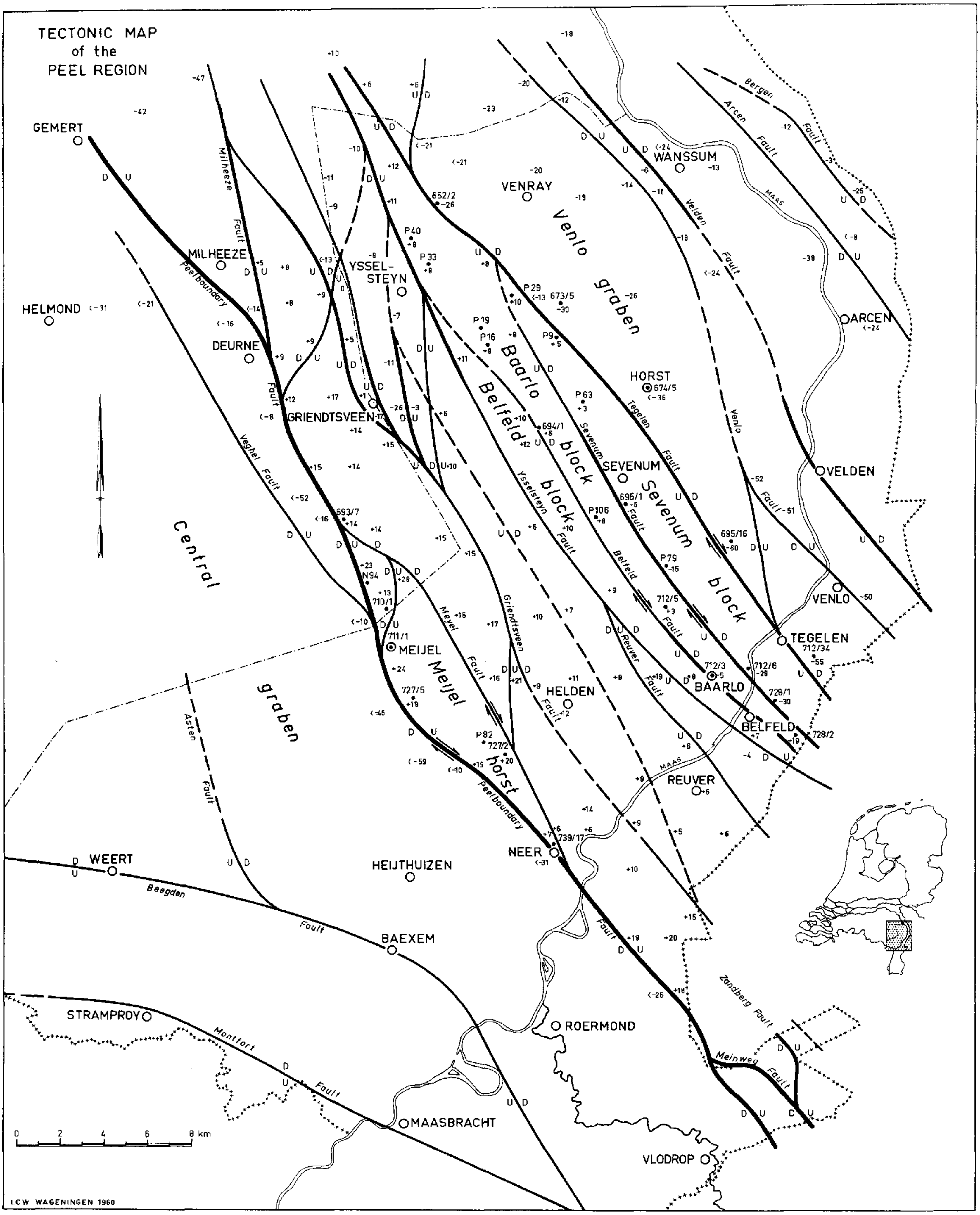
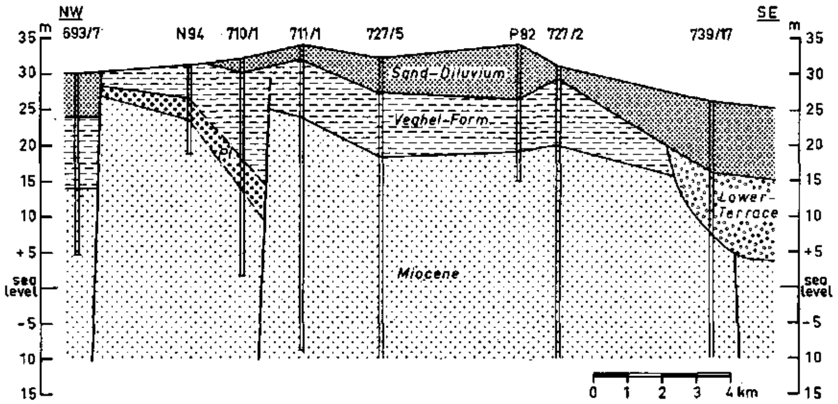


FIG. 8. FAULT PATTERN OF THE PEEL REGION, SE NETHERLANDS. THE FIGURES GIVE THE DEPTH IN m. OF THE MIOCENE ABRASION SURFACE RELATIVE TO SEA LEVEL



LEGEND

▒ 1 = Sanddiluvium (*Upper Pleistocene*)
▒ 2 = Grubbenvorst Formation (*Upper Pleistocene*)
▤ 3 = Veghel Formation (*Upper Pleistocene*)
▒ 4 = Sterksel Formation (*Middle Pleistocene*)
▨ 5 = Tegelen Formation (*Lower Pleistocene*)
▒ 6 = Pliocene (*Upper Tertiary*)
▒ 7 = Miocene (*Upper Tertiary*)

FIG. 9. SECTION THROUGH THE MEYEL HORST, PEEL REGION, SE NETHERLANDS, FOR LOCATION OF BORINGS, SEE MAP FIG. 8

A longitudinal section through the Meyel horst is shown in figure 9. In considering the Miocene abrasion surface in this section it appears that the central part of the horst forms a stable block (between the borings 727/5 and 727/2). In this part of the horst the faults run more or less parallel and repeated lateral displacements did not change the relative horizontal position of this abrasion surface. Lateral displacements, however, caused elevation and subsidence near the bifurcations, resulting in a southeasterly pitching of the Miocene abrasion surface of the wedges. These observations are in accordance with the theory that a change in strike of one of the bifurcating faults will change the amount of subsidence and will therefore cause the wedge to pitch. Elevation can cause a fracturing of the wedge and the nose then tends to slide down. This happened north of Meyel, where a joining-fault originated.

The Meyel wedge must be regarded as a transcurrent wedge. The faults are clockwise transcurrent and have been active into the Upper Pleistocene.

Unfortunately the original depth of the Miocene abrasion surface in the southeast of the horst near Neer (boring 739/17) has been destroyed by Pleistocene valley erosion. Only a new boring just outside this valley could provide the evidence for a possible southeasterly pitching of the narrow wedge near Neer.

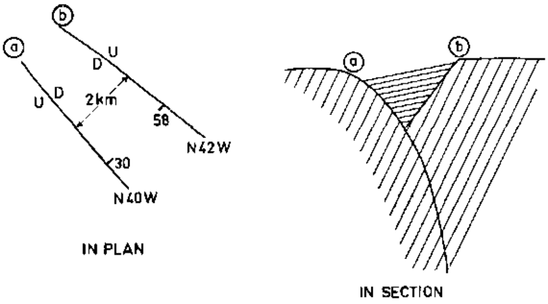


FIG. 10. FAULTS ACTIVE DURING THE 1946 ANCASH EARTHQUAKE IN PERU

Wedges are reported from many major transcurrent faults, i.e. in Venezuela. ROD (1956) reports the existence of wedges along the transcurrent El Pilar and Ocoa Faults and explains the existence of the Toas and Patos islands as wedges in transcurrent fault zones.

Not always is lateral displacement along faults bounding horsts and grabens apparent. SILGADO (1951) describes the results of the 1946 Ancash earthquake in Peru. Two faults striking N42W and N40W and dipping respectively 58SW and 30NE were active. The 2 km. wide zone between these faults subsided. Slickensides showed that the movement at the surface was purely vertical (fig. 10).

A fault-plane study of this earthquake by HODGSON and BREMNER (1953) showed that at the focus the movement along the fault striking N45W and dipping 71E was anti-clockwise transcurrent with a slight reverse component.

These apparently anomalous results can only be explained if the transcurrent horst and graben mechanism is accepted.

The facts that the faults converge in a northwesterly direction and that the fault-bounded area subsided would from theory suggest anti-clockwise transcurrent faulting. This is confirmed by Hodgson and Bremner's fault-plane study.

PITCHING GRABENS

Other characteristic features in a transcurrent shear zone are pitching wedges. In case a clockwise transcurrent fault bifurcates and the branch fault gradually changes in strike to become ultimately parallel to the other fault, the result will be the pitching of the enclosed block in the direction of the bifurcation. For further information on the mechanics of this phenomenon the reader is referred to LENSEN (1958 d).

A change in strike of one of the bifurcating faults will change the amount of subsidence and will therefore cause the wedge to pitch (LENSEN, 1958 d).

An example is shown in figure 11, showing the upper Whakatane Valley in the northeastern part of the North Island and is part of the Geological Map of New Zealand, 1:250,000 series, Sheet 8. The Tertiary sediments in the graben become progressively younger towards the bifurcation of the Whakatane Fault. Their dips are the result of two directions of pitch: towards the bifurcation and towards the Ruatahuna Fault, which is a clockwise transcurrent fault with a normal component.

Examples of pitching grabens are found in the Peel region1) which consists of several secundary horsts and grabens, like the Venlo Graben, the Sevenum Block, the Baarlo Block, the Belfeld Block and the Meyel Horst (fig. 8). When checking the depth of the Miocene abrasion surface in longitudinal section, i.e. parallel to the faults, a southeasterly pitching became evident (DE RIDDER, 1958). This southeasterly pitching is a remarkable feature, because in this region all older abrasion surfaces slope to the northwest, as a consequence of the continuous subsidence of the North Sea Basin, to which the greater part of the Netherlands belongs. The present southeasterly pitching of the Miocene abrasion surface must, therefore, be due to tectonic causes.

The *Venlo Graben* forms a subsidence in the Peel Fault-Block. Is is a narrow graben bounded on the west by the Tegelen Fault and on the east by the Venlo Fault. The Tegelen Fault has been traced from Tegelen up to the northwest of Venray, where it joins the IJsselsteyn Fault. The Venlo Fault has been found near Venlo and its continuation to the northwest is only inferred. Recent investigations near Wanssum in the north, provided some new evidence for the presence of at least two faults in this area (DE RIDDER, 1959; ERNST and DE RIDDER, 1960). The location of the eastern boundary of the Venlo Graben is only partly known.

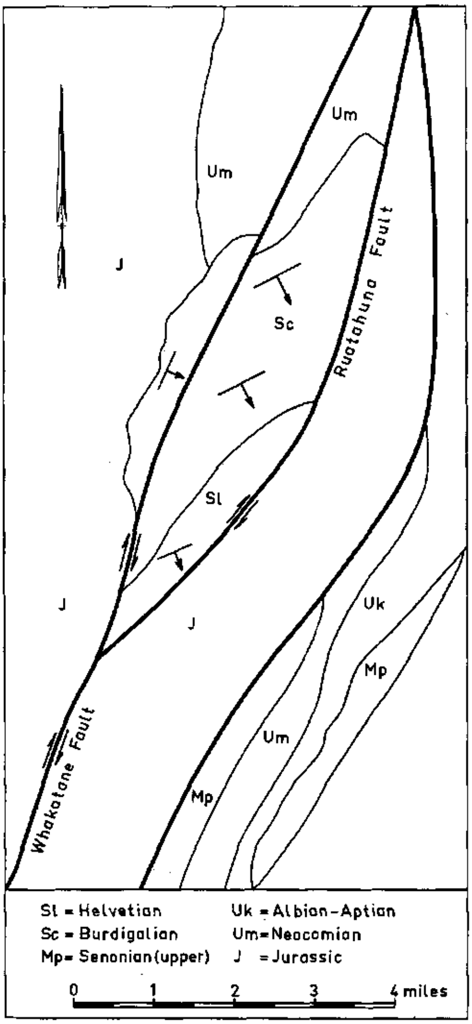


FIG. 11. GEOLOGICAL MAP OF THE UPPER WHAKATANE VALLEY, NORTH ISLAND, NEW ZEALAND (after Grindley)

The Venlo Graben broadens to the northwest; it is largely filled with thick layers of fluvial deposits of Pliocene age. Figure 12 shows a longitudinal section through the graben. From this figure it appears that the Pliocene sediments are locally overlain by sediments of the Tegelen Formation (Lower Pleistocene). During the Needian and Riss-Glacial the Maas deposited the sediments of the Veghel Formation while during the Weichselian, valley incision took place. This entrenched valley has been filled with Lower Terrace sediments.

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1) Also in the southeastward continuation of the fault system in Germany, see tectonic sketch map by PELTZ and QUITZOW (1955).

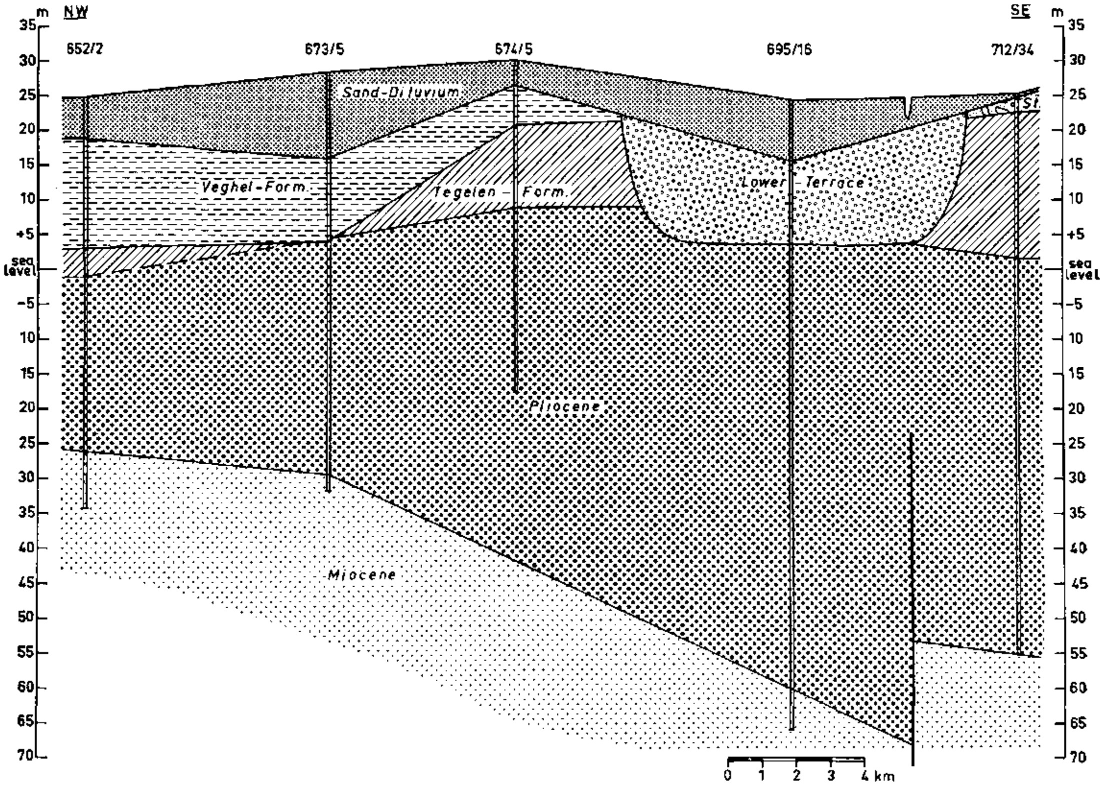

Fig. 12. Section through the Venlo Graben, Peel region, SE Netherlands, for location of borings, see map fig. 8. Legend, see fig. 9

The Sanddiluvium consists of fine Maas deposits in the lower layers, while the upper layers consist mainly of wind-blown sands.

From this section it is also clear that the Miocene abrasion surface pitches to the southeast. In this direction the graben narrows, while at the same time the pitch becomes steeper. Near Venray in the north, the bounding faults run more or less parallel and the pitch is less steep. This can be regarded as an evidence of clockwise transcurrent faulting.

Considering the nature of the tectonic activity in the Upper Tertiary it can be stated that this activity was greatest during the Pliocene period. The increasing thickness of the Pliocene sediments in a southeasterly direction must lead to this conclusion. The near-level position of the Pliocene abrasion surface indicates that this tectonic activity was dying out at the end of the Pliocene. The fact that the base of the Oligocene still pitches to the northwest (De Sitter, 1956) indicates that the original northwesterly pitch was larger than the later occuring reversal in southeasterly direction.

Two other tectonic elements of the Peel Fault-Block are formed by the *Sevenum Block* and the *Baarlo Block* (fig. 8). The Sevenum Block is enclosed between the Tegelen

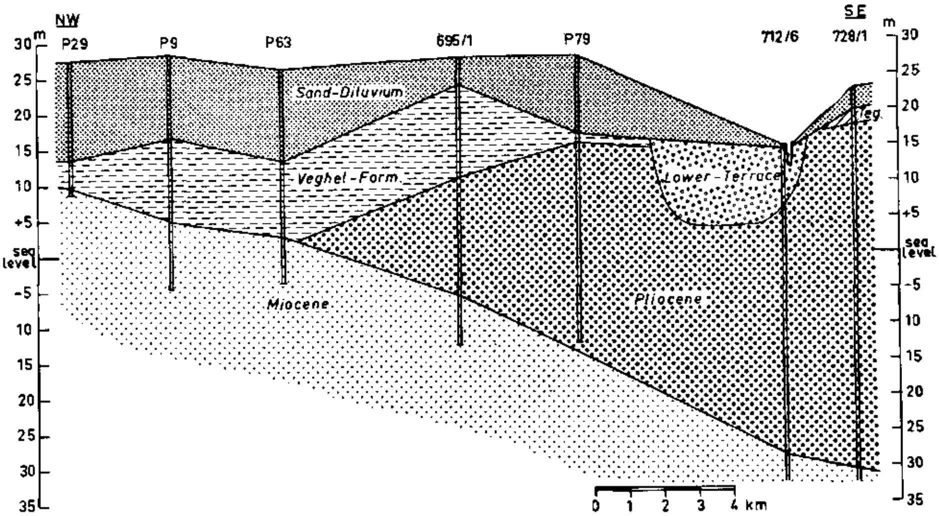

FIG. 13. SECTION THROUGH THE SEVENUM BLOCK, PEEL REGION, SE NETHERLANDS, FOR LOCATION OF BORINGS, SEE MAP FIG. 8. LEGEND, SEE FIG. 9

Fault in the east and the Sevenum Fault to the west. A longitudinal section through this block is given in figure 13. This section also clearly shows a southeasterly pitching of the Miocene abrasion surface, while a considerable increase in thickness of the Pliocene sediments can be observed in the same direction.

The Baarlo Block is a long, narrow block enclosed between the Sevenum Fault and Belfeld Fault. A longitudinal section through this block is shown in figure 14. The northwestern part of the block is relatively undisturbed as can be concluded from the nearly horizontal position of the Miocene abrasion surface between the

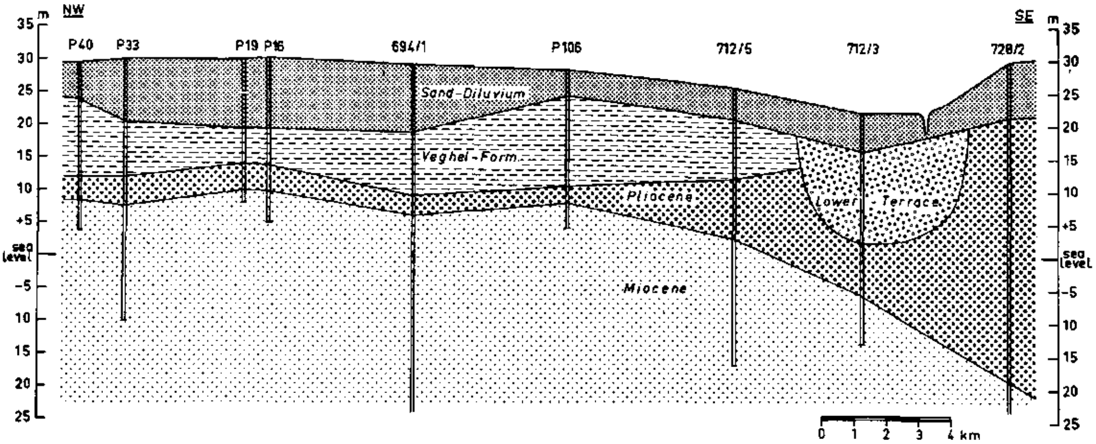

FIG. 14. SECTION THROUGH THE BAARLO BLOCK, PEEL REGION, SE NETHERLANDS, FOR LOCATION OF BORINGS, SEE MAP FIG. 8. LEGEND, SEE FIG. 9

borings P 40 and P 106. The Miocene is overlain by a thin layer of Pliocene sediments of rather uniform thickness. In this part of the block the faults run parallel and in that case the enclosed block must be stable and does not subside. From P 106 towards the southeast, the Baarlo Block tends to narrow and the Belfeld and Sevenum Faults presumably join in Germany not far from the border.

In this narrow wedge the Miocene abrasion surface pitches gradually steeper in a southeasterly direction to the point of joining. The thickness of the Pliocene sediments gradually increases in the same direction.

De Sitter (1949; 1956) regards normal faulting due to lateral tension as the actual cause of the fracture pattern of the Peel region.

The above-mentioned features, however, must be regarded as indirect evidences of the occurence of clockwise transcurrent faulting. With regard to the nature of the tectonic activity in the Upper Tertiary the same conclusions as mentioned above are valid.

It should be noted that in accepting the theory of transcurrent faulting as an explanation of the fault pattern of the Peel region, the original fault pattern, as published by De Ridder (1959), needed some slight modifications, in particular in the Belfeld region (compare fig. 8 and the map in the above-mentioned paper). These modifications were possible since they did not impair the value of the data, but were only a question of interpretation.

In general it can be stated that the smaller the horst- and graben wedge is, the steeper the pitch will be. This stands to reason as there will virtually not be a stable wedge and the distance between highest and lowest point is small. In fact this can lead to overturning of beds and sequences.

Examples of steep pitching of small graben wedges can be found in the Peel region near Griendtsveen (fig. 8). Near this village a number of faults occur, enclosing small wedges which all show a relative steep pitching Miocene abrasion surface.

Hinged faulting

Hinged faulting is defined as the relative rotation of the fault blocks around an axis normal to the strike of the fault.

In the field this will appear as a change in upthrown side without appreciable change in strike or direction of dip of the fault. This feature is an inherent part of the transcurrent mechanism for the formation of horsts and grabens. Both the Mackay and the Countess Faults in figure 7 show this hinged character.

Not all transcurrent faults showing hinged faulting, bifurcate to form horsts and grabens and in those cases this feature can be explained by the fact that the faults are almost purely transcurrent. A slight change in the Principal Horizontal Stress direction (Lensen, 1958 a and c) of the order of 2° or less can change the vertical component of a fault from a normal to a reverse character or vice versa. Wellman (1953) and Lensen (1958 e) showed this change of upthrown side, respectively for the transcurrent Awatare- and Wellington Fault.

In the Peel region (fig. 8) there are several indications of a reversal of the vertical displacements along the various faults. Examples are the Sevenum Fault, which has a down thrown W limb in the Carboniferous and a down thrown E limb in the Upper Tertiary strata. The Meyel Fault also has a down thrown W limb in the Carboniferous and a down thrown E limb in the Upper Tertiary and Pleistocene strata. The same is true for the Venlo Fault near Wanssum (DE SITTER, 1949).

SKEW SYMMETRIC FAULTING

Skew symmetric faulting is here defined as the skew symmetric relationship between the throw of the faults at the complementary bifurcations of the faults. This complementary pattern is an inherent part of the transcurrent mechanism for the formation of horsts and grabens and is the result of the junctions of hinged faults. The hinged character is not always preserved and the complementary up-down-up and down-up-down relationship at the bifurcations is the only evidence left of the transcurrent character of the fault. Figure 7 shows this skew symmetric faulting at the bifurcations clearly and is indicated by dashed circles.

REVERSAL OF PITCH OF WEDGES

The cross section (fig. 15) shows that the maximum subsidence possible for any point in the graben depends on the depth of the line of intersection of both fault planes. Any subsidence that occurs is due to lateral shift along this line of intersection. Depending on the shape of the line, the subsidence can cause a fracturing of the wedge and the nose tends to slide down and pitch in a reversed direction.

The nose of a horst can have a similar reversed pitch due to gravitational sliding.

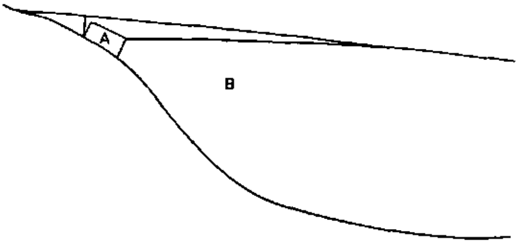

FIG. 15. CROSS SECTION SHOWING FRACTURING OF GRABEN WEDGE AND REVERSE PITCH OF THE NOSE OF THE WEDGE

RELATIONSHIP BETWEEN STRESS AND DIRECTION OF PITCH OF WEDGES

Two consistent directions of pitch of two sets of wedges indicate the sense of lateral displacement along the faults. Figure 16 shows diagrammatically the relationship between the direction of the pitch of the horsts and grabens and the direction of the P.H.S. at the bifurcations of the faults. Grabens along clockwise and anti-clockwise transcurrent faults pitch at an acute angle towards the direction of the P.H.S. at the bifurcation, while horsts both along clockwise and anti-clockwise transcurrent faults pitch at an acute angle away from the direction of the P.H.S. at the bifurcation.

EXOTIC BLOCKS

Blocks which consist of rock which is foreign to the area in which they occur are called exotics, as neither the term inlier or outlier is applicable.

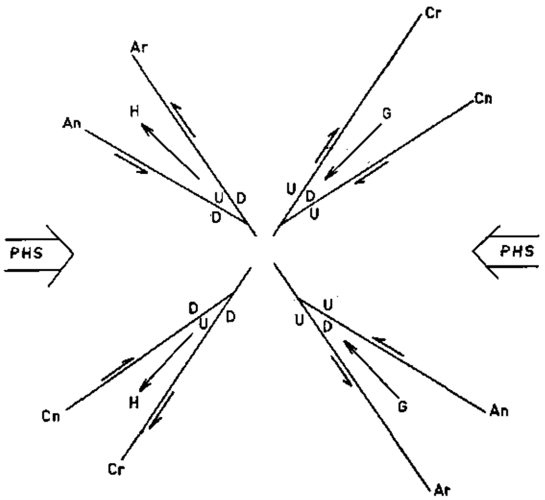

FIG. 16. DIAGRAM SHOWING THE RELATIONSHIP BETWEEN THE DIRECTION OF THE PITCH OF THE HORSTS AND GRABENS AND THE DIRECTION OF THE PRINCIPAL HORIZONTAL STRESS (P.H.S.) AT THE BIFURCATIONS.

An STANDS FOR ANTI-CLOCKWISE TRANSCURRENT WITH NORMAL COMPONENT
Ar STANDS FOR ANTI-CLOCKWISE TRANSCURRENT WITH REVERSE COMPONENT
Cn STANDS FOR CLOCKWISE TRANSCURRENT WITH NORMAL COMPONENT
Cr STANDS FOR CLOCKWISE TRANSCURRENT WITH REVERSE COMPONENT

Strings of exotics along major faults can also be regarded as transcurrent wedges, which have travelled laterally from their region of origin. Such wedges, having often existed for considerable geological time and having travelled considerable distances, are sometimes overturned due to continuously increasing pitch towards the bifurcations.

A good example can be found in California (DIBBLEE, 1955, plate 1), where along the anti-clockwise transcurrent Garlock Fault a strip, which separates the N. Garlock- and the S. Garlock Fault, consists of Pre-Cambrian Pelona schist, while the surrounding country rock consists of hornblende-biotite quartz diorite thought to be Jurassic in age.

TOTAL MOVEMENT EXPERIENCED BY A TRANSCURRENT WEDGE

The total movement of any transcurrent wedge is a combination of lateral travelling, longitudinal pitching towards the bifurcation and sideways pitching towards the fault with the more normal or least reverse component. The resulting trajectory is similar to that of a corkscrew.

The Venlo Graben in the Peel region can be cited as an example of this corkscrewing effect (fig. 8). The Miocene abrasion surface in this graben not only shows a longitudinal pitching in southeasterly direction (figs. 8 and 12), but also a sideways-pitching towards the Tegelen Fault. This sideways-pitching can be concluded for example from the following data on the depth of this abrasion surface: to the west of Wanssum: 14 m. below sea level, in Venray: 20 m. below sea level and in boring 652/2: 26 m. below sea level.

SUMMARY AND CONCLUSIONS

Fault patterns showing horsts and grabens which are currently explained by normal faulting are shown to be caused by transcurrent faulting. Examples from New Zealand

and the Netherlands are given. For New Zealand, which forms an integral part of the Circum-Pacific Mobile Belt, this could readily be expected. Regions outside the mobile belt can, however, also be subjected to lateral shear as the Peel examples have shown. In the Netherlands lateral shear took place during the Pliocene along clockwise transcurrent faults.

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