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Structure of the Hanmer strike-slip basin, Hope fault, New Zealand

/Lamarche, Geoffroy

RAY A. WOOD *Institute of Geological and Nuclear Sciences Ltd., P.O. Box 1320, Wellington, New Zealand*
JARG R. PETTINGA *Department of Geology, University of Canterbury, Christchurch, New Zealand*
STEPHEN BANNISTER
G. LAMARCHE* } *Institute of Geological and Nuclear Sciences Ltd., P.O. Box 1320, Wellington, New Zealand*
TIMOTHY J. McMORRAN *Department of Geology, University of Canterbury, Christchurch, New Zealand*

ABSTRACT

Hanmer basin (10 × 20 km), located in northern South Island, New Zealand, is evolving where two major segments of the dextral strike-slip Hope fault are projected to converge across a 6- to 7-km-wide releasing step-over. The structural geometry and development of Hanmer basin does not conform to traditional pull-apart basin models.

The respective fault segments do not overlap but are indirectly linked along the southwest margin of the basin by an oblique normal fault. The Hope River segment terminates in an array of oblique normal faults along the northwestern basin range front, and east-west–striking normal faults on the west Hanmer Plain. Faulted Holocene alluvial-fan surfaces indicate west Hanmer basin is actively subsiding and evolving under north-south extension. The Conway segment along the southeastern margin of the basin terminates in a complex series of active fault traces, small pop-up ridges, and graben depressions. Early basin-fill sediments of Pleistocene age are being folded, elevated, and dissected as the eastern part of Hanmer basin is progressively inverted and destroyed by north-south contraction.

The north margin of the basin is defined by a series of topographic steps caused by normal faulting outside of the area of the releasing step-over. These normal faults we interpret to reflect large-scale upper crustal collapse of the hanging-wall side of the Hope fault.

New seismic reflection data and geologic mapping reveal a persistent longitudinal and lateral asymmetry to basin development. Four seismic stratigraphic sequences identified in the eastern sector of the basin thicken and are tilted southward, with in-sequence lateral onlaps occurring to the north and east, and also onto basement near the fault-controlled basin margins. The basin depocenter currently contains >1000 m of sediment adjacent to the south margin and is disrupted by faulting only at depth. In the western part of the basin, the sediment fill is thinner (<500 m) and is intensely faulted across the entire basin width.

Today the rate of basin deepening under transtension at the western end is matched by its progressive inversion and destruction under transpression in the eastern sector, with the oldest basin fill now being recycled. We propose a hybrid model for Hanmer strike-slip basin, one in which geometric elements of a fault-wedge basin (downward and upward tipped, spindle-shaped ends) are combined with those of a pull-apart basin (step-over region between the major fault segments). We also conclude that changes in fault geometry (releasing and restraining bends and step-overs) at a variety of scales and over short distances control the development of the extensile and contractile parts of the basin and three-dimensional basin asymmetry. Strain partitioning is complex and cannot be related simply to local reorientation of the regional stress field.

INTRODUCTION

The Hanmer basin in northern South Island, New Zealand, is evolving at a 6- to 7-km-wide releasing step-over between *en echelon* segments of the dextral strike-slip Hope fault (Figs. 1 and 2). The basin has been frequently cited in the international literature as one of the best examples of a

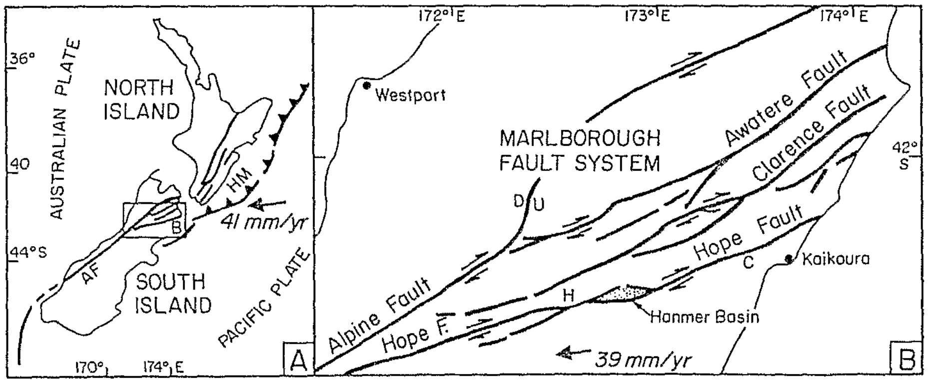

Figure 1. (A) New Zealand plate boundary setting. HM, Hikurangi Margin oblique subduction zone; AF, Alpine fault; B, region of the Marlborough fault system depicted in Figure 1B. Bold arrow is plate motion vector after de Mets and others (1990). (B) Marlborough fault system and location of Hanmer basin. Hope fault segments: H, Hope River segment; C, Conway segment. Arrows denote sense of relative horizontal displacement, and letters (U = up; D = down) sense of vertical displacement. Bold arrow represents plate motion vector (after de Mets and others, 1990).

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*Present address: ORSTOM, Nice, France.

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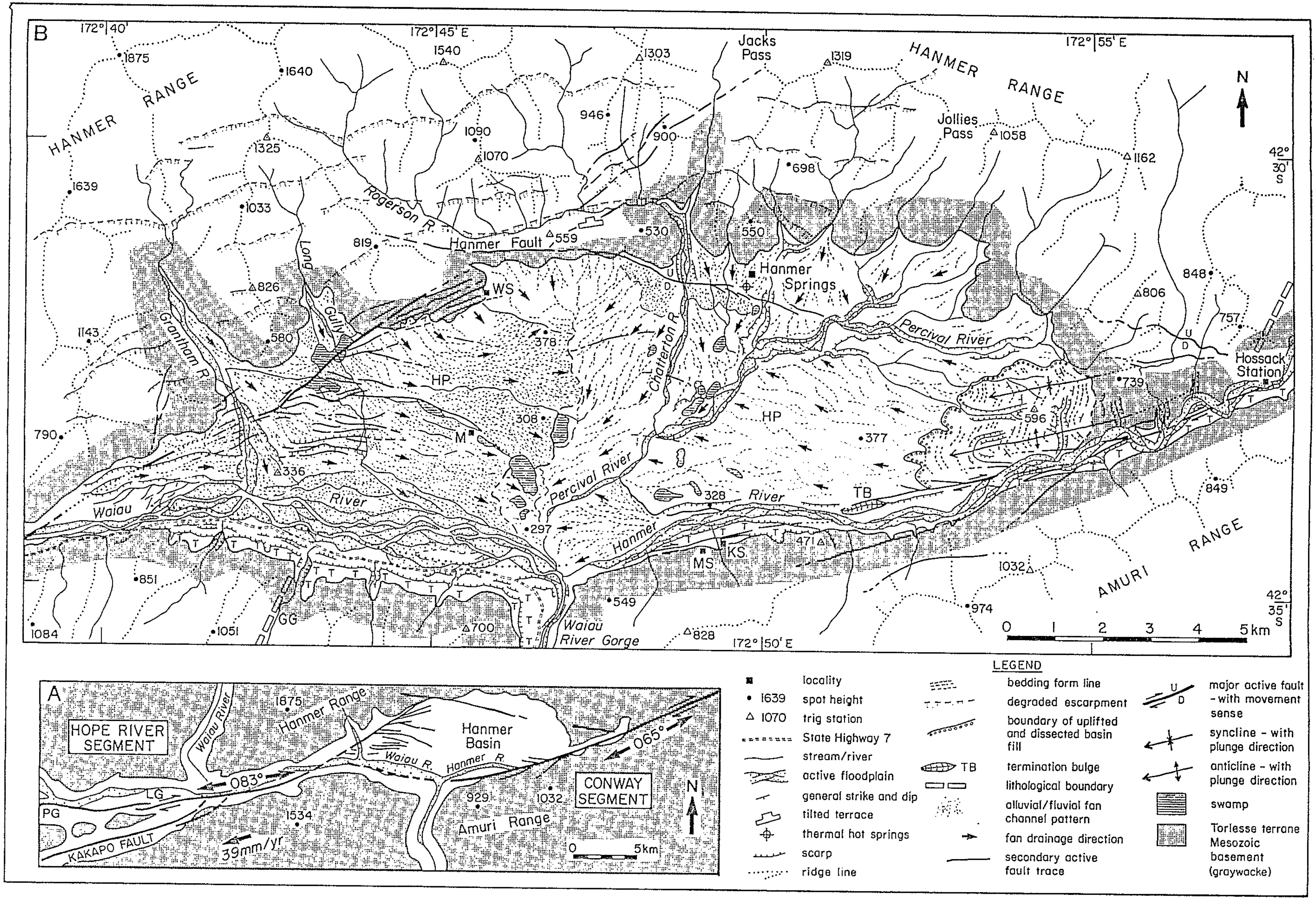

Figure 2. (A) Structural setting of Hanmer basin at the step-over between the Hope River and Conway segments of the Hope fault. Shading indicates elevated mountainous terrain. Averaged strike of segments is annotated. Bold arrow indicates relative plate motion vector (after de Mets and others, 1990). LG, Lake Glynn Wye Graben; PG, Poplars Graben. (B) Geologic and geomorphologic map of Hanmer basin. GG, Gabriels Gully; HP, Hanmer Plain; KS, Karaha Station; M, Marchmont Station; MS, Medway Station; TB, pop-up ridge or bulge; T, glacial outwash terrace; WS, Woodbank Station. Dashed/broken lines indicate projected and/or inferred continuation of structures.

structural depression, conforming closely to traditional pull-apart basin models (Schubert, 1980; Reading, 1980; Aydin and Nur, 1982, 1985; Mann and others, 1983; Christie-Blick and Biddle, 1985; Sylvester, 1988). We present here newly acquired seismic reflection data and detailed geologic mapping that reveal a strongly asymmetric longitudinal and transverse basin geometry and deformation extending well outside the immediate step-over width. The new data reveal a structural geometry conflicting with published interpretations of Hanmer basin as a "classic" pull-apart.

Structurally controlled rhombic and lazy-z–shaped depressions along major strike-slip faults are usually interpreted using well-established theoretical and empirical pull-apart basin models (for example, Crowell, 1974a, 1974b; Rodgers, 1980; Mann and others, 1983; Christie-Blick and Biddle, 1985; Aydin and Nur, 1985). Such basins evolve progressively at releasing step-overs or bends between major *en echelon* strike-slip fault segments. Basin dimensions are controlled by the perpendicular-to-strike step-over width and the overlap of the bounding fault segments. Secondary interconnecting normal and oblique normal faults strike diagonally between the master bounding faults, and it is across these that basins are "symmetrically" extended. Freund (1971) (see also Mann and others, 1983) studied several basins along the Hope fault and proposed a basin model in which the master fault segments are not strike-parallel but converge across the releasing step-over or bend. In the case of Hanmer basin, Freund also noted that the two strike-slip fault segments do not overlap but are connected by an oblique fault, facilitating gradual opening and deepening at one end of the basin, and shortening and uplift at the other.

Ben-Avraham (1992) and Ben-Avraham and Zoback (1992) have noted that although many small-scale pull-apart basins exist and conform to the traditional interpretive models established in the literature, some larger-scale basins do not fit easily into traditional pull-apart models. In the latter case the basins are notably asymmetric, bounded by linear strike-slip fault segments along one side of the basin and subparallel normal faults along the other (Ben-Avraham and Zoback, 1992). They explain partitioning of strike-slip motion and transform-normal extension by local reorientation of the regional stress field, with the minimum stress direction rotated perpendicular to the transform.

Prior to our study, understanding of the Hanmer basin was based on reconnaissance geologic mapping (Cotton, 1947; Clayton, 1966; Freund, 1971), a few shallow drill holes (Thompson, 1966), and analysis of gravity anomalies (Anderson, 1987). In this paper we present analysis of newly acquired seismic reflection data collected by the former New Zealand Department of Scientific and Industrial Research (DSIR) (Wood, 1991; Bannister and others, 1992) and recently completed detailed field mapping. These new data have allowed us to develop an improved three-dimensional understanding of the basin structure and its evolution. Our results are discussed in the light of the alternative models for strike-slip basin development, and we briefly consider the implications of strain partitioning in a transpressive plate boundary setting.

STRUCTURAL SETTING

The Hanmer basin formed on the Hope fault, the southern and most active element of the 80-km-wide Marlborough fault system. This fault system is that part of the Pacific-Australia plate boundary zone that transects the continental crust of the northern South Island, connecting the oblique-slip Alpine fault along the west coast of South Island (for example, Norris and others, 1990) to the west-directed oblique subduction zone offshore the east coast of North Island and northeastern South Island (for example, Lewis and Pettinga, 1993).

The Hanmer basin, as defined by the extent of Hanmer Plain, formed between the right step-over of two Hope fault segments. It is a spindle-shaped structural depression measuring ~15 km long and ~7 km wide (Fig. 2). The maximum dimensions of the basin are greater, however, insofar as normal faults extend into the mountainous terrain around the northern sides of the basin and the eastern sector of the basin is elevated and dissected. Accordingly, the maximum basin dimensions are ~20 km by ~10 km.

Late Jurassic to Early Cretaceous graywacke basement (Bishop and others, 1985; Bradshaw, 1989) forms rugged mountains standing ~1 km above the basin. The maximum vertical relief, summing the average elevation of the surrounding mountains and an estimate of the basin fill thickness, is ~2 km. Freund (1971) used offsets of basement rocks to estimate ~19 km of total strike-parallel separation on the Hope fault.

The Hope fault changes strike across Hanmer basin from 083° ± 10° along the Hope River segment west of the basin, to about 065° ± 5° along the eastern Conway segment (Fig. 2). Historically the Hope River segment last ruptured coseismically in 1888 (Cowan, 1991), and it is clear from the detailed report by McKay (1890) that rupture was arrested at Hanmer basin. Paleoseismic studies completed in recent years suggest that the Hope River and Conway segments are seismically independent (Cowan, 1990, 1991; Cowan and McGlone, 1991; McMorran, 1991; W. B. Bull, 1991, personal commun.), indicating that a structural break exists across Hanmer basin.

The Hope River segment represents a zone of transtension subparallel to the azimuth of the relative plate motion vector (264° ± 10°) (de Mets and others, 1990) and defines a 30-km-long releasing bend within the Hope fault zone (Cowan, 1991). Several basins have evolved at self-similar releasing bends and step-overs along this fault segment, ranging in width from several hundred meters (Lake Glynn Wye Graben, Poplars Graben) to >5 km (Hanmer basin) (Fig. 2) (Clayton, 1966; Freund, 1971, 1974; Cowan, 1990). In this context Hanmer basin represents a major segment boundary (Cowan, 1991).

The main surface trace of the Hope fault is only partially preserved in the Hope-Waiau river valley southwest of Hanmer basin. This is primarily because a restraining bend of about 12° in the fault trace ~3 km west of the basin projects the active trace northeast across the valley floor and active flood plain where it is concealed. At the western entrance to the basin, the Hope fault forms a complex splay zone adjacent to the northwestern edge of the basin (Fig. 2). Here fault scarps up to 8 m high offset floodplain terraces and alluvial fans. The main fault trace extends across the entrance of Long Gully, where oblique-slip displacements have shuttered across stream channels, disrupting drainage and facilitating the development of swamps. Farther to the northeast the fault further splays, expressed by several parallel-striking scarps, terminating in a series of horsts and grabens that disrupt the lower slopes of the basin margin. On the Hanmer Plain east of the Grantham River, a series of sinuous east-west–striking active normal faults bound several horsts and grabens. The fault traces are discontinuous but connected by many step-over ramps. Scarps are generally <4 m high but have disrupted drainage, deflecting fan sediments to the east (Fig. 2). These active fault traces are not mapped east of the Long Gully fan, except for the most prominent trace, which extends to Marchmont Station.

Remnant terraces underlain by outwash gravel, which have yielded a late last glaciation ^{14}C age (Suggate, 1965), are perched about 60 m above the Waiau River and indicate that an active oblique-slip(?) fault exists along the southwestern margin of the basin, beneath the active flood plain of the Waiau River, and may be linked to the Conway and/or Hope River segments.

The more linear Conway segment is evidenced by a complex splay of active fault traces along the southeast margin of Hanmer basin (Freund, 1971; McMorran, 1991). Numerous releasing and restraining bends and step-overs have been mapped along this segment east of Hanmer basin (Freund, 1971; McMorran, 1991). Near the east margin of the basin, Pleistocene gravel is folded in a series of anticlines that plunge and diminish in amplitude to the west-southwest (McMorran, 1991). The southern and most pronounced fold forms a 200-m-high ridge adjacent to the Hope fault. Limited outcrop exposures indicate that the folds persist to the east and basement is deformed in congruence with the Pleistocene gravel cover. The folds are actively growing and propagating westward to near seismic line 3, where a Holocene fan surface has been upwarped ~10 m across ~1 km. A conservative estimate of north-south shortening within a 3-km-wide zone is ~5%.

The Hanmer fault is mapped as a series of discontinuous active fault traces along the northeast and northern margins of the basin. Near Hanmer Springs it strikes N110°E and five left-stepping *en echelon* strands are associated with a complex 100- to 200-m-wide zone of ground surface warping. Despite its proximity to the terminal fault splays of the Hope River segment west of Woodbank Station, there is no direct surface connection between the Hanmer fault and these splays. The sense of displacement west of Hanmer Springs appears to be oblique normal, based on the trace sinuosity, development of minor depressions, and the offset of fluvial channels. McMorran (1991) reported that the projected continuation of the Hanmer fault to the east margin of the basin coincides with a major reverse-fault crushed zone in basement, as well as the series of west-plunging folds described above (Fig. 2).

BASIN FILL

Exposures of dissected Quaternary alluvial deposits are restricted to the eastern and southeastern sectors of the basin. These deposits include compacted, moderately to poorly bedded, poorly sorted, and subangular to rounded, sandy, basement-derived gravel and gravelly sand. Thin layers of interbedded carbonaceous and diatomaceous silt and silty clay are rarely present within the gravel beds (Freund, 1971; McMorran, 1991).

Gravel exposed along the north bank of the Hanmer River in the eastern part of the basin, 300 m stratigraphically above the basal unconformity, is tilted west at up to 22°. Correlations with the seismic data indicate that they are some of the earliest sediments deposited within Hanmer basin. Diagnostic fossils have not been collected. A carbonaceous mud and peat horizon has yielded a ^{14}C age of >45 000 yr B.P. (L. Brown, 1991, personal commun.). A 15-cm-thick silt layer directly overlying this carbonaceous horizon (McMorran, 1991) contains the cold-water benthic diatom *Pinnularia maior*, which is associated with nutrient-poor, acidic waters, typically a swamp environment (P. A. Broady, 1991, personal commun.; Hawarth, 1991, personal commun.). Our inferred paleoenvironment is a pond formed on or between alluvial fans or a flood plain of a braided river system during a cold climatic period.

Aggradation terraces underlain by coarse gravel outwash of the late last glaciation (ca. 14 000 yr B.P.) (Suggate, 1965) (Fig. 2) are present along the south margin of the basin, 60–70 m above the Waiau and Hanmer Rivers. Near the Waiau River outlet, these outwash gravels have a 4- to 8-m-thick interbedded sequence of lacustrine sediment.

Large Holocene coalescing alluvial fans extend across the entire Hanmer Plain from each of the major catchments along the north and east sides of the basin. Sediments are mostly derived from the graywacke basement but along the east side are also cannibalized from uplifted and deformed older basin-fill sediments. The present-day depocenter of Hanmer basin is located where the various coalescing fans interfinger near the southern edge (Fig. 2), giving rise to small swamps in which silt, clay, and peat accumulate. Peat deposits encountered at a 5.5 m depth in a drill hole near Hanmer Springs have been dated at 13 000 ± 200 yr B.P. (L. Brown, 1990, personal commun.).

SEISMIC DATA

A total of 38 km of multichannel seismic lines were collected to investigate subsurface structure and sedimentation history of the basin (Wood, 1991; Bannister and others, 1992) (Fig. 3). Lines 1, 3, 4, and 5 (Figs. 4, 6, 7, and 8, respectively) run north-south, nearly perpendicular to the major mapped structures, and parallel to the basement dip direction. Line 2 (Fig. 5) runs east-west, tying lines 1 and 3. Reflection events within the sedimentary section are visible below 1 s two-way time (TWT) in the southeast part of the basin, near the Hope fault. Interval velocities (derived from the stacking velocities) increase from 1300–1500 m/s at the surface to 3000–3500 m/s at the base of the sedimentary fill. The sediments appear as a thick, well-stratified sequence of reflectors in the eastern part of the basin. They are thinner and more disrupted by faults at the west end of the basin. On the north-south lines the reflections are fairly continuous, only locally disrupted by inferred channels. The east-west–trending line 2 shows a much greater variability in reflection character. The line is subparallel to structures and inferred paleodrainage, and it is difficult to distinguish between the effect of faults and facies changes.

We have divided the sedimentary section for the east basin into four seismic sequences on the basis of their reflection character and lateral distribution.

Sequence 1 (S1)

Sequence 1 is a basal sequence of relatively low-frequency, parallel reflectors with little divergence toward the Hope fault. These reflectors onlap basement to the north. The dip of the deepest reflectors changes abruptly in several places, suggesting disruption by basement faults.

Sequence 2 (S2)

This overlying sequence thickens markedly southward and has signs of fan deposition and/or deformation adjacent to the Hope fault. The reflectors appear disrupted to chaotic. The sequence thins and onlaps basement to the north.

Sequence 3 (S3)

The next youngest sequence has good reflector continuity and only moderate thickening toward the south basin margin (line 1,

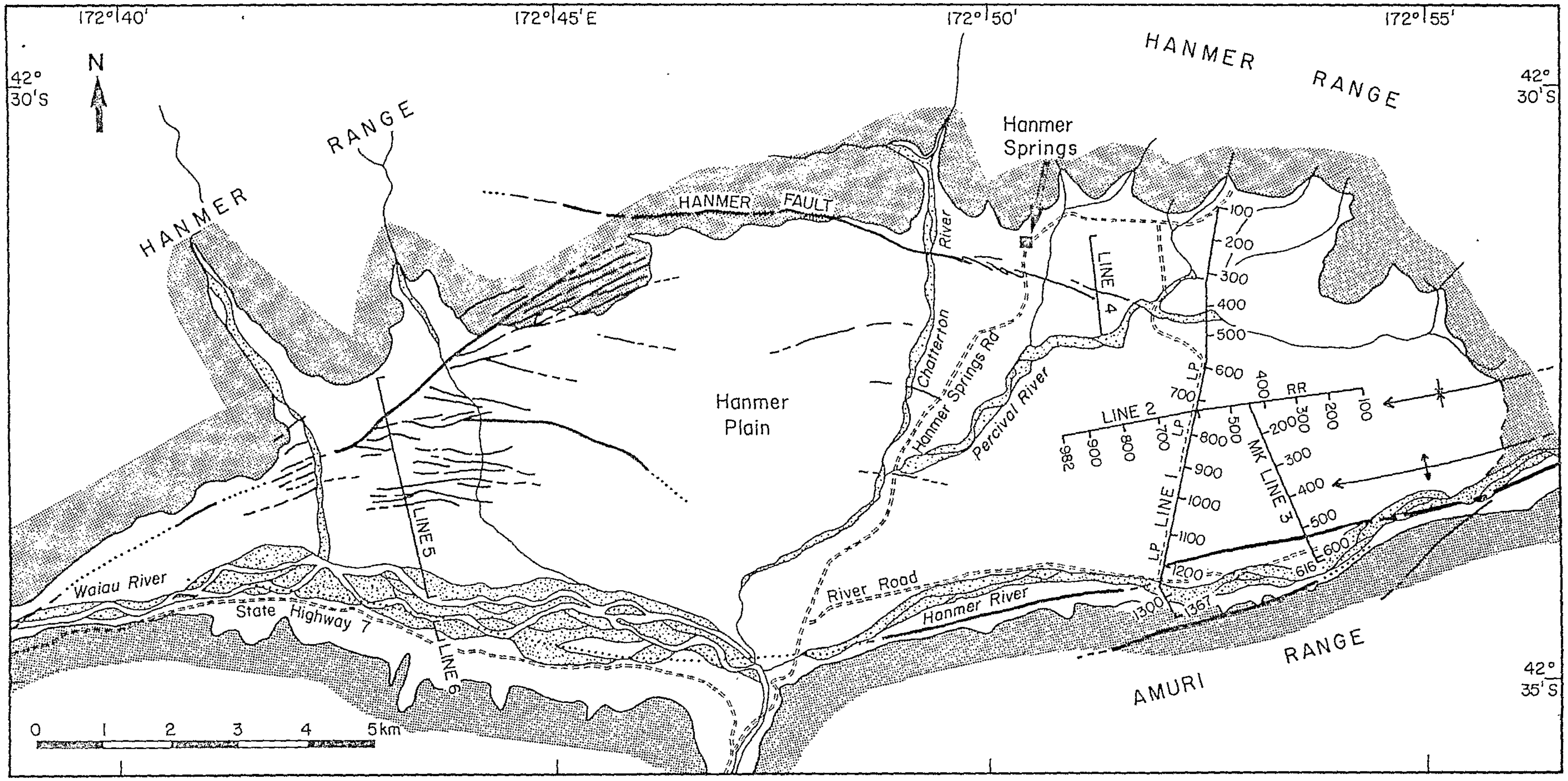

Figure 3. Sketch map of Hanmer basin depicting location of seismic reflection lines 1–6 with common depth point numbers. LP, Leslie Pass Road; MK, McKays Road; RR, Roche Road.

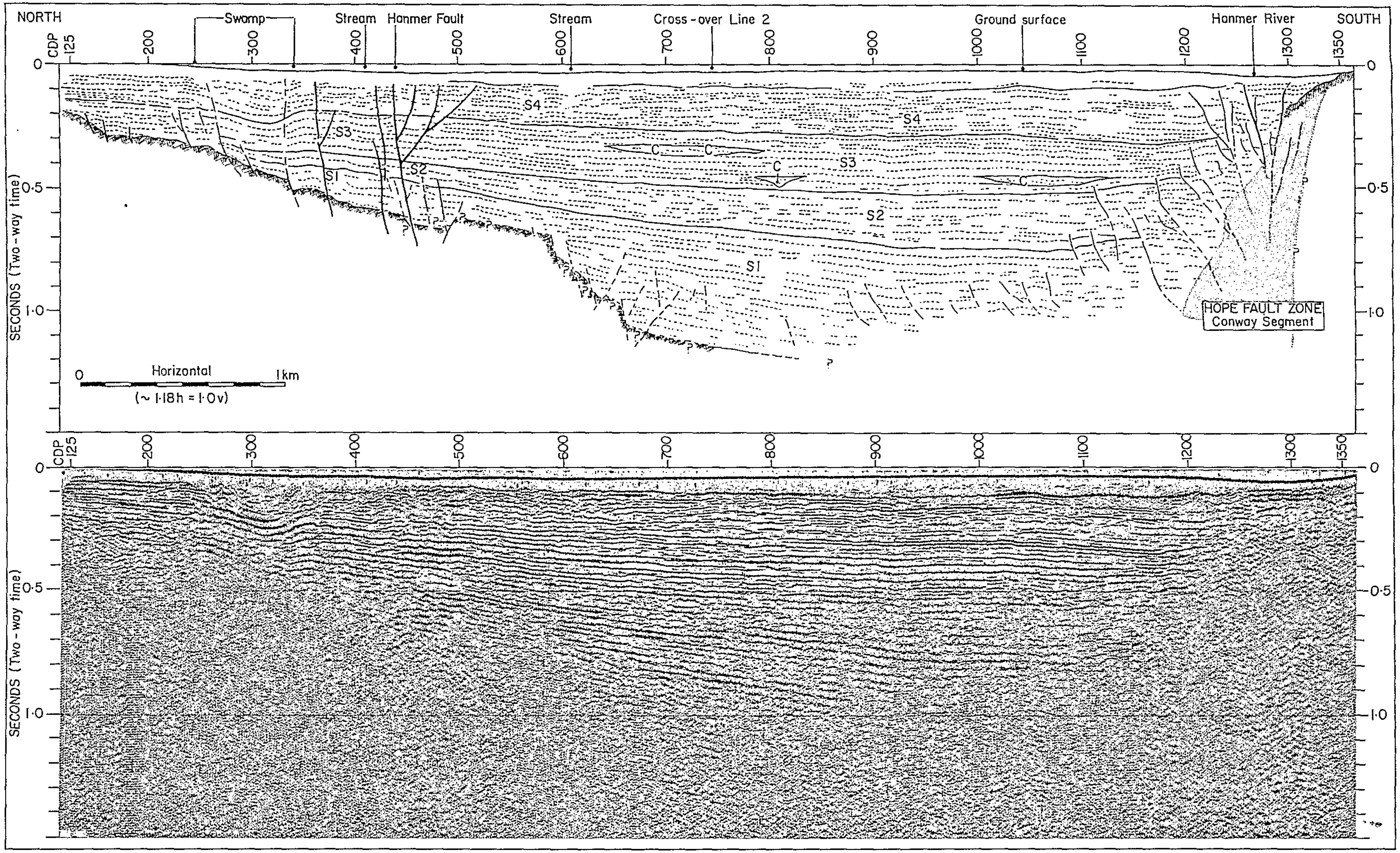

Figure 4. Seismic reflection line 1 migrated section with line interpretation. S1–S4, seismic sequences referred to in text; C, inferred channels.

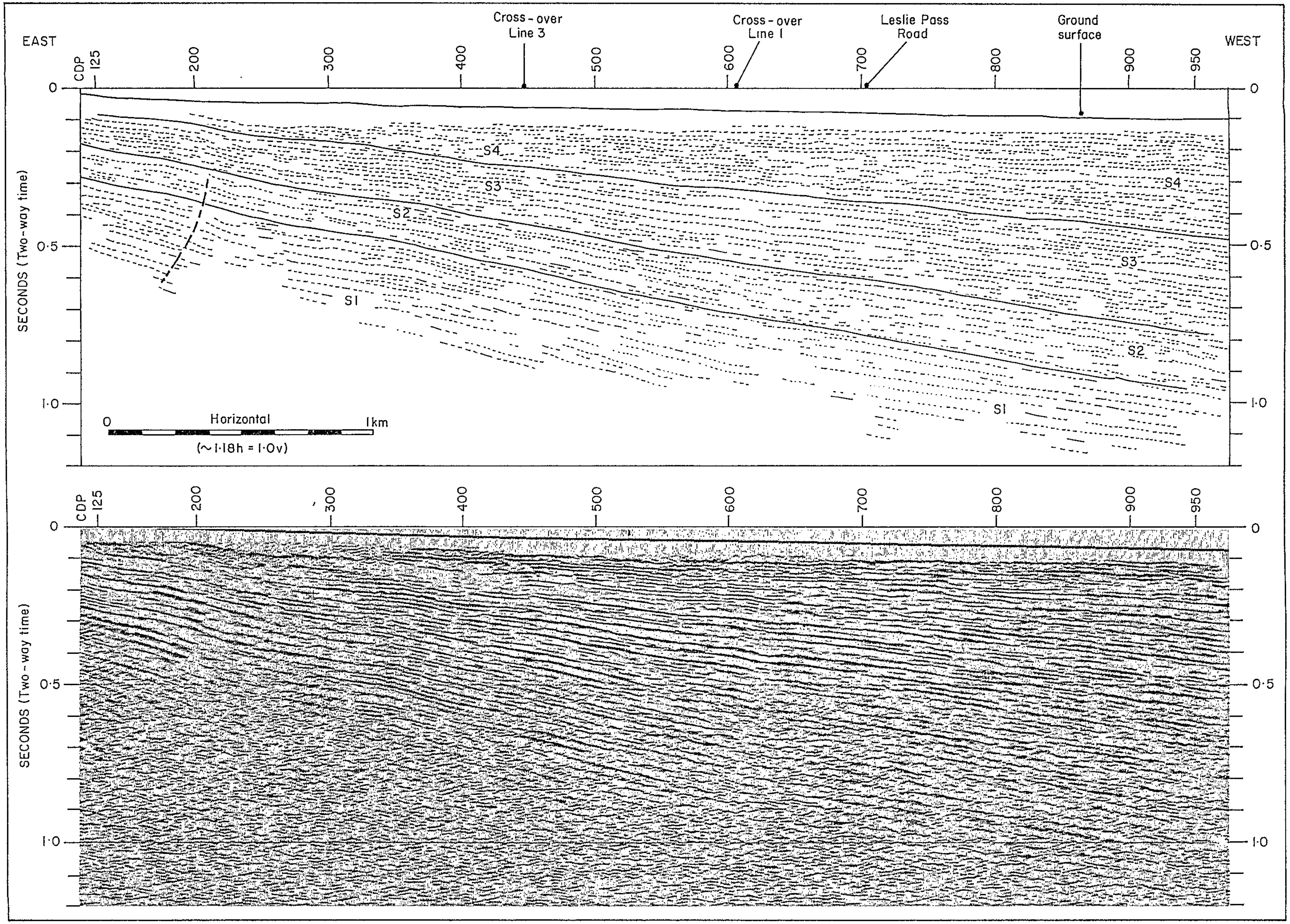

Figure 5. Seismic reflection line 2 migrated section with line interpretation. S1–S4, seismic sequences referred to in text.

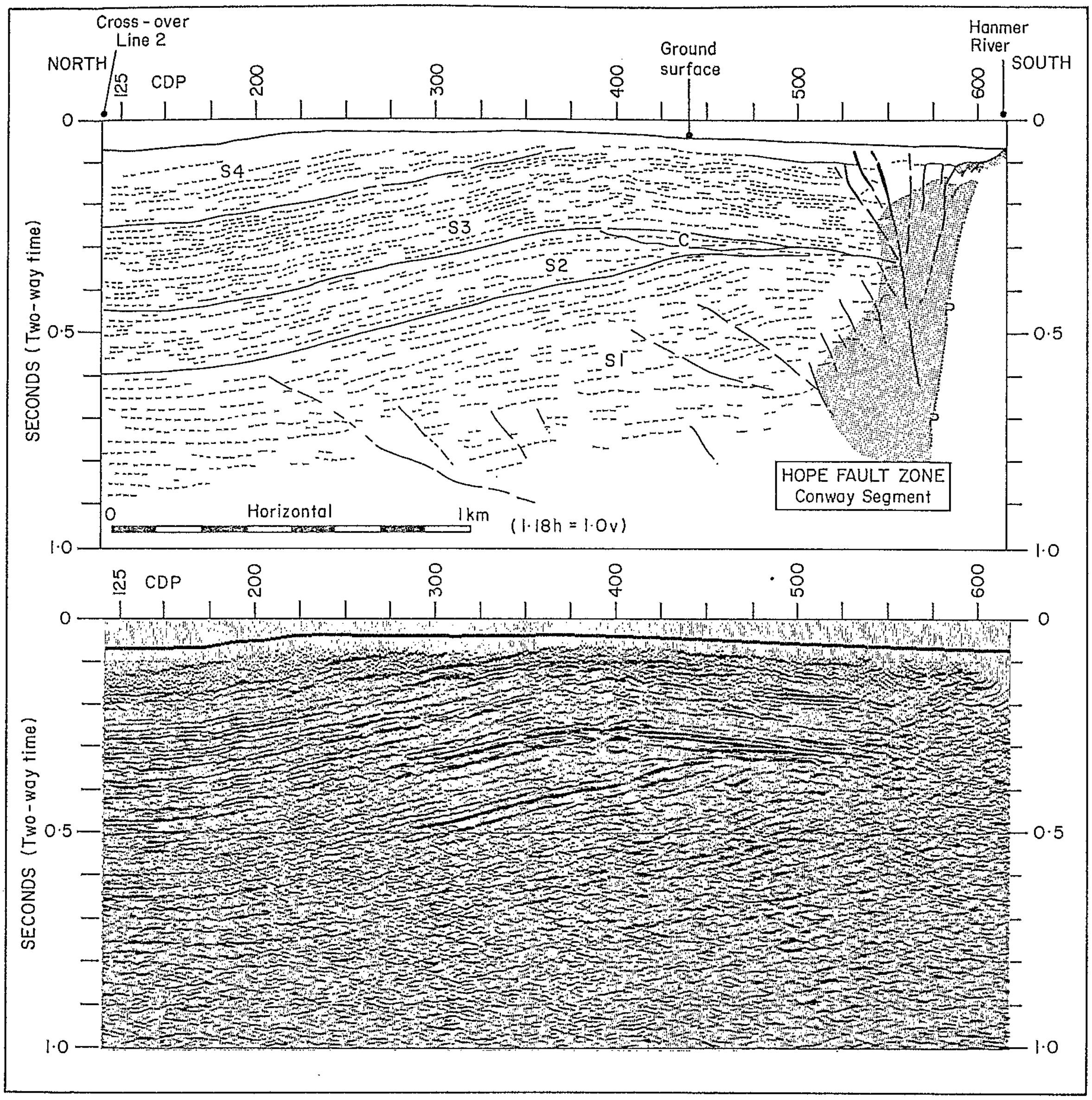

Figure 6. Seismic reflection line 3 migrated section with line interpretation. S1–S4, seismic sequences referred to in text.

Fig. 4) and marked thickening toward the center of the basin (line 2, Fig. 5). Channels may occur throughout the sedimentary section but have only been recognized in this sequence near the Hope fault (line 3, Fig. 6) and above the sharp basement drop to the north (line 1, Fig. 4). Sequence 3 extends beyond the north end of line 1.

Sequence 4 (S4)

The youngest sequence is higher in frequency and less continuous in appearance than the older units. It thickens to the south (line 1) and west (line 2). Channels associated with the present streams are evident, and a swamp at the north end of line 1 may be fault controlled.

Data from the west end of the basin (line 5, Fig. 8) indicate a much thinner basin fill, too disrupted to correlate with the seismic sequences established for the east end. Changes in seismic character on line 5 permit subdivision of the sedimentary section into two units (Fig. 8). Both units thicken toward the south basin margin. Onlap relationships cannot be picked confidently, but the upper unit in particular may show signs of truncation and erosion at the north end of line 5.

Basement is not well imaged on the sections. In the deeper parts of the basin (lines 1, 2, and 3) this could be due to the relatively short offsets and limited source energy, but that should not be a problem to the north or west where basement is within a few hundred meters of the surface or where a dynamite source was used. It is possible that the lack of reflectivity is due to paleoweathering or pervasive fracturing of the graywacke. It is unknown to what extent paleorelief on basement may be influencing the quality of the seismic data.

Faults are difficult to interpret but are usually steep and have a variety of styles, from normal in the west (line 5) and north (lines 1 and 4), to reverse, (?)oblique reverse, and (?)oblique strike slip in the south-

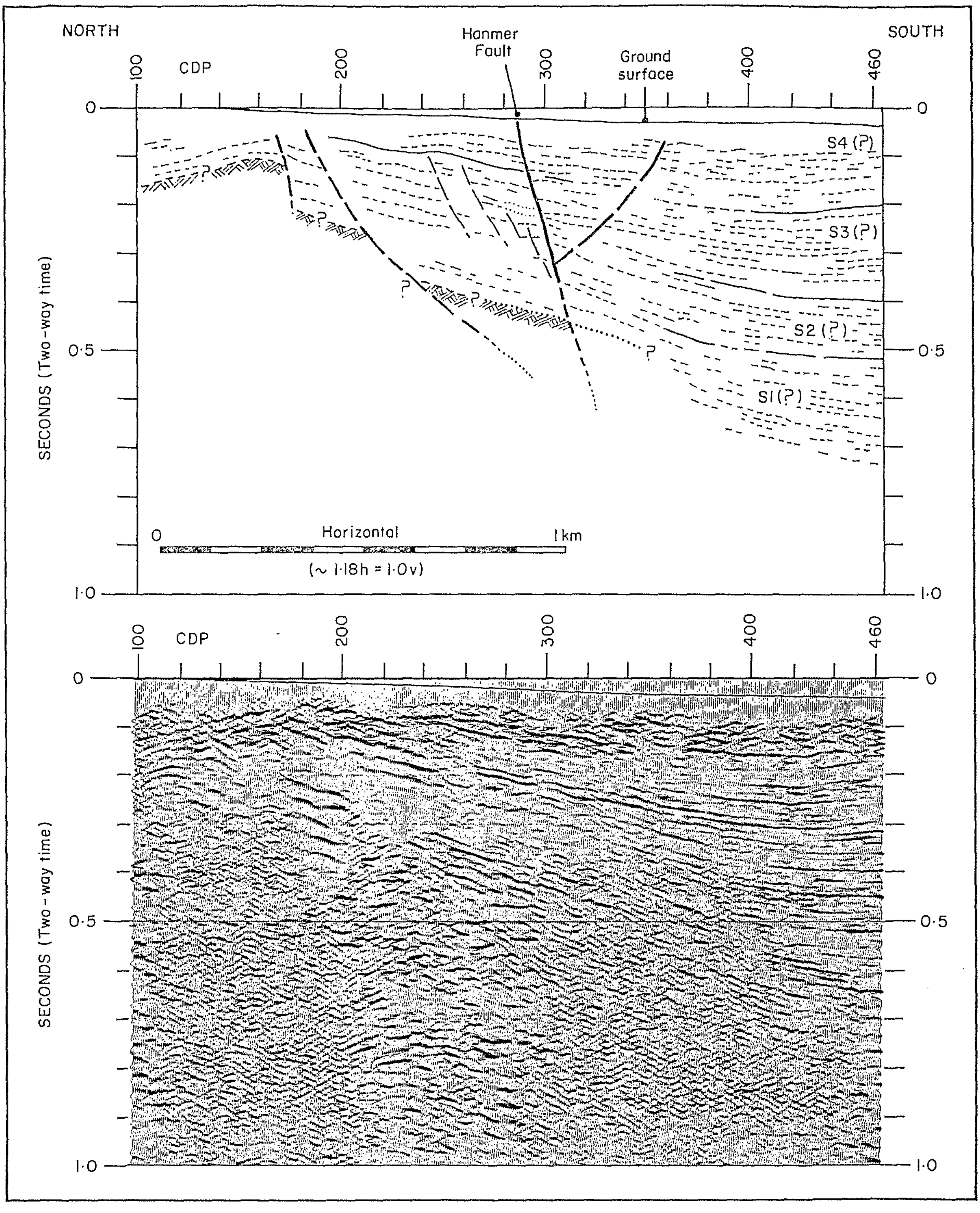

Figure 7. Seismic reflection line 4 migrated section with line interpretation. S1–S4, seismic sequences referred to in text.

east part of the basin (lines 1 and 3). In the east part of the basin active faults are confined to the basin margin, whereas in the west they are distributed across the entire basin floor and adjacent mountain range front.

TRANSPRESSION: EAST AND SOUTHEAST HANMER BASIN

The eastern part of the basin is undergoing north-south shortening. The Conway segment of the Hope fault strikes in a more northward direction than the Hope River segment (by ~20°), resulting in convergent strike slip. The main fault zone is narrow at depth, but faults splay and branch outward as they near the surface. Folds affecting both basement and basin fill are propagating

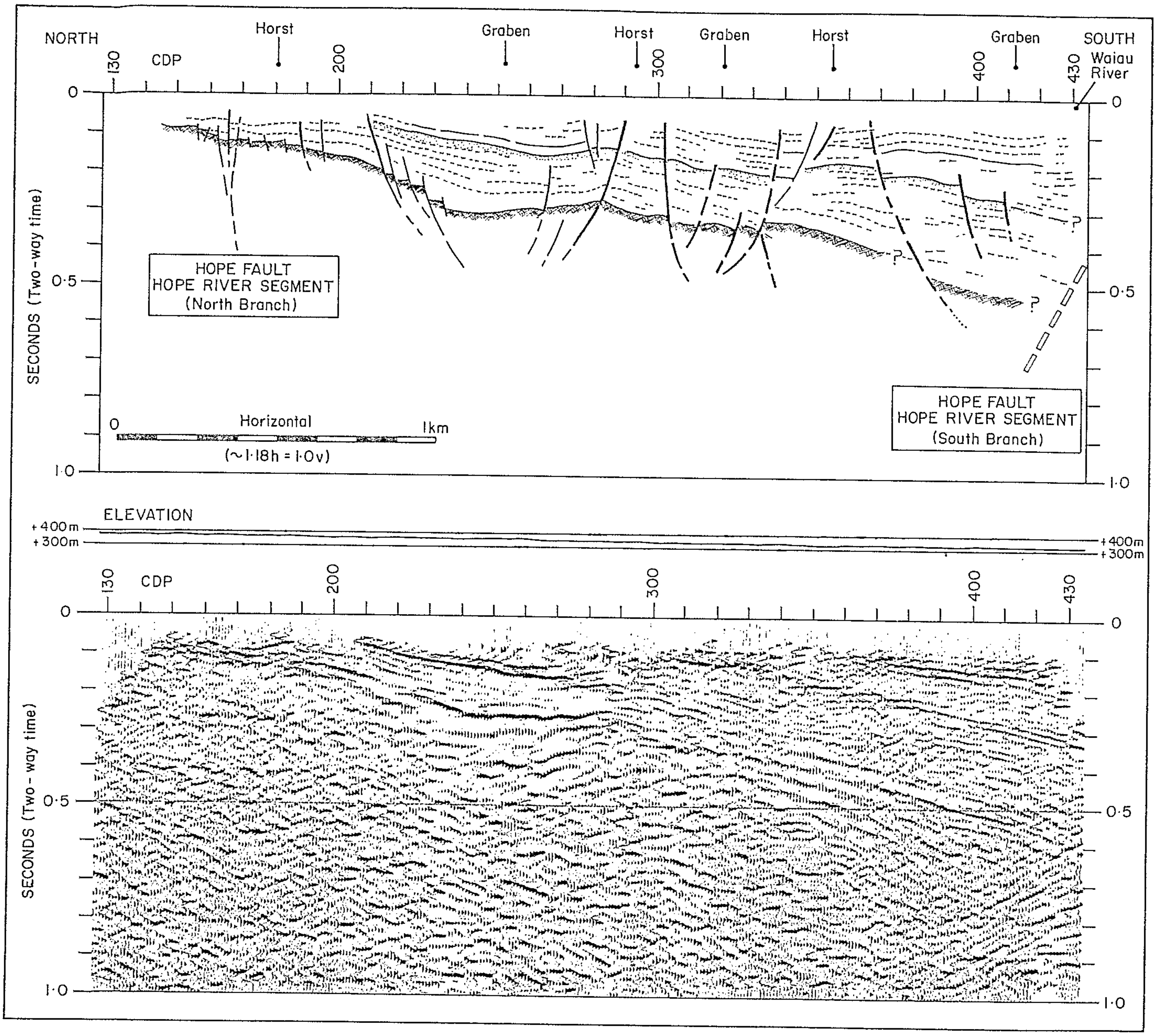

Figure 8. Seismic reflection line 5 migrated section with line interpretation. The seismic sequences have not been correlated with those on lines 1–4.

southwest into the basin in response to reverse and/or thrust faulting at depth. An associated network of discontinuous strike-slip faults and diverging reverse faults is common.

Active fault traces are confined to the southeast margin of the Hanmer basin (Freund, 1971; McMorran, 1991). The main strand of the Hope fault is partly concealed beneath the Hanmer River flood plain, but discontinuous traces are preserved on terraces near the entrance to the Waiau River gorge. East of seismic line 1 several discontinuous subsidiary faults splay to the west-northwest from the main trace. These faults dip steeply and are difficult to delineate because they strike parallel to local degradational terrace risers and may therefore be fluvially modified.

Seismic line 1 crosses the Hope fault zone at the southeast margin of Hanmer basin (Fig. 4). Basement crops out on the south side of Hanmer River (common depth point [CDP] 1340–1360) and is traced on the seismic profile into the fault zone. Within the fault zone resolution of basin-fill seismic sequences is poor because of the numerous steeply dipping outward-branching fault splays. We have interpreted four fault strands that project close to the surface (Fig. 4). The northern splays appear to be high-angle south-dipping reverse or oblique reverse faults.

Freund (1971) identified a prominent bulge (or *pop-up ridge* in the terminology of Biddle and Christie-Blick, 1985) adjacent to and south of the main fault trace, east of seismic line 1 on the north bank of the Hanmer River (Fig. 2). Its projected position is centered between the two northernmost major splays of the Hope fault zone (CDP 1200–1225, Fig. 4). The doubly plunging ridge warps the highest surface equivalent to the Hanmer Plain to a maximum height of 25–30 m and is >2 km long. Low terraces immediately to the west of seismic line 1 are unaffected by the fault. The pop-up dies out to the east before reaching seismic line 3 (Fig. 6), but its projected position lies between CDP 550 and 575 in line 3. Seismic line 1 suggests that the fault steps over ~100 m on a number of small faults. Faulting has disrupted basin fill at progressively greater depth to the north (line 1), suggesting coeval sedimentation and faulting at the basin margin.

Seismic line 3 (Fig. 6) also crosses the Hope fault at the southeast margin of the basin, ~2 km east of line 1. Basement crops out on the south side of Hanmer River but is not imaged in the profile. The Hope fault zone is similar in its appearance on this seismic section, with several major strands branching upward and outward near the surface. On both lines the recent faulting is restricted to the vicinity of the main fault trace; the splay faults mapped at the surface and seen on the seismic data do not extend far north into the basin.

On line 3 the basin-fill sequence is open folded, inferred to result from reverse or thrust faulting at depth. The anticlinal crest is located at about CDP 400, and this correlates well with the projected continuation of the southernmost fold mapped farther east by McMorran (1991). The surface expression of this fold indicates it plunges and dies out west of line 3.

All four seismic sequences are folded congruently, but S2 has been eroded and onlaps S1 south of CDP 400, reflecting an earlier phase of folding closer to the Hope fault zone. We have interpreted a channel at this unconformity. The units on line 3 do not noticeably thicken toward the Hope fault as they do on line 1.

Seismic line 2 (Fig. 5) is the only east-west profile, approximately parallel to geologic structures in the basin. No major structural complications are recognized in line 2. We were unable to identify a basement reflection, and at the west end of the profile the greatest stratigraphic thickness for basin fill is imaged to >1 s TWT. Seismic sequences S1 and S2 appear to be parallel stratified, whereas S3 and S4 wedge out to the east, although evidence for onlap is only seen clearly in S4. Minor onlap of S2 at the eastern end is possible.

In summary, west from Hossack Station to Hanmer basin the Hope fault becomes a braided system of discontinuous active fault traces and zones of warping and tilting associated with a wide crushed zone in basement. The structurally controlled geomorphologic expression of deformation within this zone highlights local complexities, with numerous small step-overs and bends, characterized by the development of pop-up ridges and graben depressions. Interpretations from seismic lines 1 and 3 reveal upward and outward branching faults (similar to those described by Wilcox and others, 1973) across a 1–2 km zone of deformation, agreeing well with the field mapping data. The three-dimensional style of deformation indicated is similar to a palm tree structure (compare with Sylvester and Smith, 1976; Sylvester, 1988). In Hanmer basin faults and folds with surface expression splay away from the main fault zone in a more northwest direction, dying out within ~1 km.

The termination of the Conway segment is not clear. The small splays in Hanmer basin may represent an extensile fan (compare with Woodcock and Fischer, 1986), in which case the fault segment beneath the Waiau River would connect the two main fault segments and, as interpreted by Clayton (1966), act as a releasing bend. Alternatively, the Conway segment may continue along the south margin as a complex zone of small step-overs and curve to the northwest, dying out as the strike of the fault changes, the strike-slip displacement decreases, and the normal displacement increases (for example, Reading, 1980; Royden, 1985).

PASSIVE: NORTHEAST HANMER BASIN

Basement crops out ~250 m beyond the north end of line 1. On both lines 1 and 4 basement initially slopes from north to south and is offset by minor normal faults, and then it drops away sharply into the basin. The strike of the basement step is not related to the Hanmer fault; on line 4 the basement step occurs near the Hanmer fault, but on line 1 it is near CDP 600, south of the Hanmer fault. Vertical offsets on individual faults may be as much as several hundred meters, but the basement dip is much less than along the south margin. Gravity data collected along line 4 support this interpretation (Anderson, 1987; A. Hull, 1991, personal commun.).

Seismic sequences 1–4 progressively onlap northward onto basement and indicate gradual enlargement of the basin floor sedimentary "sump." In line 1, sequence S2 thickens to the south and clearly onlaps northward onto sequence S1 and basement, and seismic sequence S4 has a similar relationship to S3.

The seismic sequence correlation to line 4 is tentative because no direct tie exists to other lines. This does not affect the interpretations we propose, as the thickness and onlap relations are the same.

Thickness variations of the seismic units across the faults at the northern side of the basin are best interpreted as indicating some component of strike-slip displacement on these faults (see, for example, line 1 CDP 325). Field mapping along the Hanmer fault zone to the west near Hanmer township indicates that the Holocene displacement history has been oblique normal but is complicated by a series of left step-overs in the surface trace of the fault.

On line 1 between CDP 250 and 330, swampy ground decreased data quality and we consider some of the downward deflection of reflectors to be an artifact of data processing. The presence of the topographic depression at the surface probably indicates deeper-seated fault control.

We have interpreted the faults between CDP 400 and 500 on line 1 as the extension of the Hanmer fault. The Hanmer fault may, however, step-over farther to the northeast where Freund (1971) mapped an active trace and connected it with a zone of faulting and associated crushed bedrock near Hossack Station identified by McMorran (1991) as the possible continuation of the Hanmer fault.

TRANSTENSION: WEST HANMER BASIN

West Hanmer basin is undergoing north-south extension. We infer that the Hope River segment terminates as a series of extensional splays near Woodbank Station (Fig. 2). The well-preserved fault scarps and historical record provide evidence of repeated Holocene rupture.

Another segment of the Hope fault lies beneath the active flood plain of the Waiau River along the southwest margin of the basin. As discussed above, this may be (1) the termination of the Conway segment, (2) a southern splay of the Hope River segment,

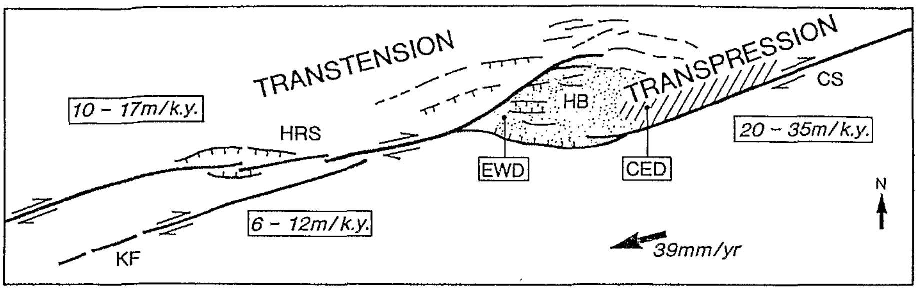

Figure 9. Present-day tectonic setting of Hanmer basin and Hope fault segmentation. KF, Kakapo fault; CS, Conway segment; HRS, Hope River segment; HB, Hanmer basin (bold arrow indicates relative plate motion vector; after de Mets and others, 1990); EWD, extensional western domain; CED, contractional eastern domain; k.y., thousands of years. Dot shading represents basin-fill sedimentation; hatching covers area of basin inversion. Range of determined late Pleistocene/Holocene average slip rates for each segment are indicated in boxes (based on Cowan, 1989, 1990; Yang, 1991; van Dissen, 1991; McMorran, 1991; W. B. Bull, 1991, personal commun.).

or (3) a short, separate segment accommodating slip transfer between the two major segments. Like Freund (1971), we consider most of the deformation in the west part of the basin to be occurring on this short connecting(?) fault as oblique dextral strike slip.

Line 5 reveals the structure beneath the western end of the basin. Basement is well imaged as a strong reflector in this line, with a high velocity contrast between the basement and sedimentary fill. Basement crops out at the north end of line 5 and the south end of line 6. The basin-fill sequence is much thinner than at the east end of the basin, reaching a maximum of 400–500 m near CDP 400 on line 5. Several active fault traces may be correlated with faults interpreted on line 5. Numerous faults disrupt the reflection sequences and displace basement by tens of meters, creating a series of east-west–trending horsts and grabens. At the south end of line 5, a 200 m thickness of low-velocity sediment suggests local subsidence adjacent to the basin margin fault.

Line 6 was located to record reflections from the basin margin fault plane, but results were disappointing. Anomalous arrivals and complex velocity structure did not allow unambiguous interpretation. Our favored interpretation suggests that reflectors terminate against a strong, dipping basal reflection. The data indicate basement at a shallow depth beneath late Pleistocene outwash and gravel associated with a flight of Holocene degradational terraces on the south bank of the Waiau River, suggesting that bedrock exposures elsewhere along the southwest margin are continuous. Basement appears to drop away sharply beneath the river itself, lending support to the inference of a major fault beneath the river bed. The vertical throw on this fault increases significantly to the east (see line 1). Remnant late Pleistocene aggradation gravels 60 m above the Waiau River on the southwest margin of the basin limit the minimum throw on this fault.

DISCUSSION

A variety of structural models for pull-apart basins have been proposed based on both field analogues (for example, Crowell, 1974a, 1974b; Mann and others, 1983; Hempton, 1983; Woodcock and Fischer, 1986; ten Brink and Ben-Avraham, 1989; May and others, 1993) and laboratory-based modeling (for example, Rodgers, 1980; Segall and Pollard, 1980; Naylor and others, 1986; Hempton and Neher, 1986). These studies highlight the complexity and individuality of pull-apart basin formation and proposed mechanisms for basin development. Most studies describe basins forming at step-overs or bends along strike-slip faults. It has generally been assumed that this occurs in accordance with "classical" faulting theory (Anderson, 1951; Wilcox and others, 1973), where the direction of maximum horizontal compression will lie between 30° and 45° to a near-vertical strike-slip fault.

Ben-Avraham (1992) and Ben-Avraham and Zoback (1992) have suggested that strain partitioning may govern development of many large asymmetric basins that are bounded by major strike-slip faults on one margin and by normal faults on the other. Such basins develop by extension normal to the strike-slip fault, coeval with strike-slip motion. This interpretation is in conflict with the classical Mohr/Coulomb faulting theory but may occur if the bounding strike-slip fault is much weaker than the adjacent crust (Ben-Avraham and Zoback, 1992). The horizontal principal stresses in a relative convergent or divergent plate motion setting would be reoriented approximately parallel and perpendicular to the fault to facilitate minimum shear stress on the fault. Ben-Avraham and Zoback (1992) conclude that many strike-slip basins around the world conform to this model, with respect to both structural style and state of stress, and that a fundamental characteristic of such basins is their asymmetry.

Clayton (1966) proposed that Hanmer basin formed at a simple releasing bend on the Hope fault. Observations by Freund (1971) led him to modify Clayton's original model. Freund noted that the bounding master faults are not parallel but converge across the basin and also do not overlap but may connect by a short oblique fault segment (Fig. 9). His model for basin evolution explains how extension and shortening may occur at opposite ends of a basin. Crowell (1974a, 1974b) further elaborated on this, describing the formation of fault wedge basins where strike-slip faults diverge and the corollary situation when uplift of the tip of a fault wedge occurs where strike-slip faults converge (see Crowell, 1974b, Fig. 11). Mann and others (1983) used Freund's work from Hanmer basin as one of a series of pull-apart basin models. However, it must be noted that there are significant differences between their model and the structures and structural geometry described in this paper. Although the western end of Hanmer basin broadly conforms to the extensional gap as proposed by Freund (1971) and Mann and others (1983) (compare also the downward tipped fault wedge of Crowell, 1974b), the east end of the basin, with its contraction and development of a pop-up structure, does not. Freund related the 2-km-long narrow pop-up ridge to the overlap caused by the convergence of the major fault strands. Mann and others (1983) noted that the pop-up area occurs adjacent to but outside of the converging major fault strands. Our mapping and reinterpretation of east Hanmer basin has revealed a much more extensive area of uplift and inversion of older basin fill and basement graywacke north of the Conway segment. Two factors may be important in controlling the location and extent of this contraction and uplift: (1)

the northward dip of ~70° on the main fault plane of the Conway segment east of Hanmer basin and (2) the presence of a wide fault zone of crushed and sheared basement argillite and sandstone. South of this main fault strand, thick-bedded graywacke sandstone in the footwall remains coherent, effectively forming a buttress against which the northern hanging-wall block is being uplifted and deformed by the converging strike-slip displacement. The structural inversion affecting east Hanmer basin resembles the upward-tipped fault wedge of Crowell (1974b); however, there is an important difference in that the master faults are projected to converge across the basin but do not overlap and meet.

Freund (1971) concluded that because the length of the basin appeared to be less than the total offset on the Hope fault (19 km), the short oblique fault segment along the southwest basin margin must have evolved after motion on the Hope fault began. He argued against the formation of the oblique segment as a connection between propagating fault segments. Our revised determination of basin length (20 vs. 15 km) means that the step-over may have been established at the time of Hope fault initiation. Consequently we infer that the oblique segment along the southwest basin margin formed as a result of westward propagation of the Conway segment.

The age of basin formation is not well delineated. From structural and stratigraphic evidence, Cotton (1947) and Clayton (1966) concluded that the basin could be no older than mid-Quaternary. Freund (1971) found no Tertiary sediments and concluded that sedimentation began near the beginning of the Pleistocene.

Late Pleistocene and Holocene slip rates (Fig. 9) for the Hope River segment (10–17 m/k.y., Cowan, 1989, 1990), and for the Kakapo fault (6–12 m/k.y., Cowan, 1989; Yang, 1991), agree broadly with slip rates of about 20–35 m/k.y. for the Conway segment east of the basin (McMorran, 1991; van Dissen, 1991; and W. B. Bull, 1991, personal commun.). An average slip rate of 20 m/k.y. would imply that fault motion began ca. 1 Ma.

From these average deformation rates, the limited age control provided by the ^{14}C sample, and the cold climate indicated by the diatom species, we infer an upper age limit of mid- to late Pleistocene for the onset of sedimentation within this part of Hanmer basin.

The basement structure and onlap of seismic unit 1 on line 1 suggests that an early graben formed, followed by localization of fault motion and asymmetric subsidence along the south margin. Sediments onlap basement to the north, indicating basin growth in that direction. The fanning of sedimentary reflectors toward the Hope fault shows that this is not due to increased sediment supply but to continued tilting of the basin floor about a hinge north of the basin. Changes in thickness of the seismic units reflect changes in basin geometry, with the depocenter migrating west along the basin axis in response to episodic shortening and uplift at the east end of Hanmer basin, and progressive deepening of the west half of the basin.

The Hope River segment terminates as a horsetail splay in the west part of Hanmer basin. The Conway segment probably terminates as the oblique segment along the southwest basin margin, similar to the model proposed by Reading (1980). This interpretation could be tested by extending seismic line 2 along the length of the basin to look for basement structures subparallel to the fault beneath the Waiau River and further detail the westward "shingling" of progressively younger basin fill.

Our preferred interpretation for present basin dynamics (as depicted in Fig. 10) involves a hybrid model in which geometric elements of a fault wedge basin (downward and upward tipped, spindle-shaped ends) are combined with those of a pull-apart basin (step-over region between the major fault segments). At the west end of the basin the master bounding faults converge beneath the depression. The oblique-slip south margin of the basin plays a dominant role in basin evolution as is clearly reflected by the basin-fill asymmetry, westward-directed shingling, and long-term location of the depocenter. The model as drawn shows basin inversion at the east end of the basin and progressive cannibalization of older basin fill. We interpret the Hanmer fault west of Hanmer Springs as a listric oblique normal fault forming the modern northern basin-floor margin. We infer that the fault east of Hanmer Springs is progressively affected by movement reversal, in response to the transpressional setting of east Hanmer basin. A series of other listric normal faults north of Hanmer Plain are reflected by the rising stepped topography of the Hanmer Range (see Fig. 2). We show no preferred vertical scale in our model, but it seems probable that the master faults merge within the seismogenic upper crust.

We see in seismic line 3 that north-south contraction at the east end of the basin has been episodic. Contraction and uplift began after deposition of seismic unit 2. On line 1 units 1 and 2 show the greatest thickening next to the Hope fault. On line 2 units 1 and 2 are nearly constant in thickness, and units 3 and 4 thicken toward the center of the basin. The depocenter shifted west in response to the onset of contraction and uplift. Truncation of seismic unit 2 resulted from this early phase of transpression. Overlying units 3 and 4 show no onlap and only minor thickening toward the Hope fault, reflecting a period of localized quiescence or even transtension. Deformation of these latter units is due to a resumption(?) of transpressive shortening adjacent to and north of the main fault splay. We attribute these episodic variations to local adjustments in master fault geometry at depth.

The segmented Hope fault is subparallel to the relative plate convergence direction (de Mets and others, 1990). Nicol and Wise (1992) and Pettinga and Wise (1994) have studied the upper Cenozoic and modern stress field orientation across the plate boundary zone of northern South Island and concluded that simple strain partitioning and the presence of a weak fault in a strong crust as envisaged for the San Andreas fault (Zoback and others, 1987; Ben-Avraham and Zoback, 1992) cannot easily be applied to the Alpine and Marlborough fault system in New Zealand. The structural evidence presented here for the Hope fault and Hanmer basin suggests local stress field conditions may be highly variable and complex along strike of the fault and may differ significantly from regional stress field conditions. Pettinga and Wise (1994) attribute the complex strain partitioning and highly variable local stress field conditions to the presence of a semidetached crustal slab, where the stresses within and immediately adjacent to this slab are insulated and in part independent of the deeper motions and regional stress conditions associated with the oblique convergence of the Australian and Pacific plates. Further discussion of these concepts are beyond the scope of this paper.

Our data indicate that strain partitioning such as that suggested by Ben-Avraham (1992) and Ben-Avraham and Zoback (1992) is not occurring in Hanmer basin. The occurrence of transpression and trans-

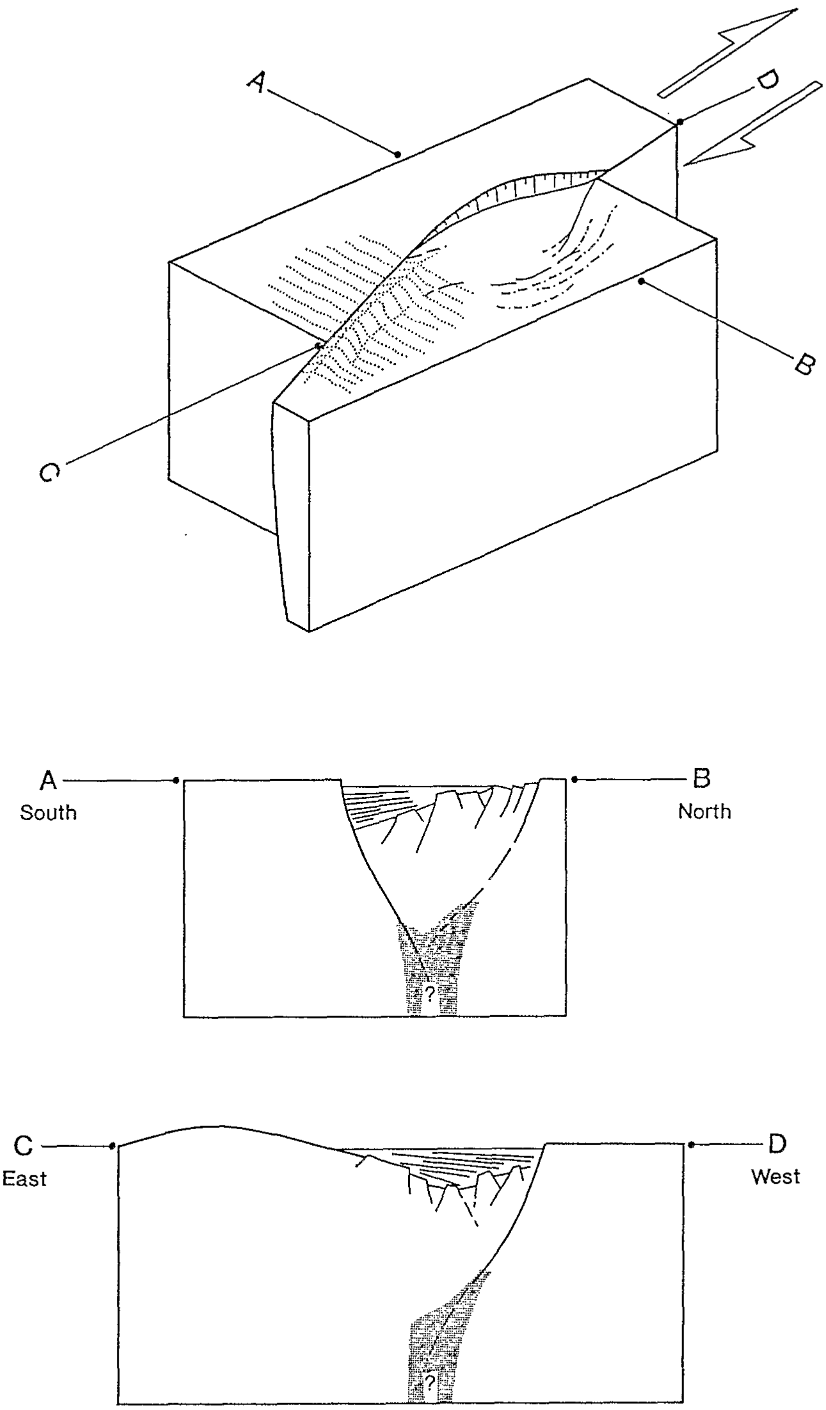

Figure 10. Schematic block diagram of Hanmer basin depicting present-day steady-state stage of evolution. Inferred position of Hope fault zone is indicated at depth by shading.

tension at opposite ends of the basin and the temporal variation of transtension and transpression at the east end of the basin argue against this hypothesis. We conclude that changes in fault geometry (releasing and restraining bends and step-overs) at a variety of scales and over short distances control development of the extensile and contractile parts of the basin as well as longitudinal and transverse basin asymmetry. However, Hanmer basin does not conform to traditional simple models of pull-apart basins but rather is an example of a broader grouping of "hybrid" strike-slip basins.

SUMMARY AND CONCLUSIONS

1. Hanmer basin is evolving at a 6–7 km releasing step-over along the 230 km dextral strike-slip Hope fault. The two bounding master fault segments do not overlap but are connected by an oblique-slip fault along the southwest margin of the depression, which is probably the westward extension of the Conway segment.

2. Basin formation probably began in the middle Pleistocene, based on extrapolation of average late Pleistocene slip rates, climatic factors, and the faunal content of sediments.

3. The depositional environment for the basin-fill sequence is inferred to be analogous to that of the present day and includes distributary alluvial/fluvial fan systems characterized by sandy gravel and peat, silt, and clay deposits associated with swamps and ponded areas. Late Pleistocene glacial deposits indicate lacustrine conditions may have prevailed over parts of the basin from time to time, also.

4. The eastern part of Hanmer basin is undergoing transpression, with sequence inversion occurring in response to north-south shortening caused by the projected convergence in strike of the master fault segments across the basin. The Conway segment along the southeast margin of the basin forms a complex series of diverging oblique reverse fault splays and associated folds. In seismic reflection profiles the fault zone geometry is that of a palm-tree structure. A well-stratified sequence >1 s TWT thick fills the east and central parts of the basin. Four seismic stratigraphic units are identified that show migration of the basin depocenter and variation in motion on the Conway segment. Basin fill is asymmetric, with >1 km of sediments along the south side of the basin, thinning and wedging to the north, and shingled to the west.

5. The west part of the basin is under transtension, actively subsiding in response to north-south extension. The Hope River segment terminates in a complex extensional horsetail array of faults. The basin fill at the west end of the basin is <500 m thick and strongly disrupted by active normal and oblique normal faults widely distributed across the basin and adjacent northwest range front. The seismic sequences established for the eastern part of the basin could not be identified with certainty on these lines.

6. The north margin to the basin extends 4–6 km beyond the area of the releasing

step-over and is defined by a series of topographic steps on the south flank of Hanmer Range, caused by south-facing listric(?) normal faults. These normal faults we interpret to reflect large-scale upper crustal collapse of the hanging-wall side of the Hope fault.

7. We propose a hybrid model for Hanmer strike-slip basin, one in which geometric elements of a fault wedge basin are combined with those typical of a pull-apart basin. Our interpretation of basin evolution modifies the model first proposed by Freund (1971), in which extension and shortening may occur at opposite ends of the basin. Basin formation began with an initial graben and evolved as the two major *en echelon* fault segments propagated and became indirectly linked by the short oblique-slip fault along the southwest margin, so providing for much of the slip transfer between the two master faults. As a consequence, basin subsidence is concentrated adjacent to the southwest margin, leading to progressive asymmetric deepening of the basin, a situation analogous to a basin evolving at a releasing bend along a major strike-slip fault.

8. Hanmer basin today has evolved to what we believe is a more or less steady state, with the rate of basin development in an extensional western domain matched by its progressive inversion and destruction in a contractional eastern domain. Changes in fault geometry, including releasing and restraining bends and step-overs at a variety of scales, have controlled these extensile and contractile domains. Strain partitioning is complex and cannot be simply related to the reorientation of the regional stress field.

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REFERENCES CITED

Anderson, E. M., 1951, The dynamics of faulting and dike formation with applications to Britain (second edition): Edinburgh, Oliver and Boyd, 83 p.

Anderson, H. J., 1987, A gravity survey of the Hanmer Depression, North Canterbury: New Zealand Department of Scientific and Industrial Research (DSIR) Research Report No. 214a, p. 4–20.

Aydin, A., and Nur, A., 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v. 1, p. 91–105.

Aydin, A., and Nur, A., 1985, The types and role of stepovers in strike-slip tectonics, *in* Biddle, K. T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 35–44.

Bannister, S., Wood, R., and Lamarche, G., 1992, Seismic reflection data from the Hanmer basin, New Zealand: New Zealand Department of Scientific and Industrial Research (DSIR) Technical Report No. 116, 23 p.

Ben-Avraham, Z., 1992, Development of asymmetric basins along continental transform faults: Tectonophysics, v. 215, p. 209–220.

Ben-Avraham, Z., and Zoback, M. D., 1992, Transform-normal extension and asymmetric basins: An alternative to pull-apart models: Geology, v. 20, p. 423–426.

Biddle, K. T., and Christie-Blick, N., 1985, Glossary: Strike-slip deformation, basin formation, and sedimentation, *in* Biddle, K. T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 375–386.

Bishop, D. G., Bradshaw, J. D., and Landis, C. A., 1985, Provisional terrain map of the South Island, New Zealand, *in* Howell, D. G., ed., Tectonostratigraphic terranes of the circum-Pacific region: Houston, Texas, Circum-Pacific Council of Energy and Mineral Resources, Earth Science Series 1, p. 515–521.

Bradshaw, J. D., 1989, Cretaceous geotectonic patterns in the New Zealand region: Tectonics, v. 8, p. 803–820.

Christie-Blick, N., and Biddle, K. T., 1985, Deformation and basin formation along strike-slip faults, *in* Biddle, K. T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 1–34.

Clayton, L., 1966, Tectonic depressions along the Hope fault, a transcurrent fault in North Canterbury, New Zealand: New Zealand Journal of Geology and Geophysics, v. 9, p. 95–104.

Cotton, C. A., 1947, The Hanmer Plain and the Hope fault: New Zealand Journal of Science and Technology, v. B29, p. 10–17.

Cowan, H. A., 1989, An evaluation of the late Quaternary displacements and seismic hazard associated with the Hope and Kakapo faults, Amuri District, North Canterbury [Master's thesis]: Christchurch, New Zealand, University of Canterbury, 212 p.

Cowan, H. A., 1990, Late Quaternary displacements on the Hope fault at Glynn Wye: New Zealand Journal of Geology and Geophysics, v. 33, p. 285–293.

Cowan, H. A., 1991, The North Canterbury earthquake of 1 September 1888: Journal of the Royal Society of New Zealand, v. 21, p. 1–12.

Cowan, H. A., and McGlone, M. S., 1991, Late Holocene displacements and characteristic earthquakes on the Hope River segment of the Hope fault, New Zealand: Journal of the Royal Society of New Zealand, v. 21, p. 373–384.

Crowell, J. C., 1974a, Sedimentation along the San Andreas fault, California, *in* Dott, R. H., Jr., and Shaver, R. H., eds., Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication No. 19, p. 292–303.

Crowell, J. C., 1974b, Origin of late Cenozoic basins in southern California, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication No. 22, p. 190–204.

de Mets, C., Gordon, R. G., Argus, D. F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425–478.

Freund, R., 1971, The Hope fault—A strike slip fault in New Zealand: New Zealand Geological Survey Bulletin 86, 47 p.

Freund, R., 1974, Kinematics of transform and transcurrent faults: Tectonophysics, v. 21, p. 93–134.

Hempton, M. R., 1983, The evolution of thought concerning sedimentation in pull-apart basins, *in* Boardman, S. J., ed., Revolution in the earth sciences: Advances in the past half century: Proceedings of a symposium, Carleton College, Northfield, Minnesota, April 1983: Dubuque, Iowa, Kendall-Hunt Publishing Co., 385 p.

Hempton, M. R., and Neher, K., 1986, Experimental fracture, strain and subsidence patterns over *en echelon* strike-slip faults: Implications for the structural evolution of pull-apart basins: Journal of Structural Geology, v. 8, p. 597–605.

Lewis, K. B., and Pettinga, J. R., 1993, Emerging marginal prism of the Hikurangi Trench slope, *in* Ballance, P. F., ed., Sedimentary basins of the world volume 2: Amsterdam, Elsevier, p. 225–250.

Mann, P., Hempton, M. R., Bradley, D. C., and Burke, K., 1983, Development of pull-apart basins: Journal of Geology, v. 91, p. 529–554.

May, S. R., Ehman, K. D., Gray, G. G., and Crowell, J. C., 1993, A new angle on the tectonic evolution of the Ridge basin, a "strike-slip" basin in southern California: Geological Society of America Bulletin, v. 105, p. 1357–1372.

McKay, A., 1890, On the earthquakes of September 1888 in the Amuri and Marlborough Districts of the South Island: New Zealand Geological Survey Report of Geological Explorations 1888–1889, v. 20, p. 1–16.

McMorran, T. J., 1991, The Hope fault at Hossack Station east of Hanmer basin, North Canterbury [Master's thesis]: Christchurch, New Zealand, University of Canterbury, 85 p.

Naylor, M. A., Mandl, G., and Sijpesteijn, C.H.K., 1986, Fault geometrics in basement-induced wrench faulting under different initial stress states: Journal of Structural Geology, v. 8, p. 737–752.

Nicol, A., and Wise, D. U., 1992, Paleostress adjacent to the Alpine fault of New Zealand: Fault vein and stylolite data from the Doctors dome area: Journal of Geophysical Research, v. 97, p. 17685–17692.

Norris, R. J., Koons, P. O., and Cooper, A. F., 1990, The obliquely-convergent plate boundary in the South Island of New Zealand: Implications for ancient collision zones: Journal of Structural Geology, v. 12, p. 715–725.

Pettinga, J. R., and Wise, D. U., 1994, Paleostress adjacent to the Alpine fault: Broader implications from fault analysis near Nelson, South Island, New Zealand: Journal of Geophysical Research, v. 99, p. 2727–2736.

Reading, H. G., 1980, Characteristics and recognition of strike-slip fault systems, *in* Ballance, P. F., and Reading, H. G., eds., Sedimentation in oblique-slip mobile zones: International Association of Sedimentologists, Special Publication No. 4, Blackwell Scientific Publications, p. 7–26.

Rodgers, D. A., 1980, Analysis of pull-apart basin development produced by *en echelon* strike-slip faults, *in* Ballance, P. F., and Reading, H. G., eds., Sedimentation in oblique-slip mobile zones: International Association of Sedimentologists, Special Publication No. 4, Blackwell Scientific Publications, p. 27–41.

Royden, L. H., 1985, The Vienna basin: A thin-skinned pull-apart basin, *in* Biddle, K. T., and Christie-Blick, N., eds., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 319–338.

Schubert, C., 1980, Late Cenozoic pull-apart basins, Boconó fault zone, Venezuelan Andes: Journal of Structural Geology, v. 2, p. 463–468.

Segall, P., and Pollard, D. D., 1980, Mechanics of discontinuous faults: Journal of Geophysical Research, v. 85, p. 4337–4350.

Suggate, R. P., 1965, Late Pleistocene geology of the northern part of the South Island, New Zealand: New Zealand Geological Survey Bulletin 77, 92 p.

Sylvester, A. G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666–1703.

Sylvester, A. G., and Smith, R. R., 1976, Tectonic transpression and basement-controlled deformation in the San Andreas fault zone, Salton Trough, California: American Association of Petroleum Geologists Bulletin, v. 60, p. 2081–2102.

ten Brink, U. S., and Ben-Avraham, Z., 1989, The anatomy of a pull-apart basin: Seismic reflection observations of the Dead Sea basin: Tectonics, v. 8, p. 333–350.

Thompson, G. E. K., 1966, Temperature survey at Hanmer, November 1962: New Zealand Department of Scientific and Industrial Research (DSIR) Geophysics Division Report 42, 7 p.

van Dissen, R. J., 1991, An evaluation of seismic hazard in the Kaikoura region, Southeastern Marlborough: New Zealand Geological Survey Record 43, p. 93–99.

Wilcox, R. E., Harding, T. P., and Seely, D. R., 1973, Basic wrench tectonics: American Association of Petroleum Geologists Bulletin, v. 57, p. 74–96.

Wood, R., 1991, Seismic reflection data from the Hanmer basin, New Zealand: Exploration Geophysics, v. 22, p. 503–508.

Woodcock, N. H., and Fischer, M., 1986, Strike-slip duplexes: Journal of Structural Geology, v. 8, p. 725–735.

Yang, J. S., 1991, The Kakapo fault—A major active dextral fault in the central North Canterbury–Buller regions of New Zealand: New Zealand Journal of Geology and Geophysics, v. 34, p. 137–143.

Zoback, M. D., and others, 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, p. 1105–1111.

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