Seabed instability near the epicentre of the 1929 Grand Banks earthquake

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This open file consists of a sidescan sonar mosaic at 1:200,000 of about 5000 km^2 of continental slope off the Laurentian Channel and St. Pierre Bank, around the epicentre of the 1929 Grand Banks earthquake, together with a short interpretative text and illustrations.

ABSTRACT

The continental slope around the epicentre of the 1929 Grand Banks earthquake on the continental slope south of Newfoundland has been investigated using high-resolution seismic profiles, piston cores, and Sea MARC I: a deeply towed mid-range sidescan sonar and 4.5 kHz subbottom profiler package. The head of the Eastern Valley of the Laurentian Fan is marked by arcuate slide scars cutting undisturbed upper-slope sediment. Downslope from the scars is a lineated erosional seabed, which at a water depth of about 1600 m passes into extensive fields of large-scale gravel waves situated on the broad, irregular valley floor. On St. Pierre Slope to the east, surface gassy muds have been removed over large areas and shallow slumps passing downslope into debris flows are common. Sediment instability features are not seen above the 500 m isobath. Their development may be controlled by the downslope change from till to pro-glacial silty muds on the upper slope. All the morphological features appear fresh on the sidescan sonograms, suggesting that they date from the 1929 earthquake event, and the distribution of slides corresponds to the area of instantaneous cable breaks in 1929. The main 1929 turbidity current probably resulted from the sliding of a till tongue that rested on proglacial mud. Similar geologic conditions are common on continental slopes off eastern Canada, so that another large magnitude earthquake elsewhere on the continental slope might have similarly catastrophic consequences.

INTRODUCTION

In June 1983 a 10-day sidescan sonar survey was carried out on Hudson Cruise 83-017 using Sea MARC I in the area around the epicentre of the 1929 Grand Banks earthquake (Doxsee, 1948). The epicentre of this magnitude 7.2 earthquake was located near the eastern margin of a complex valley system on the eastern Canadian continental slope above the Laurentian Fan (Stewart, 1979). This earthquake triggered sediment failure within 100 km of the epicentre (Figure 1) and initiated a turbidity current that flowed a distance of more than 900 km to the Sohm Abyssal Plain (Heezen and Ewing, 1952; Heezen et al., 1954a,b; Piper et al., 1984).

Subsequently, on Dawson Cruise 84-003, 20 piston cores were collected in water depths of less than 1500 m within the survey area (Table 1), and high resolution seismic profiles were obtained in water depths of less than 700 m. Detailed geotechnical investigations of the cores are in progress.

The purpose of this survey was to establish the style and magnitude of seabed instability features associated with a historical earthquake of known magnitude.

Methods

Sea MARC I is a deeply-towed instrument package containing 27 and 30 kHz sidescan sonar transducers and a 4.5 kHz subbottom profiler (Ryan, 1982; Chayes, 1983). The sidescan system may be operated to produce records with real-time slant range corrections and swath widths of 1, 2 or 5 km. The 5 km swath was used throughout most of this survey. Navigation was by LORAN C with phase lag corrections empirically applied by comparison of LORAN C and satellite data. Sea MARC I towbody positions were estimated from acoustic ranging with the ship.

The 4.5 kHz sub-bottom profiler was operated continuously throughout the first half of the survey. In the second half, an experimental CHIRP sonar package was used (Mayer and LeBlanc, 1983), and about 14 hours of data were recorded. A surface-towed ORE 3.5 kHz profiler was run throughout the survey, and the data displayed at sweep speeds of 1 and 4 secs.

The orthorectified sidescan images were manually compiled into a mosaic at a scale of 1:40 000. Where recorder paper advance speed was not correctly adjusted aboard ship to offset variations in tow speed, the images have been cut and either spaced or overlapped. The mosaic was compiled in thirteen 15' lat. by 30' long. sheets (Fig. 2) which have been photographically reproduced as Plates 1-13.

On Dawson cruise 84-003, high resolution seismic reflection profiles (Fig. 3) were obtained using the Nova Scotia Research Foundation Corporation V-fin sparker system (Bidgood, 1974). Both sparker and hydrophone were towed at about 100 m below the water surface; the sparker was operated at 400 joules and a half second firing rate. A hull mounted 3.5 kHz profiler was operated simultaneously.

Geological Setting

The 1929 Grand Banks earthquake epicentre was located on the continental slope immediately southeast of the Laurentian Channel, a 400 m deep, 70 km wide glacially-excavated trough that separates Banquereau and St. Pierre Bank on the outer continental shelf (Fader et al., 1984). The continental slope between the Laurentian Channel and the upper Laurentian Fan is steep (4-5°) and generally lacks soft, stratified sediments. It is traversed by a complex network of shallow valleys that merge into two main fan valleys at 3000-3500 m depth (Masson et al., in press). In contrast, the continental slopes adjacent to Banquereau and St. Pierre Bank have a thick Pleistocene sequence of stratified sediments, and are traversed by a few well-defined canyon-valley systems.

The Laurentian Channel was filled with grounded ice in the mid-Wisconsinan (King and Fader, in press) and the channel was subsequently a significant iceberg route (King and Maclean, 1970). Till occurs in water depths of up to 500 m on the upper continental slope (Meagher, 1984). Piston cores (Stow, 1981) suggest that the levees of the Laurentian Fan valleys were the site of thick mud turbidite deposition in the Wisconsinan but have accumulated hemipelagic sediments throughout the Holocene. Cores from the fan valleys contain sand or gravel.

During the 1929 earthquake, submarine cables were broken instantaneously over a large area of the continental slope above the Laurentian Fan within 100 km of the epicentre. On the Laurentian Fan and northern Sohm Abyssal Plain, cables broke sequentially from one to 13 hours after the earthquake (Fig. 1). These breaks indicate a turbidity current with velocities of at least 65 km/hr on the upper fan. Sands apparently derived from this event have been identified over much of the northern Sohm Abyssal Plain (Fruth, 1965; Piper et al., 1984), but there is no evidence of recent turbidites on the levees of the Laurentian Fan.

We can distinguish three physiographic regions within our study area. The western part is informally termed the "Intervalley Divide", and extends westwards to the Western Valley of the Laurentian Fan. The central region is the Eastern Valley of the Laurentian Fan. The eastern area, adjacent to St. Pierre Bank, we call the "St. Pierre Slope", and it is traversed by a tributary valley which we call the "St. Pierre Valley".

MORPHOGENETIC SEABED TYPES

Method

The seabed in the survey area has been divided into nine morphogenetic types (Fig. 4) on the basis of features visible in sidescan and subbottom profiler records that are interpreted as being of genetic significance. The most important features are seabed morphology (as seen in sonograms and acoustic profiles), surface acoustic reflectivity (as an indicator of surficial sediment type), and the style of sub-bottom stratification as seen in 3.5 kHz or 4.5 kHz profiles.

The nine morphogenetic types are:

1. Flat undisturbed seabed, generally smooth with parallel sub-bottom reflectors on sub-bottom profiles. Surface reflectivity suggests sand in less than 400 m water depth, and mud elsewhere. Rare pockmarks occur locally.
2. Gullied ridges and spurs, dissected by valleys with tributary gullies that have eroded headwards to produce sharp-crested ridges. Sub-bottom profiles show no clear evidence for morphological control imparted by acoustically stratified sediment.
3. Channel floors, generally uniform low reflectivity within continuous depressions with little sub-bottom penetration in acoustic profiles, suggesting a mud veneer over sandy channel fill.
4. Lineated valley floor, relief less than 30 m. Sidescan sonograms show pronounced lineations oriented downslope that are interpreted as low scarps or ridges sculpted by turbidity

current scour. Sub-bottom acoustic profiles show little penetration.

5. Irregular valley floor, with relief 20-50 m high. Occurs mainly on the Eastern Valley floor, and has highly reflective surficial sediment, so that the relationship to sub-bottom strata is unclear.

6. Low relief valley floor, in the Eastern Valley. Relief <20 m, with some small scale roughness (but lacking lineations) and no sub-bottom acoustic penetration.

7. Dissected stratified sediments with debris, relief >25 m. These are relatively high areas, cut by valleys, in which relief appears to be controlled by acoustically horizontally stratified beds that produce a scarp and terrace morphology, often mantled by debris flows. In a few areas, this morphogenetic unit may comprise large slide blocks.

8. Dissected stratified sediments with debris, relief 5-25 m. This includes series of arcuate or valley wall slump and slide scars, developed in acoustically stratified beds. Debris flows occur locally, but the principal relief elements are scarps and terraces.

9. Thin slides and debris flows overlying acoustically stratified sediments, generally on rather flat seafloor. Many of the allochthonous sediments have surface ridges, and are acoustically transparent (c.f. Piper *et al.*, 1983).

REGIONAL DESCRIPTION OF SEABED GEOLOGY

Intervalley Divide

The Intervalley Divide comprises gullied ridges and spurs (Fig. 5) dissected by a network of sinuous valleys, with rare small areas of flat undisturbed seabed. Submarine headward erosion through a variety of mass wasting processes is the mechanism most widely cited for the development of this type of morphology (Shepard, 1981; Twichell and Roberts, 1982; McGregor *et al.*, 1982; Farre *et al.*, 1983). It is presumed that these processes act over considerable periods of time, so that gullied ridge and spur morphology is one that is relatively mature.

Eastern Valley

The uppermost part of the Eastern Valley comprises three valley heads separated by ridges with gullied morphology (Figs. 4 and 6). Smooth, relatively undisturbed sediments are preserved in depths shallower than 800 m. They are cut by a series of arcuate slide scars, typically about 1 km across. The seabed immediately below the scars has irregular relief with scattered isolated sidescan targets interpreted as large blocks. From 1000 to 1600 m depth, the seabed is strongly lineated downslope (Fig. 6). The lineations have relief of less than 30 m. This upper slope region is also traversed by several shallow channels (Figs. 4 and 6).

Below approximately 1600 m, the Eastern Valley floor becomes relatively flat, although some regions have irregular relief of up to 50 meters in elevation. Fields of sediment waves, interpreted below as consisting of gravel, first occur in water depths of about 1500 m at the ends of the shallow channels crossing the upper slope. The gravel waves become more widespread further downvalley (Figs. 7, 8, 9 and 10).

In water depths less than 2500 meters, the cross-profile of the Eastern Valley shows a central elevated region bounded by a thalweg channel adjacent to each valley wall. Below this depth the valley cross-profile becomes more complex. At 2700 m, a ridge on the western side of the valley rises above the valley floor, gradually merging down valley with a gullied ridge 300 m above the thalweg near 3000 m (Fig. 4). Two south-facing depressions, up to 1 km in length, occur on this ridge and are morphologically similar to the "giant flute marks" described by Normark et al. (1979). This ridge extends southwards to become the western levee of the Eastern Valley (Piper and Normark, 1982a). A similar topography occurs on the eastern side of the valley at 3000 m, where an elevated section of the valley floor rises southwards to 150 m above thalweg depth. In this way, between 2000 and 3000 m water depth, two distributary valleys appear to split off from the Eastern Valley. These distributaries can be traced at least to the 4000 m contour (Edgar and Piper, 1979).

Gravel waves are not common at the valley margins, where the thalweg is largely floored by less reflective sediment. On one sonogram (Fig. 8) a tongue of acoustically transparent sediment interpreted as a debris flow overlies the gravel waves along the eastern margin of the valley. In some areas a narrow sinuous channel occupies the thalweg at the valley margin. These channels show a lower acoustic reflectivity on sidescan sonograms, with little penetration evident on subbottom profiles. This suggests a thin mud layer occurs over sand or gravel.

St. Pierre Slope

The uppermost part of St. Pierre Slope is a smooth, apparently undisturbed seabed. In water depths of 500 to 800 m, the slope is cut by a series of slide scars which open downslope into elongate zones of reflective debris. The slide scars tend to be larger, but more isolated, than those at the head of the Eastern Valley.

Slide scars on the western part of St. Pierre Slope open into a region of dissected terraced morphology with relief of 5-25 m; this region in turn leads into St. Pierre Valley. From 1200 to 2400 m the floor of St. Pierre Valley has a flat lineated surface (Fig. 11), with isolated segments of weakly reflective channel floor. From 1400 to 2000 m, a large, blocky, allochtonous mass from the valley wall fills the western part of the valley floor. The flat lineated morphology is truncated near the mouth of St. Pierre Valley by a small gravel wave field at a depth of 2300 m. Both of these morphogenetic types are overlain by a debris flow. The same flow also overlies gravel waves at the edge of the Eastern Valley (Fig. 8).

The ridge separating Eastern Valley from St. Pierre Valley slopes steeply to the northeast and more gently to the southwest below 1200 m. The crest of this ridge, below depths of 1200 m, is mantled by thin debris flows. The ridge flanks have a dissected, terraced morphology with local debris. This morphogenetic type is discordant to the flat, lineated surface of the Eastern Valley floor.

Arcuate slide scars on the slope east of St. Pierre Valley are similar to the scars on the upper slope, but occur in water depths ranging from 800 to 1900 m. In this region large areas of seabed appear only slightly disturbed. Sidescan sonograms show downslope-trending lineations which suggest that superficial flows may have occurred and sub-bottom profiles suggest several metres of surficial sediment is missing. Very faint contour-parallel lineations in some areas suggest slumping or creep may have occurred (Piper et al., 1983).

have occurred (Piper *et al.*, 1983).

SEISMIC STRATIGRAPHY OF THE UPPER SLOPE

The seismic stratigraphy of the upper slope is known from two data sets. Multichannel 40 cu. in. air-gun profiles (Piper and Normark, 1982c; Meagher, 1984) show a mid-Miocene reflector at about 0.5 secs subbottom (J. Wade, pers. comm., 1984). Above this level, acoustically homogeneous zones interpreted as till (Meagher, 1984) occur both on the St. Pierre Slope and at the head of Eastern Valley.

Deep-towed sparker profiles provide information on the upper 100 msec of sediment on the upper St. Pierre Slope (Fig. 12). These show three acoustic stratigraphic units:

(a) acoustically homogenous material interpreted as till. This unit extends downslope from the outer continental shelf to the 500 m isobath, where it thins out.

(b) overlying and laterally equivalent to the till is acoustically well-stratified sediment that acoustically resembles the Emerald Silt on the Scotian Shelf. Small lift-off moraines mark its contact with the till near the feather edge of the till (Fig. 12).

(c) the surface sediment is an acoustically poorly stratified transparent unit that resembles the La Have clay on the Scotian Shelf. This unit is about 15 msec thick, and over wide areas has been removed by slumping. Upslope the unit thins and becomes less transparent, probably reflecting increased silt content.

The core control confirms this lithologic interpretation of surficial sediments on the upper slope. The "La Have Clay" equivalent comprises bioturbated gassy olive-grey mud. The "Emerald Silt" equivalent consists of a variety of red and grey silty and muddy facies. The "till" consists of silty sand with rare pebbles.

DESCRIPTION OF INDIVIDUAL SEABED FEATURES

Gravel Waves

Gravel waves in the Eastern Valley of Laurentian Fan are mainly restricted to the elevated plateau in the centre of the valley (Fig. 7), which rises approximately 50 meters above the thalwegs near the east and west valley margins. A few gravel waves are observed in waters shallower than 1500 meters in the valley. The main field (illustrated in Fig. 10) occupies a V-shaped area, which widens from an apex at 2000 meters depth to a field more than 10 km across on our deepest line at 3000 meters. The field thus extends more than 50 km down valley (Fig. 7). Three cores from this area taken during Cruises Vema 2-2 and Dawson 84-003 (Fig. 1) recovered gravel and coarse sand at the surface. The very high acoustic reflectivity also suggests that the bedforms are composed of gravel. The field is believed to extend further down-valley, as waves on the deeper sonograms are quite well-developed and the field continues to broaden in the downslope direction. Furthermore, piston cores collected from the valley axis at a water depth of 4500 meters were described by Stow (1977; 1981) to contain graded gravel and sand up to 6.5 m thick (Fig. 1).

Gravel waves in the Eastern Valley are typically 2 to 5 meters high, 50 to 100 meters in wavelength, and are highly asymmetrical. The lee or slip slope faces downvalley (Fig. 8). The gravel waves are too small to be clearly resolved even with an echosounder towed 80 m above the bottom. Our only information on the bedform shape comes from sidescan sonograms, which clearly indicate that acoustic shadows are cast by the bedform crests when looking down-valley. When looking upvalley, the steeper lee slope returns a strong reflection, and shadows are not cast. Shadow length when the tow vehicle was close to bottom was used to estimate bedform height.

Core 84-003-2, from 1800 m water depth near the upslope limit of gravel waves, recovered about 2 metres of normally graded slightly muddy gravel overlain by 45 cm of well sorted coarse gravel. The muddy gravel resembles the A-division of coarse proximal turbidites in deep-sea fan valleys (e.g. Piper and Normark, 1971; Stanley, 1980), whereas the coarse gravel resembles a reworked or lag deposit probably equivalent to the well-developed gravel waves further downslope.

Sand Ribbons

The surface of the gravel wave field is crossed by a number of long, lower reflectivity streaks. The reflectivity of these streaks is intermediate between that of the gravel waves and the reflectivity of stratified, acoustically transparent muds on St. Pierre Slope. The streaks are quite similar in appearance and size to sand ribbons on gravel substrate illustrated from the English Channel by Belderson _et al._ (1972). The streaks in the Valley are parallel or sub-parallel to the valley trend, and are typically 100 to 500 meters across and up to 25 km or more in length (Fig. 10). The streaks emanate from intra-valley channels of the upper valley and from the St. Pierre Valley.

The Eastern Valley streaks do not exhibit significant relief nor subbottom reflectors. This suggests that either they are too thin to resolve with the SeaMARC 4.5 kHz subbottom profiler (approx. 1 meter resolution) or that their acoustic impedance is not significantly different from that of the underlying gravel waves. We conclude that they are probably sand ribbons, although we have no corroborating evidence from direct observations, photographs, or samples.

Upper Slope Slide Scars

The location of the prominent arcuate slide scars on the upper slope corresponds to two other significant geological features. The material that has slumped away is largely the gassy mud of the "La Have Clay" equivalent. The slump scars occur at approximately the upslope limit of this gassy mud, which becomes increasingly silty upslope. Second, the scars occur approximately along the feather edge of the till. Geotechnical analysis of core samples is currently in progress to assess which of these factors is of greater importance.

Pockmarks

Closed depressions approximately 10-30 m in diameter are visible in areas of flat undisturbed seabed in water depths of 400 to 1700 m. Cores from the uppermost 5-10 m of sediment in these areas ("La Have Clay" equivalent) recovered mud which expanded and gave off gas. Samples of mud canned shortly after core recovery contained mostly methane, but also small amounts of ethane, propane and butane (Table 2). The closed depressions in gaseous mud are interpreted as pockmarks.

Stripped off Sediment on St. Pierre Slope

Over widespread areas of the St. Pierre Slope, the uppermost 5-15 m of sediment appear to have been removed. Limited core and 3.5 kHz data suggest that this "missing" sediment is the "La Have Clay" equivalent. The present sediment surface frequently has a wrinkled or streaked appearance.

Rotational Slumps

On the St. Pierre Slope, there are large areas of seabed with prominent surface ridges a few metres high and a spacing of many tens to hundreds of metres. They occur downslope from 5 to 50 m high scarps. This "wrinkled" or "thumbprint" seabed is similar to regressive slumps described on land from the St. Lawrence Lowlands by LaRochelle *et al.* (1970) and Mollard (1975, Figs. 11.6, 11.7)

Debris Flows

Debris flows are difficult to distinguish acoustically from many slumps, and furthermore, thin debris flows may overlie slumps (see discussion in Piper, Farre and Shor, 1984). Much of the St. Pierre slope has irregular acoustically homogenous seabed that may result from either slumping or debris flow. The feature at the mouth of St. Pierre Valley, interpreted acoustically as a debris flow in Figure 8, was cored: the upper 17 cm consist of clay clasts in a fine grained matrix, overlying what appears to be a block of laminated silty mud (core 84-003-6).

DISCUSSION

Morphological Features of Pleistocene Age

The scale of the major morphologic features of the study area indicates that the features pre-date the 1929 earthquake. The complex gullied morphology of the Intervalley Divide (and isolated intra-valley sites) could not have developed from only one or two catastrophic events. The Eastern Valley is unusually wide, and has incised channel thalwegs along both its eastern and western margins that lead downslope into distinct upper-fan valleys. This broad valley may have developed by complex valley piracy, although its flat floor may be partly depositional in origin. The Eastern Valley thus was probably sculpted by a variety of processes.

During the Wisconsinan glaciation, grounded ice or an ice shelf extended beyond the shelf break, and turbidity currents on the Laurentian Fan were more frequent than in the Holocene (Stow, 1981). Many of the features of the Eastern Valley might date from this time. On the St. Pierre Slope, muds and silts accumulated throughout the late Pleistocene and Holocene to give a thick, acoustically well stratified, sediment sequence (Piper and Normark, 1982b).

Morphological Features Dating from 1929

The slide scars and debris flows on St. Pierre Slope appear morphologically fresh and have no observable overlying sediment drape. Their distribution corresponds approximately to the extent of "instantaneous" cable breaks of 1929 (Piper and Normark, 1982b), and there is no acoustic evidence for slumping in the underlying 30 to 100 m of sediment on the upper slope. The slide scars and debris flows are thus interpreted to have resulted directly from the 1929 earthquake.

On the more gently sloping areas of St. Pierre Slope, debris extends downslope from the slide scars as debris flows. In contrast, in the Eastern Valley and St. Pierre Valley, slide scars pass downslope into areas of lineated topography, which may result from erosion by debris flows or turbidity currents. Further downslope from these lineated areas, the valley floor has low, irregular relief with fields of gravel wave. This region shows neither gully dissection nor acoustic evidence of subsurface stratification, and thus may be debris flow deposits, the top of which has been winnowed to form gravel waves.

Although there is no direct evidence for the age of the lineated seabed or gravel waves in the Eastern Valley, the freshness of the features and the unusual flow conditions which would be necessary to build gravel waves suggest that both morphogenetic types were formed during the 1929 event. The age of sediment beneath the gravel waves is unknown.

Piper et al. (1984) demonstrate that the current velocities required to transport and build the gravel waves are less than these inferred for the 1929 turbidity current from the timing of cable breaks.
The gravel modal grain size of about 2 cm implies a friction velocity of 14 cm/sec, corresponding to a mean current velocity of some 4 m/s (14 km/hr) for bed load transport (Dyer, 1972; Walker, 1975; Bowen et al., 1984). The thick, sorted and graded beds in Stow's cores from 4500 m water depth imply high transport rates resulting from initial transport in suspension which would require a velocity of at least 10 m/s (36 km/hr) (Bowen et al., 1984). A flow velocity in excess of 18 meters per second (65 km/hr) was estimated for the initial phase of the turbidity current which was generated by the Grand Banks earthquake (Heezen and Ewing, 1952). This estimate suggests that the head of the 1929 turbidity current could have transported 2 cm gravel in suspension, accounting for the occurrence of thick graded gravel beds in 4500 m water depth. As velocity decreased, bedload transport could have built the gravel into waves. In the Eastern Valley, gravel waves are best developed on the central elevated region: this may be because of flow restriction and hence increased flow velocity over this feature (Fig. 13).

The small area of gullied morphology at the crest of the high area in the southwest part of Eastern Valley shows no evidence of having been eroded by the flow, implying a maximum thalweg flow thickness of 300 m in this area. Further evidence for a relatively thin flow is found in St. Pierre Valley, where the change from lineated valley floor to gullied valley wall occurs about 150 m above the thalweg depth (Fig. 11).

Origin of the Main 1929 Turbidite

The data of Fruth (1965), confirmed by re-examination of cores by Aksu (1984), suggest that on the Sohm Abyssal Plain the main 1929 turbidite comprises about 90% sand or coarse silt and 10% mud. The gravel deposited within the fan valleys would further increase the proportion of coarse sediment.

Both cores and acoustic data suggest that the St. Pierre slope is predominantly muddy, and the SeaMARC and seismic reflection data do not show slump features cutting coarse upper slope facies. The source of the coarse material in the 1929 turbidite thus probably lies at the head of Eastern Valley.

The occurrence of till overlying stratified proglacial sediments ("Emerald Silt equivalent") on the upper St. Pierre Slope suggests that similar conditions probably existed at the head of Eastern Valley, at the end of the Laurentian Channel, which was the major outlet for ice from Atlantic Canada. Such a till tongue would contain a high proportion of sand and gravel, and on a steep slope overlying laminated silty clay might be potentially unstable.

Evidence for Multiple Slump Events in 1929

There is evidence that some slumping followed the main 1929 slump-turbidity current event. A debris flow overlies prominent gravel waves at the mouth of St. Pierre Valley.

CONCLUSIONS: IMPLICATIONS FOR HYDROCARBON DEVELOPMENT

1. The magnitude 7.2 Grand Banks earthquake caused widespread sediment failure on the continental slope within 100 km of its epicentre.
2. Gassy muds, 5-15 m thick, on the upper slope were particularly susceptible to failure.
3. Even near the epicentre, sediment instability features are not seen in water depths of less than 500 m, where the seabed consists of till overlain by sand.
4. Failure of a thick till tongue overlying stratified silts at the head of Eastern Valley was probably responsible for the 1929 turbidity current, which transported at least 10^9 m^3 of sediment. Part of this sediment load may have been derived from sand with the Eastern Valley of Laurentian Fan.
5. Rotational slumps developed in muddy sediment on the St. Pierre Slope. Debris flows and turbidites derived from this area are volumetrically less important.
6. Powerful currents with velocities of at least 4 m/sec occurred in water depths as shallow as 1500 m in Eastern Valley during the 1929 event. The main turbidity current in Eastern Valley had a velocity in excess of 10 m/sec.
7. The geologic conditions that led to these sediment mass movements as a result of the 1929 earthquake are widespread on eastern Canadian continental slopes: they result primarily from glacial ice extending to the shelf edge and floating off on the upper slope. A similar magnitude earthquake elsewhere on the continental slope could thus have similarly catastrophic effects.
8. Gas samples recovered from muds on St. Pierre Slope contains

significant ethane, propane and butane and may be petroliferous in origin: there may thus be gas seeps on the continental slope in this area.

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FIGURES

Fig. 1. Location map showing area of survey in box (Fig. 2), approximate epicenter of 1929 earthquake, location of cable breaks and cores sites containing gravel.

Fig. 2. Key map to the 13 sheets of sidescan mosaic (Plates 1-13).

Fig. 3. Key map to location of seismic reflection profiles.

Fig. 4. Classification of surface morphology of the study area around the epicenter of the 1929 earthquake, based on interpretation of Sea MARC I sidescan sonograms and sub-bottom profiles. Morphogenetic types defined in more detail in text. Also shows location of cores. Inset shows three physiographic regions, Sea MARC I tow vehicle tracks, and location of figures 5,6,8,9,10 and 11.

Fig. 5. Gullied ridges and spurs at approximately 1000 m water depth on Intervalley Divide. R = major ridges, V = major valleys.

Fig. 6. 5-km swath sidescan sonogram of the head of the Eastern Valley. In the northeast, undisturbed seabed on the upper slope is cut by shallow slide detachment scarps, partly filled by blocky reflective debris. In the central area, the seabed appears eroded with down-slope lineations and widespread irregular blocks. In the south-west, gullied ridges and spurs with a flat channel floor in extreme southwest.

Fig. 7. Distribution of gravel waves in Eastern Valley and St. Pierre Valley, interpreted from sidescan sonograms.

Fig. 8. 1-km swath sidescan sonogram from 2500 m water depth at the eastern margin of Eastern Valley. Gravel waves in west are in sharp juxta-position with smooth, low-reflectivity seabed in northeast. 4.5 kHz sub-bottom profile shows that the smooth seabed is a 10 m thick

debris flow that overlies the gravel waves. (Thick line above subbottom profile is artefact produced by outgoing acoustic signal.)

Fig. 9. 5-km swath sidescan sonogram of gravel waves and irregular valley floor at 2400 m water depth in Eastern Valley.

Fig. 10. 5-km swath width sonogram of gravel waves at 3000 m water depth in Eastern Valley.

Fig. 11. 5-km swath sidescan sonogram of a cross-section of St. Pierre Valley. In extreme northeast, seabed appears only slightly disturbed. Floor of St. Pierre Valley is lineated in east and smooth in west. Steep walls of St. Pierre Valley are dissected by gullies.

Fig. 12. Selected sparker profiles showing acoustic stratigraphy and location of cores on upper St. Pierre Slope.

Fig. 13. Schematic cross-section of waning stages of 1929 turbidity current flow in Eastern Valley, showing inferred flow thickness and vertical distribution of suspended sediment.

PLATES

1-13 Mosaics of SeaMARC I sidescan images. For location, see Fig. 2. Scale approximately 1:200 000.

TABLE 1. CORES OBTAINED ON CRUISE 84-003

These cores are archived at Bedford Institute of Oceanography; detailed core descriptions are available on request.

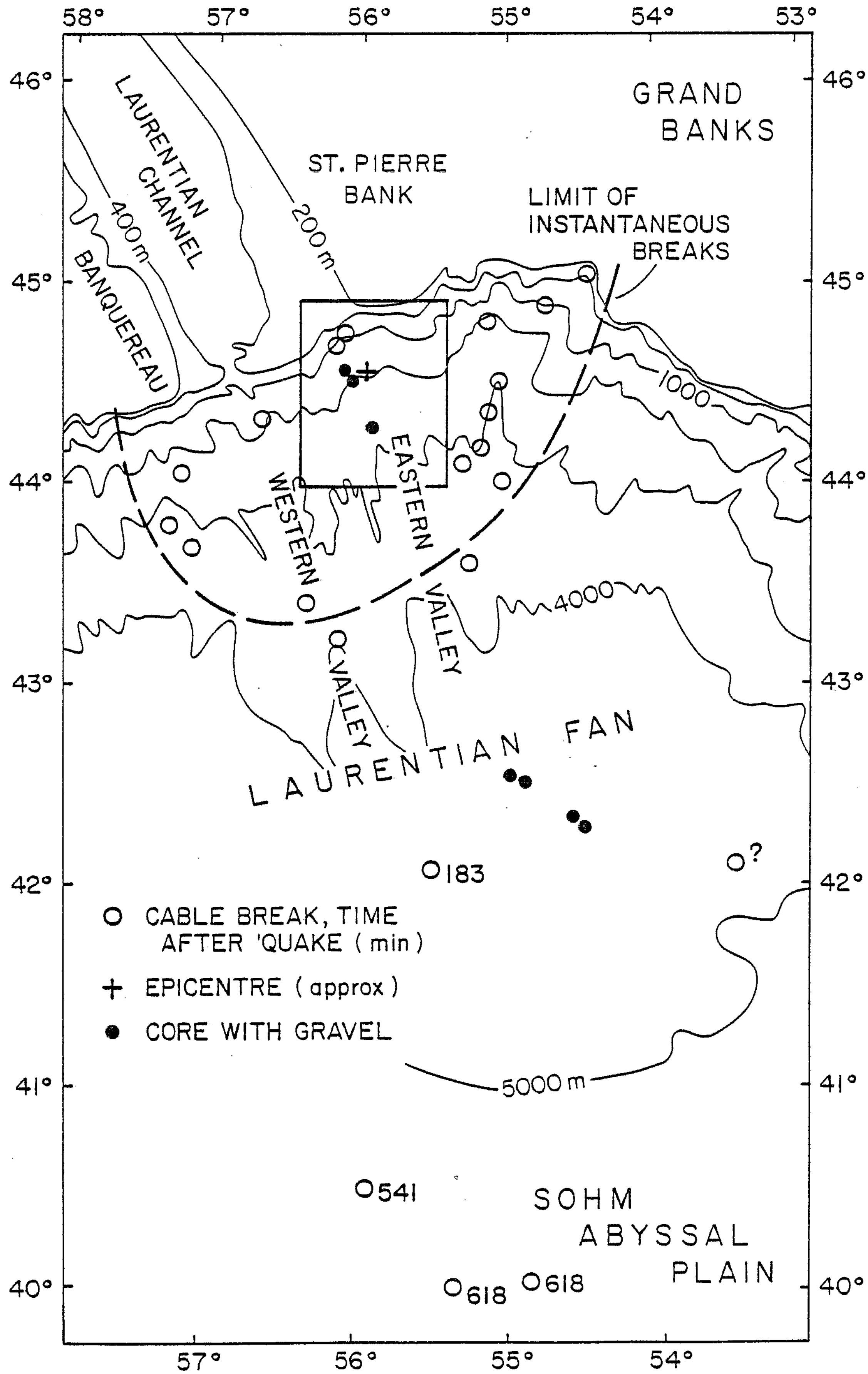
Number	Lat. °N	Long. °W	Water depth m	Trigger weight core length (cm)	Piston core length (cm)
1	44 33.75	56 18.05	1063	43*	348*
2	44 33.35	56 08.77	1793	CC only	16
3	44 31.49	56 03.59	2013	-	129
4	44 39.01	55 45.10	1405	84*	823*
5	44 36.96	55 47.83	1537	-	809*
6	44 25.65	55 49.94	2661	65*	-
7	44 42.52	55 32.02	1124	28*	616*
8	44 48.44	56 06.66	560	117*	624*
9	44 49.06	56 04.24	586	106	783
10	44 50.19	55 58.69	564	-	719
11	44 50.12	55 54.10	586	-	827*
12	44 50.07	55 51.15	571	-	752*
13	44 49.96	55 44.08	483	-	672*
14	44 50.03	55 42.14	470	-	758*
15	44 50.84	55 51.15	516	-	729*
16	44 49.72	55 41.86	494	-	105*
17	44 49.49	55 40.82	469	-	255*
18	44 47.26	55 55.14	1078	-	128*
19	44 48.20	56.09.14	480	-	100*

* - geotechnical core

TABLE 2. GAS ANALYSES FROM PISTON CORES, UPPER ST. PIERRE SLOPE

Samples of mud were taken from cores on board ship and canned immediately. Analyses by Ocean Chem Ltd.

84-003-009	C_1 (Methane)	3%
	C_2 (ethane)	<0.1 (0.08)%
	C_3 (propane)	<0.1 (0.08)%
	C_4 (butane)	<0.1 (0.08)%
84-003-010	C_1 (methane)	1.6%
84-003-015	C_1 (methane)	2.3%



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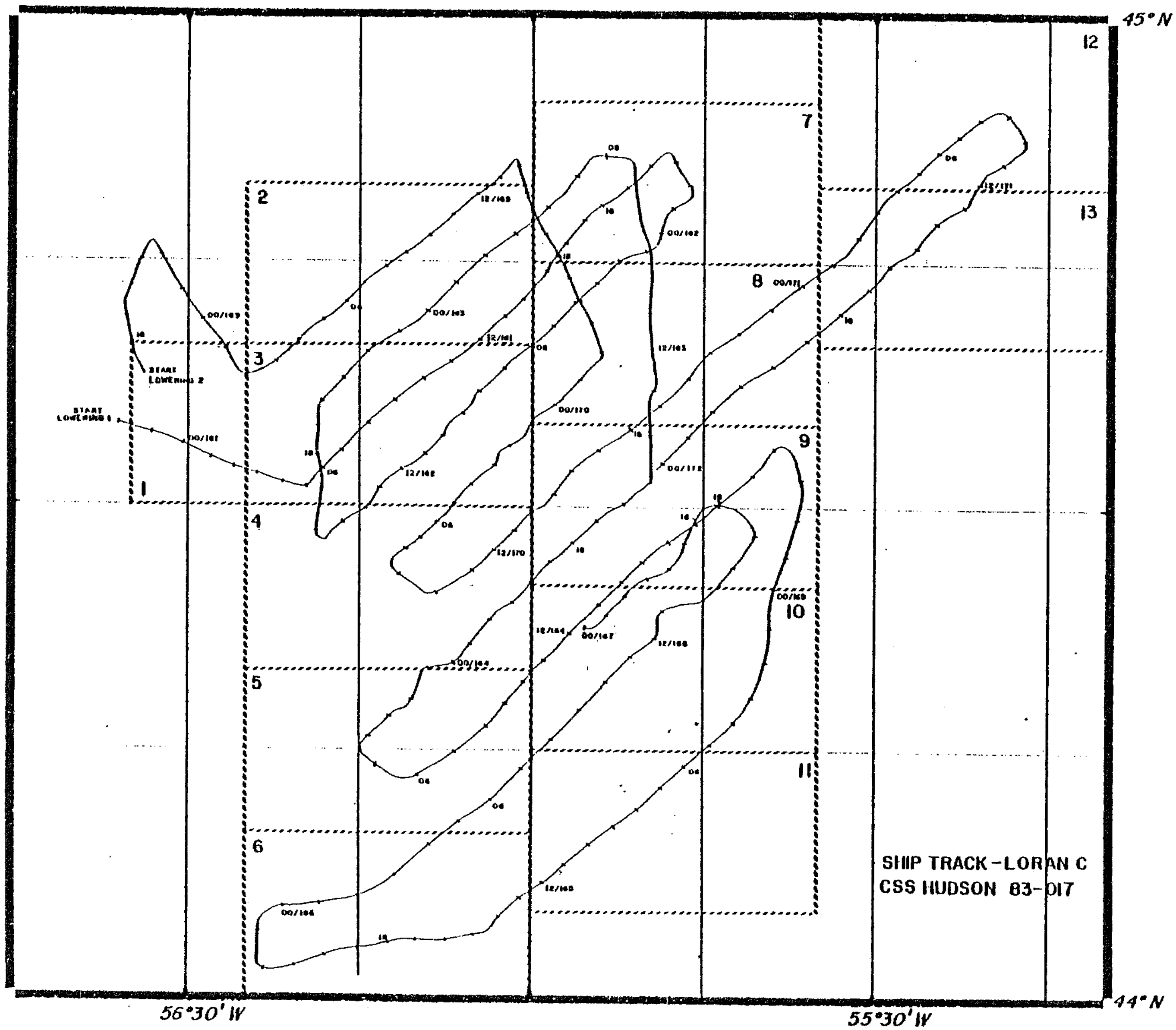

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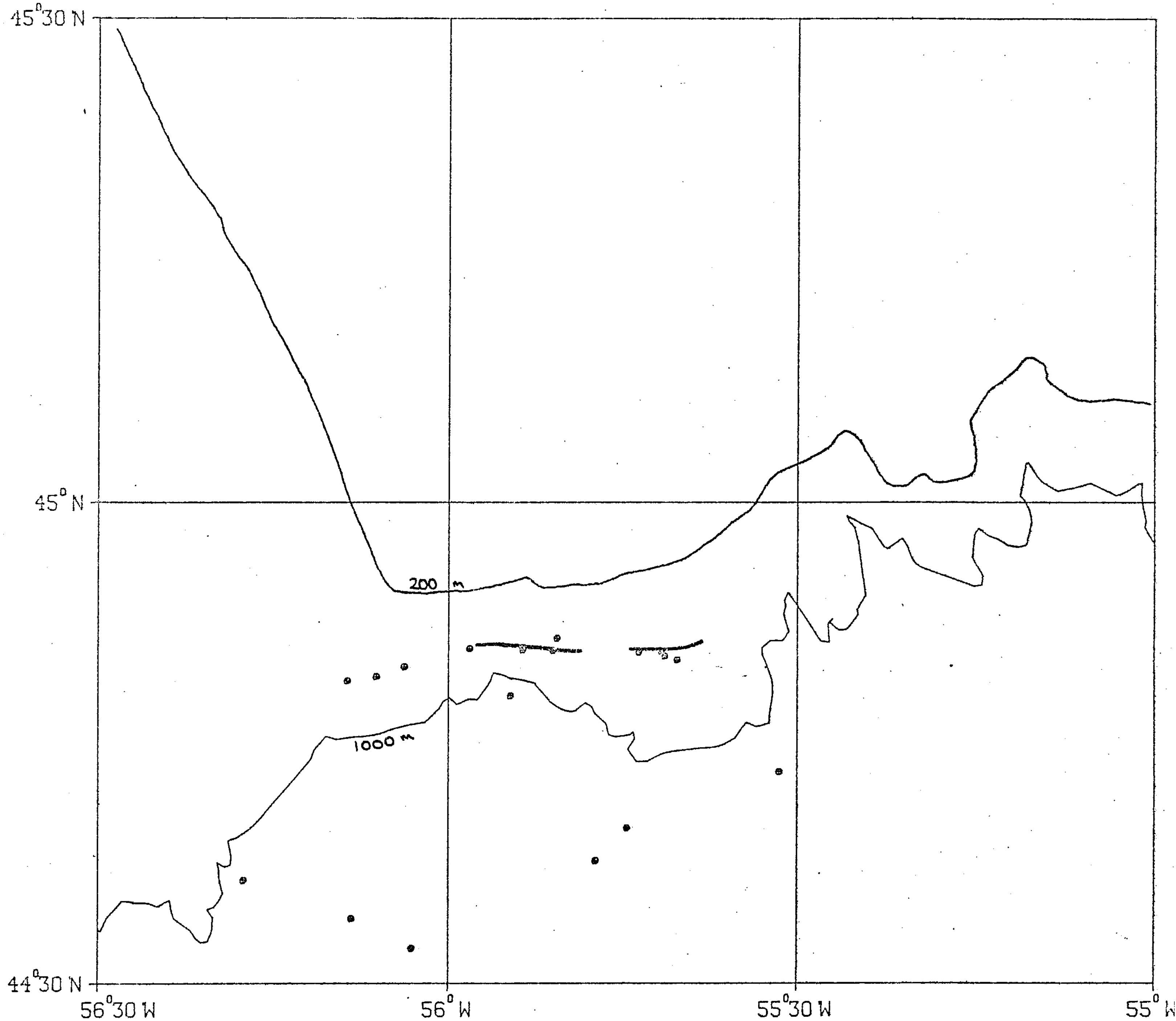
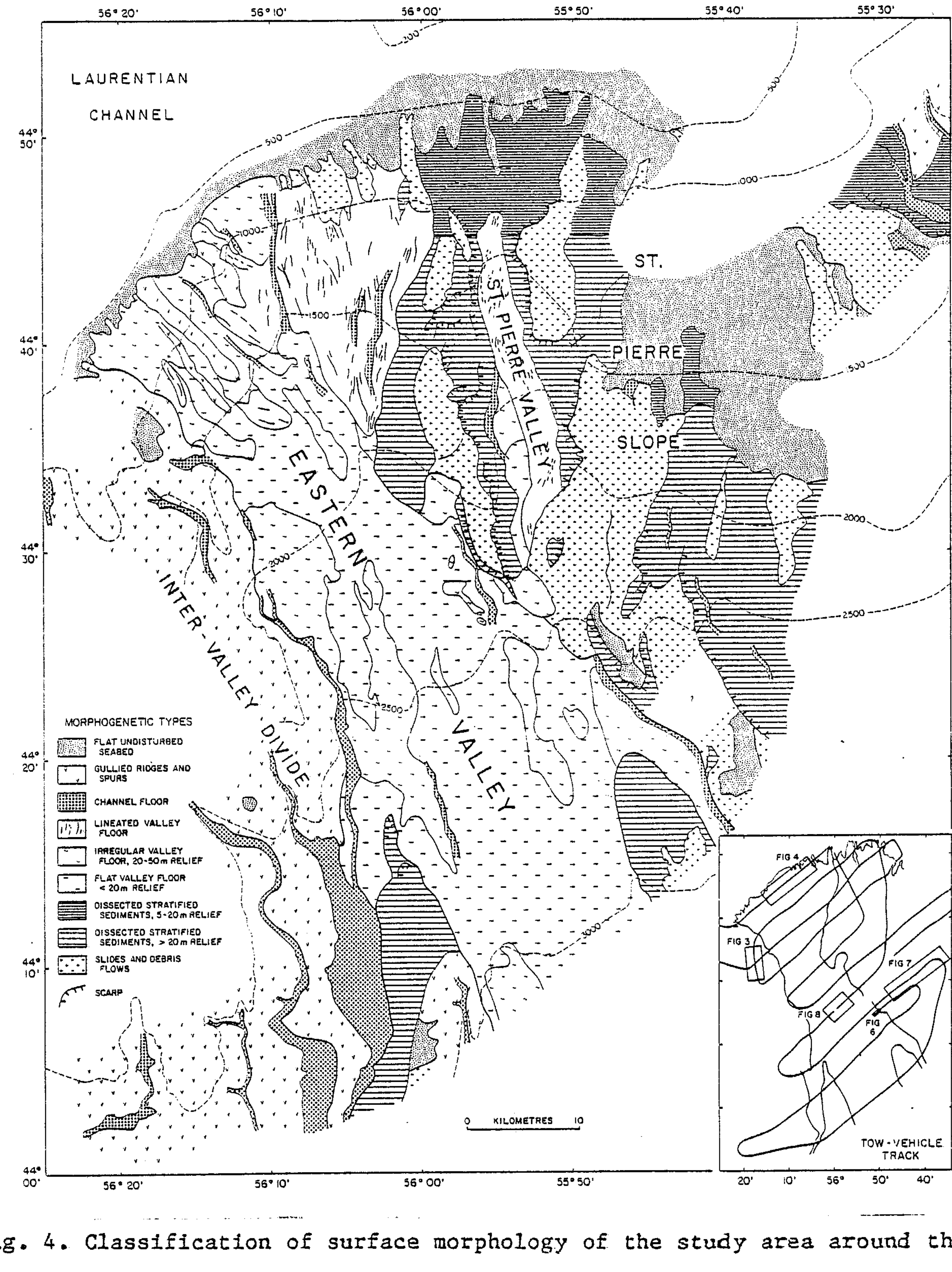


Fig. 3. Key map to location of seismic reflection profiles.



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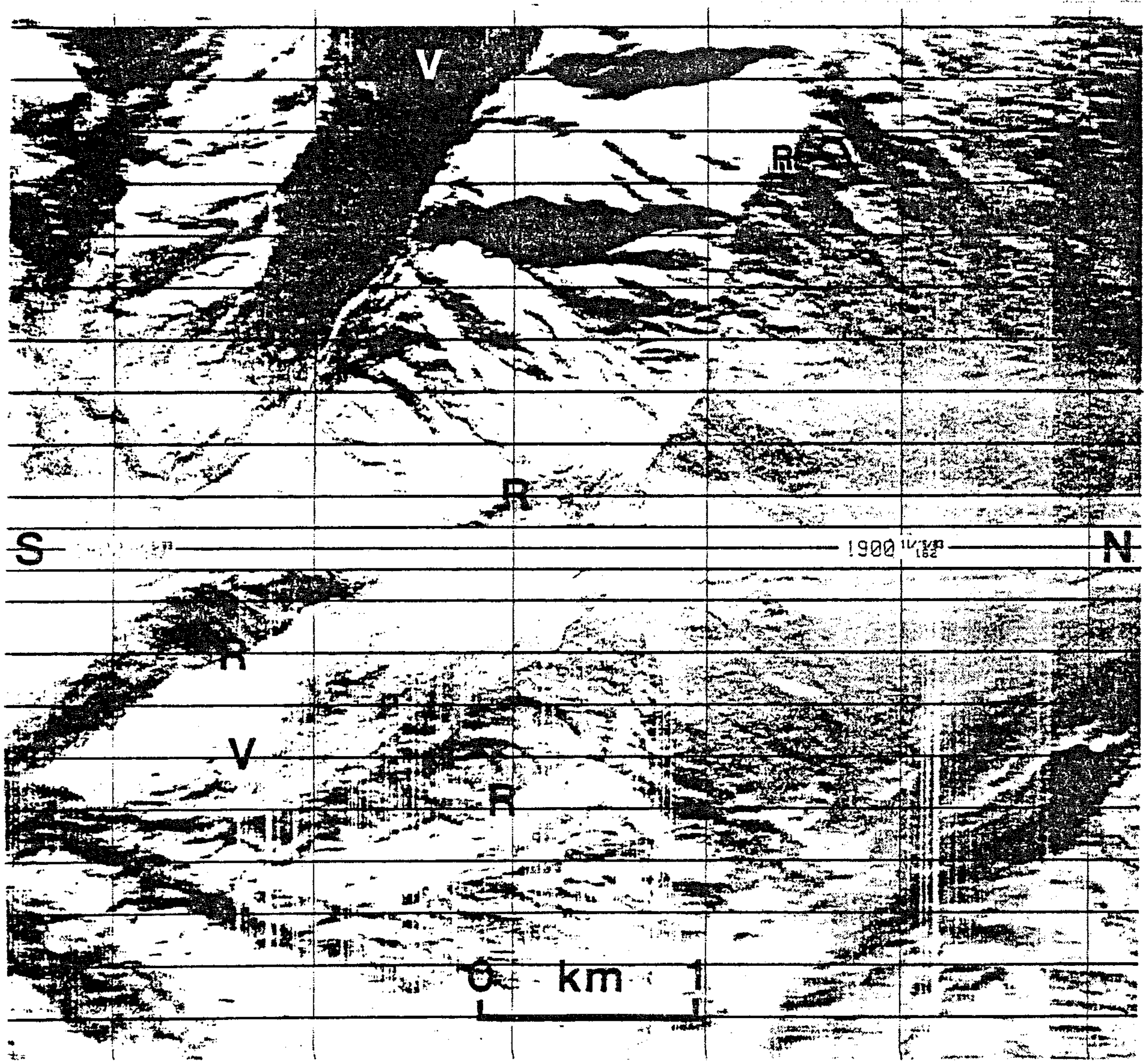

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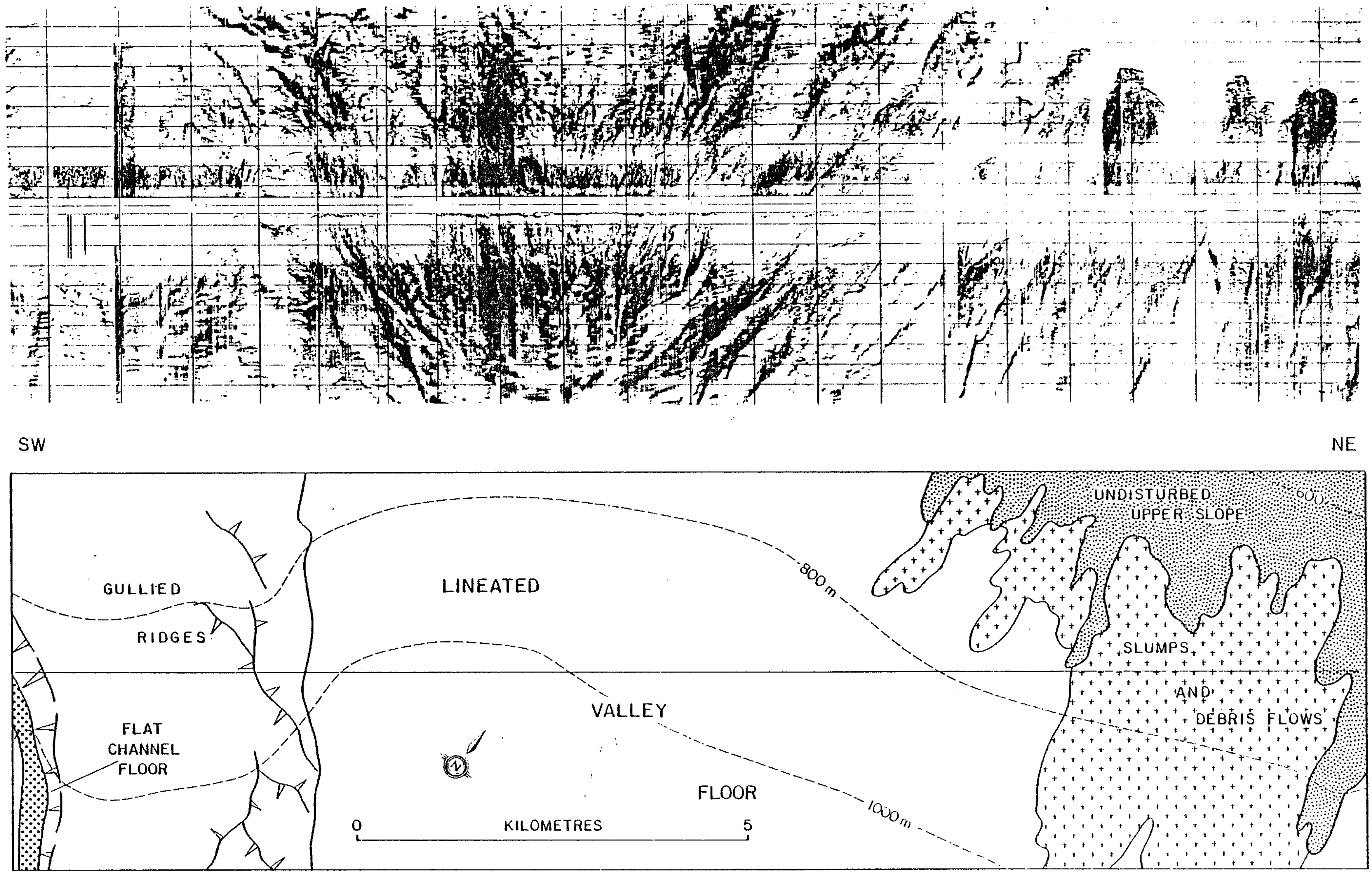

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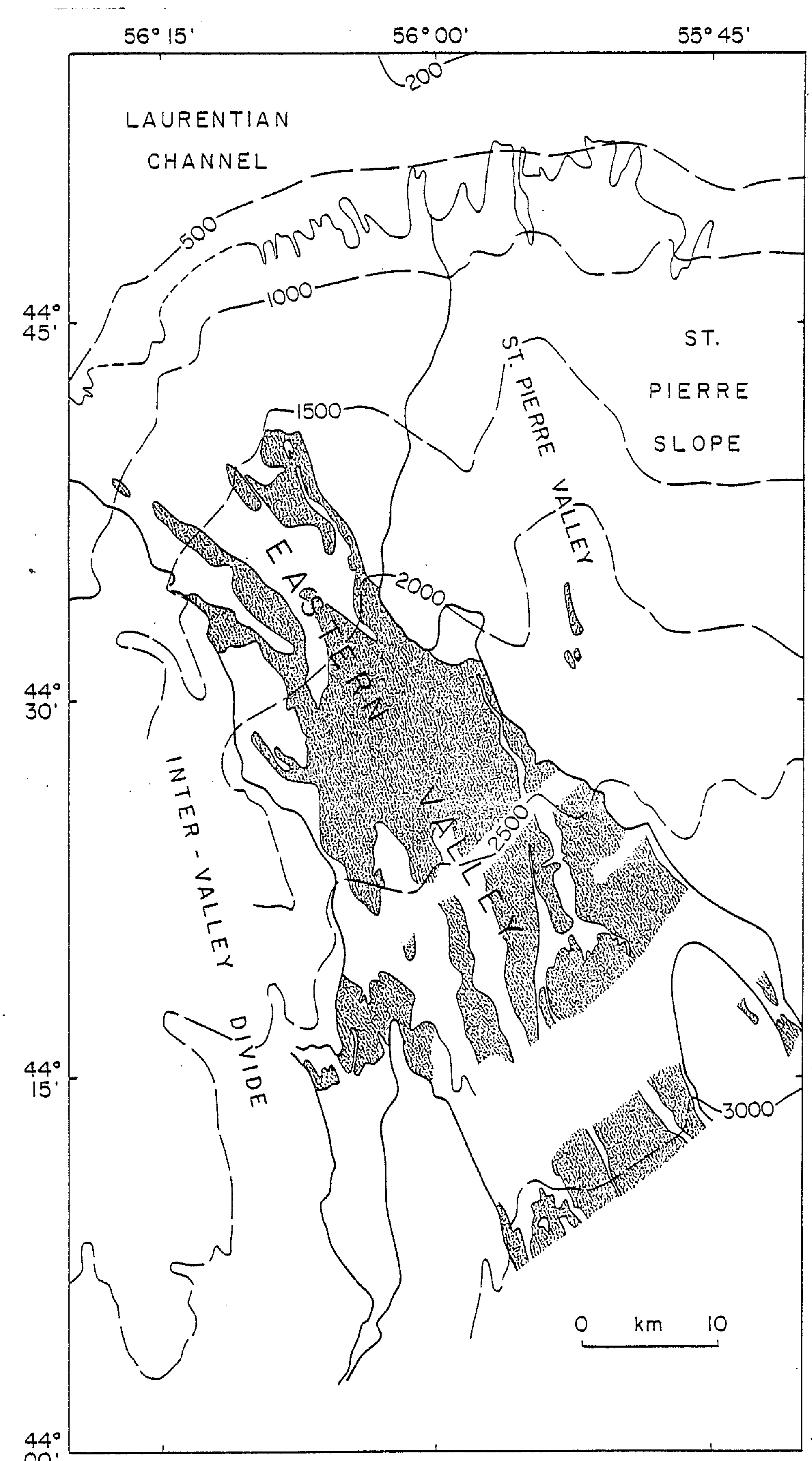

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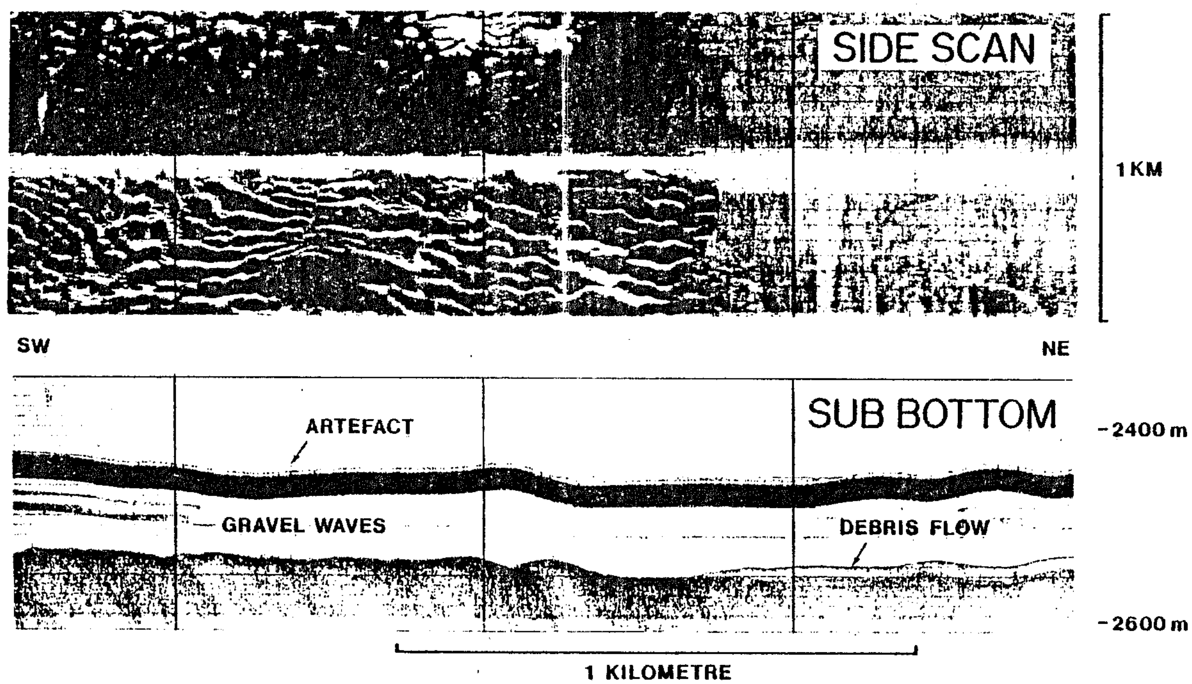

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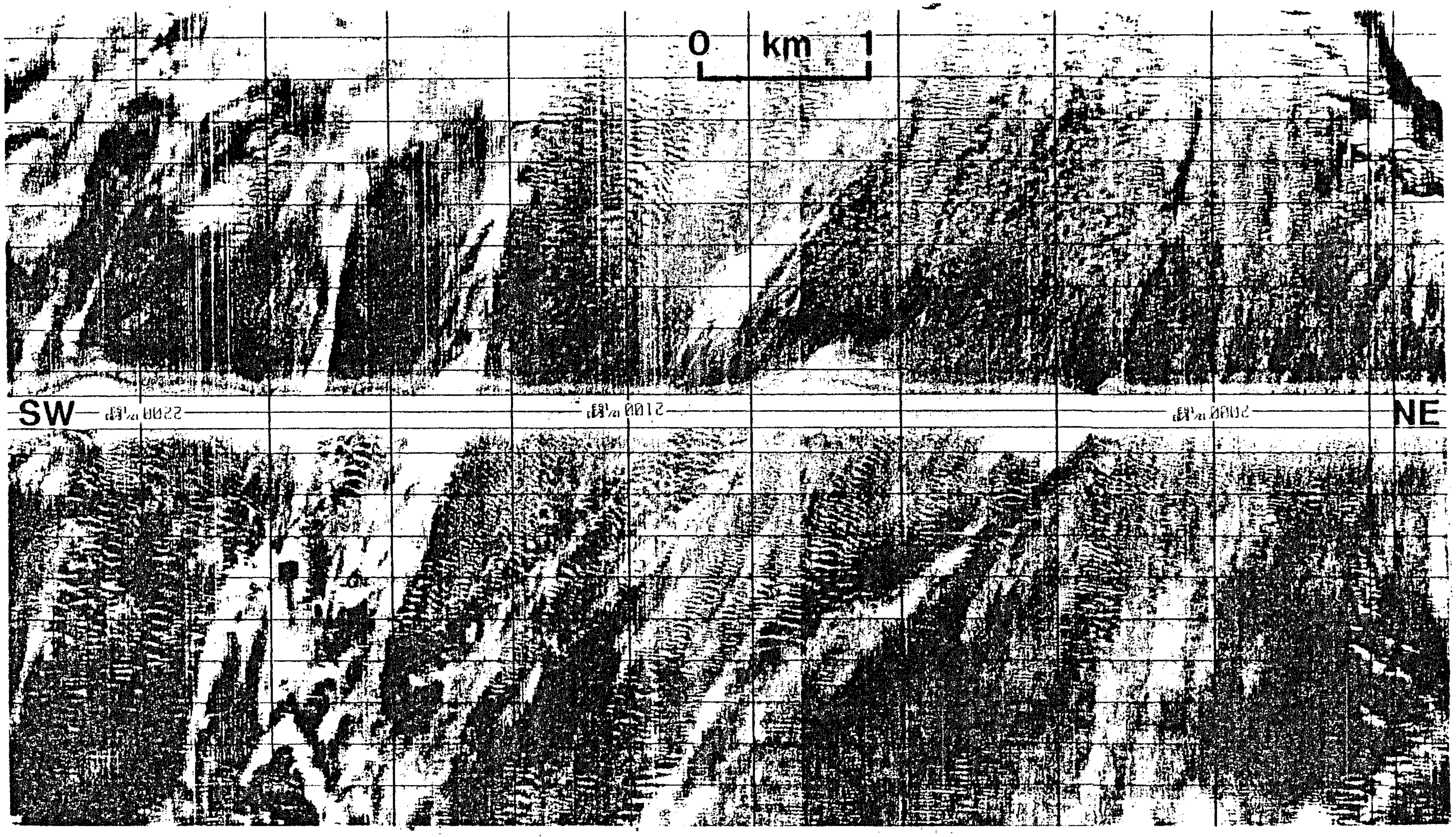

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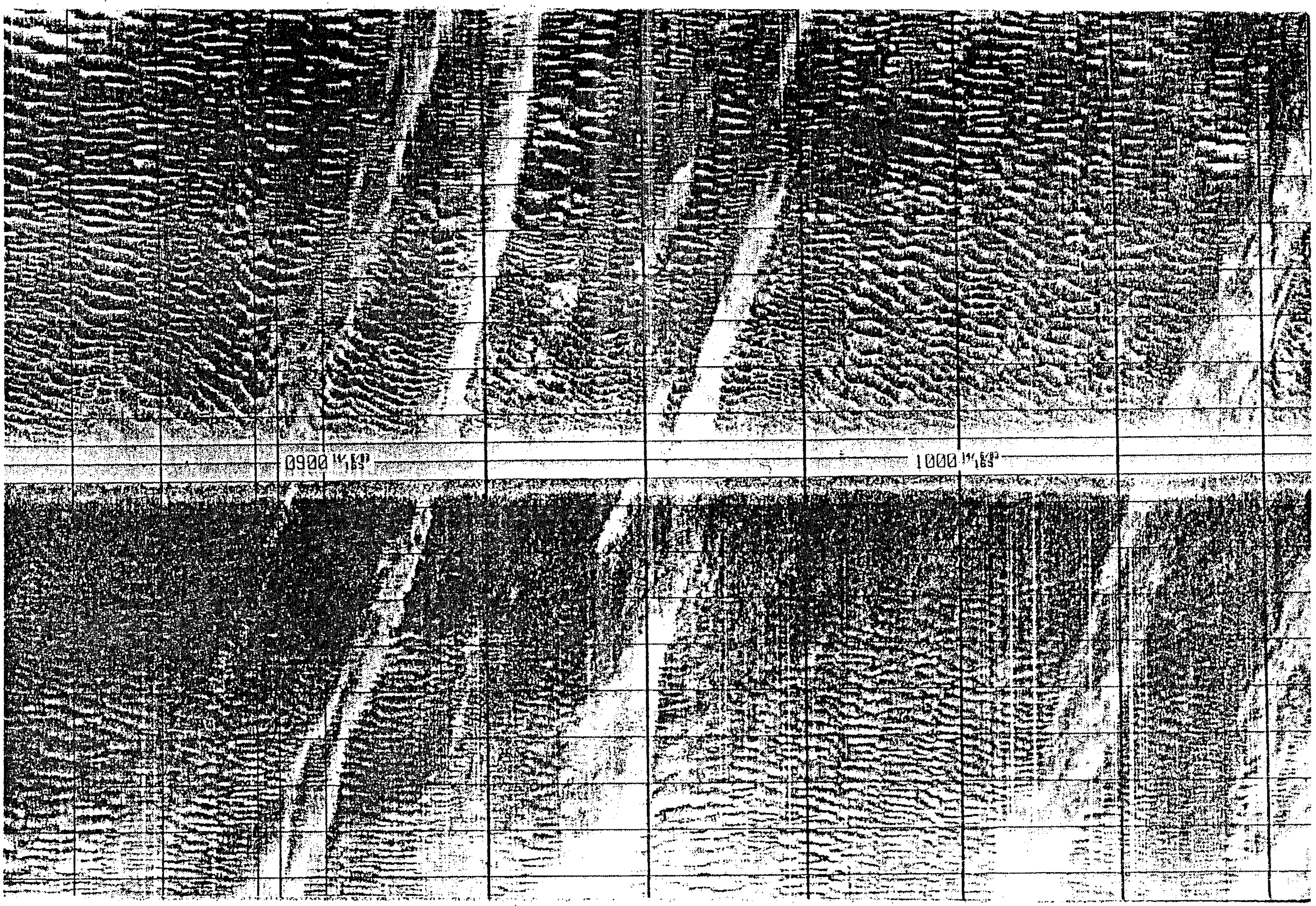

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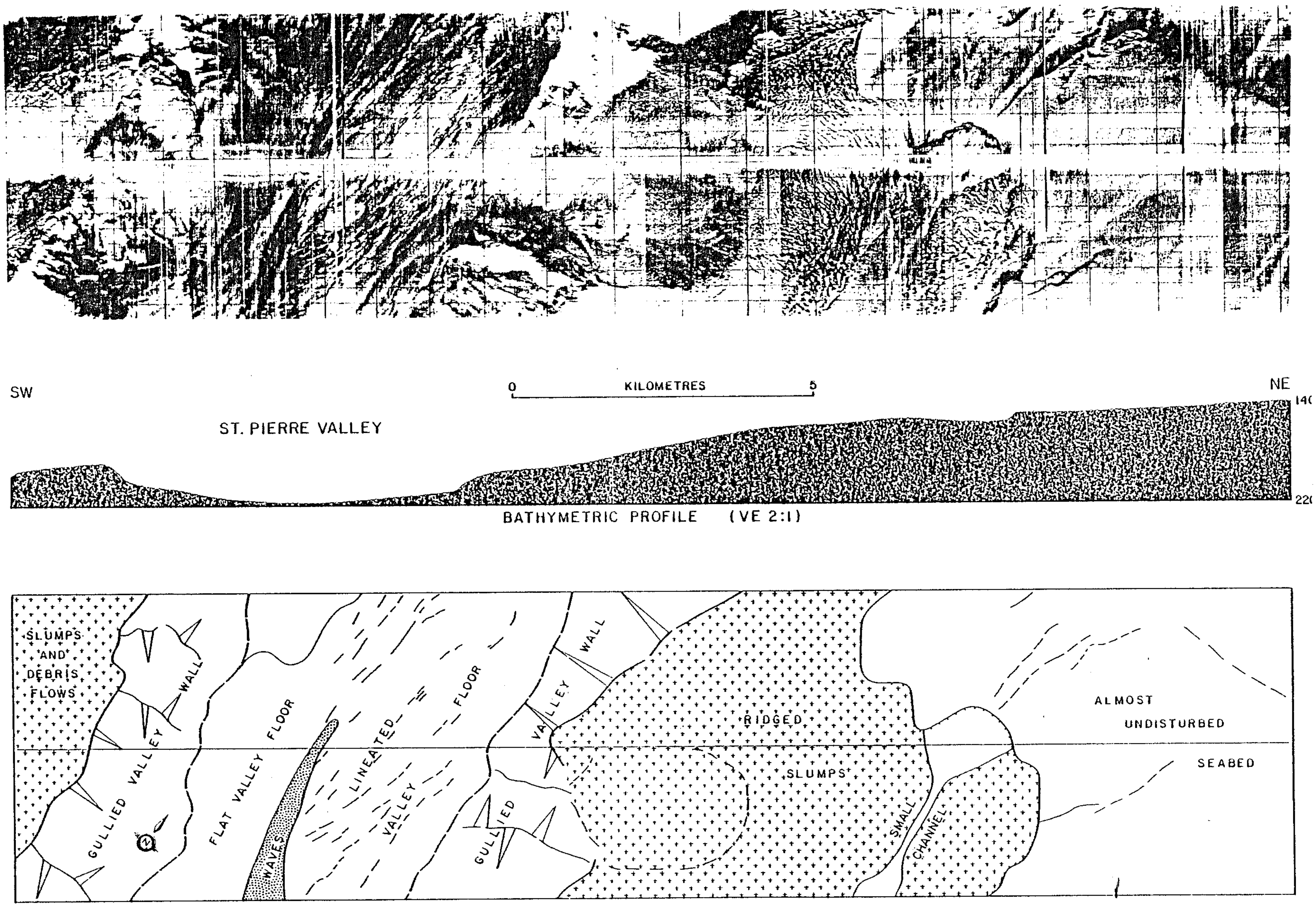

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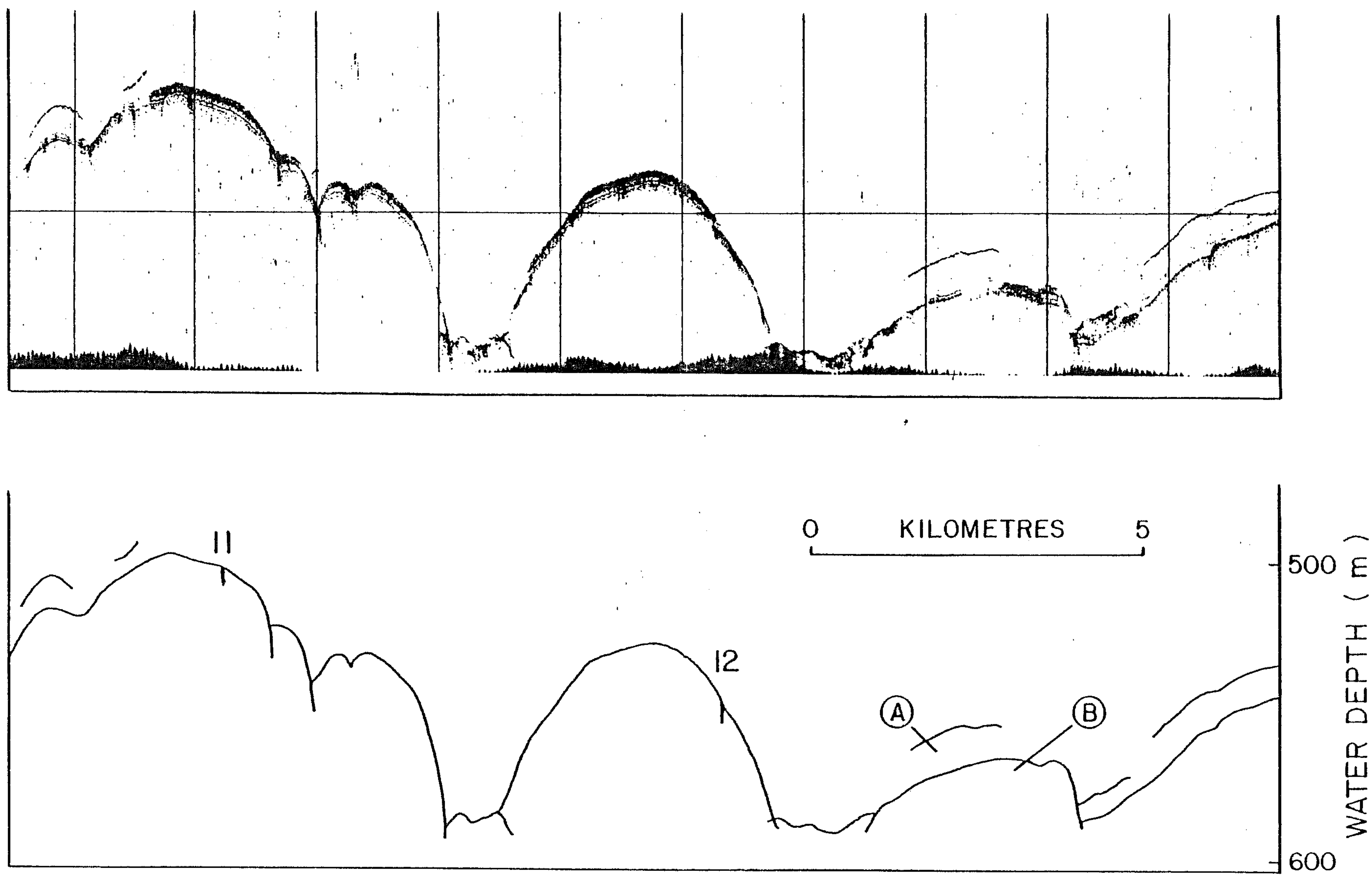

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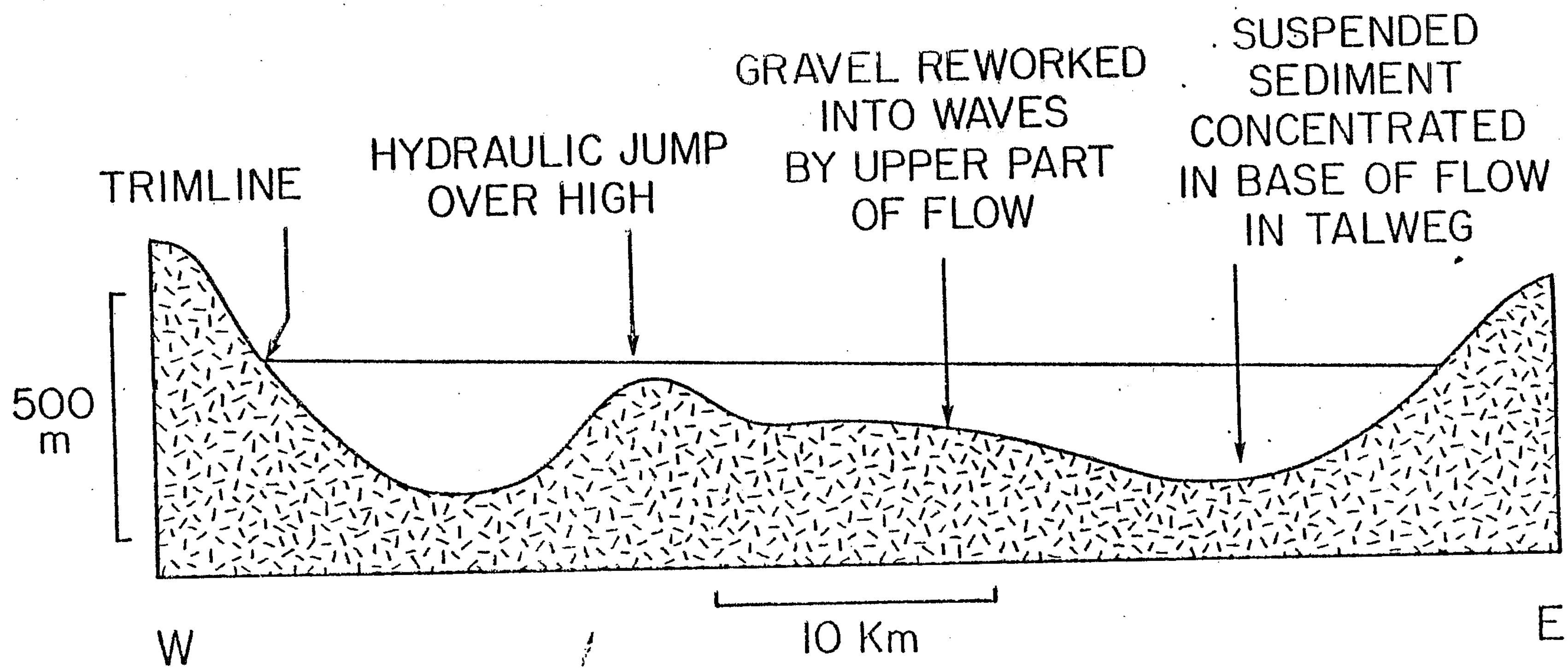

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PLATES

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Scale approximately 1:200 000.

Piper, Sparkes, Mosher, Shor & Farre

PLATE 1

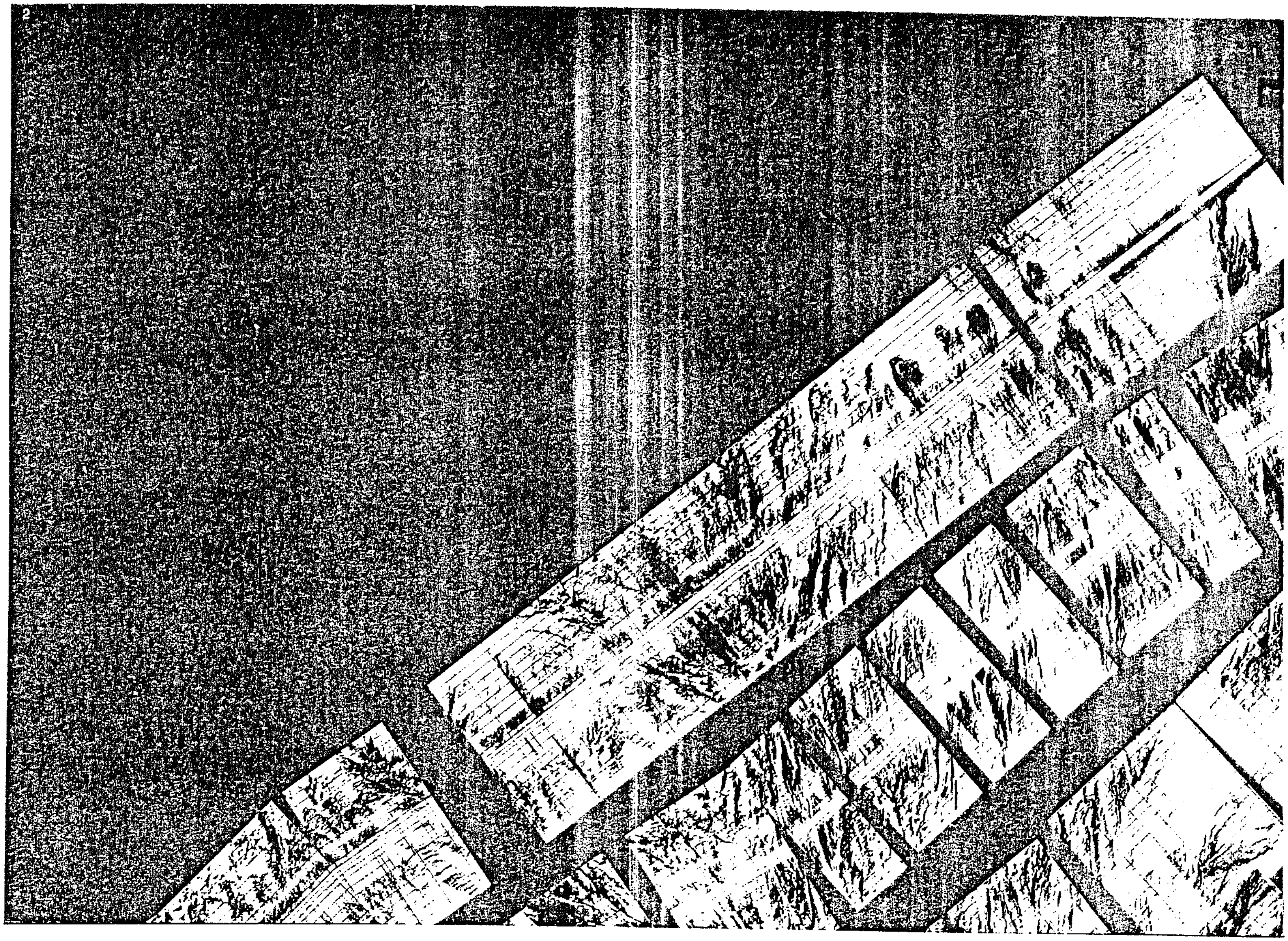

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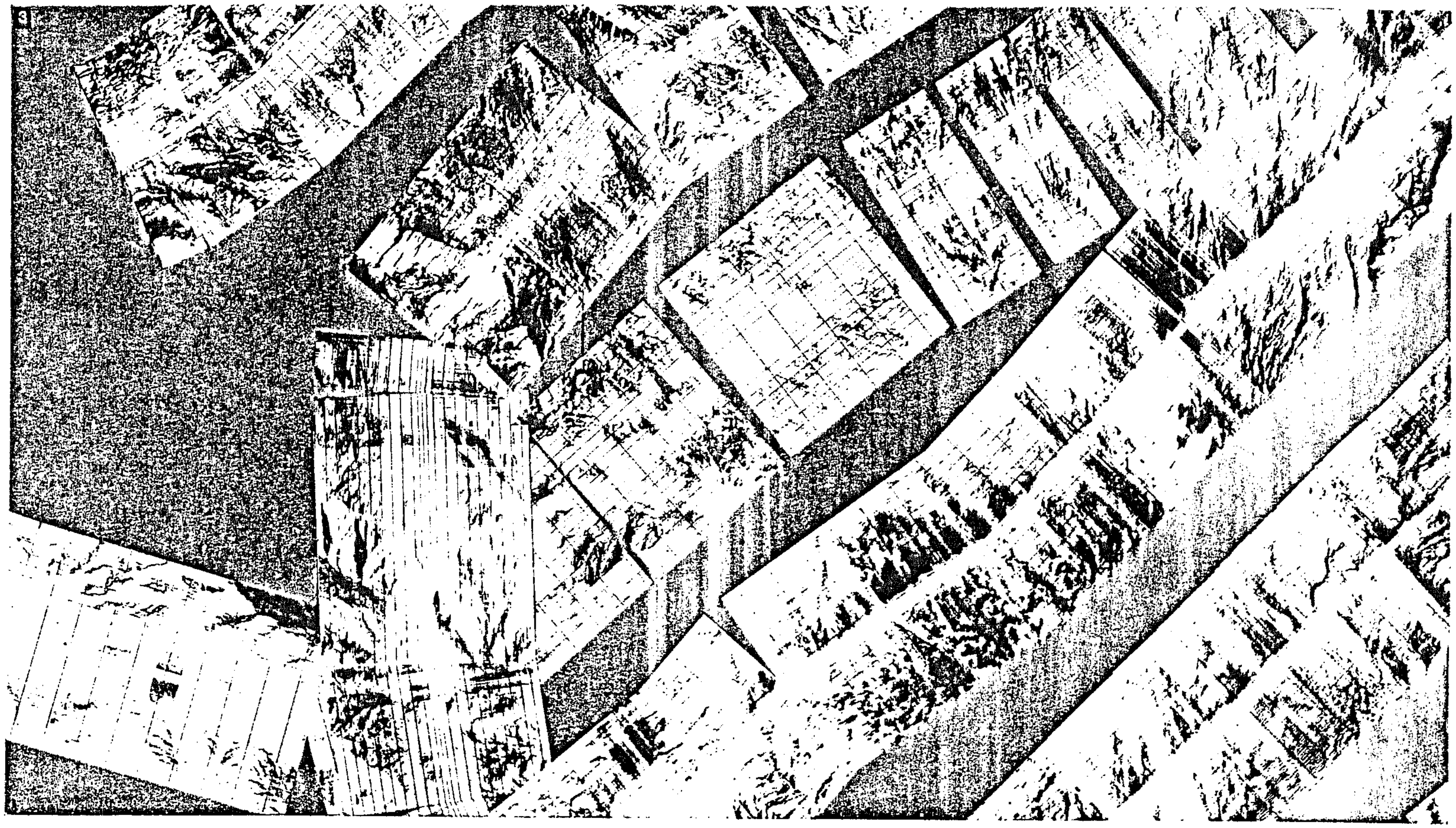
PLATE 2



Piper, Sparkes, Mosher, Shor & Farre

PLATE 3

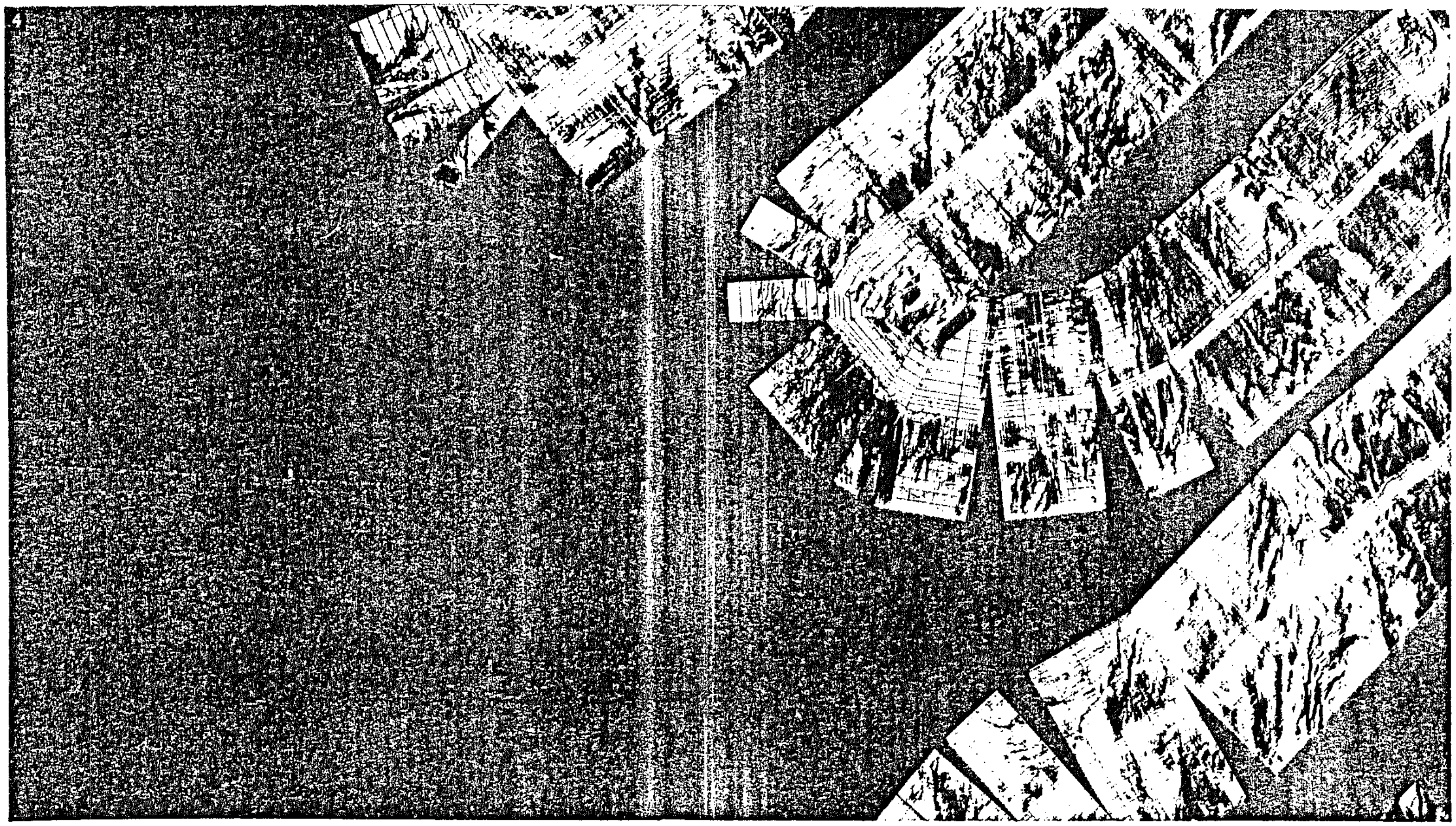


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PLATE 4

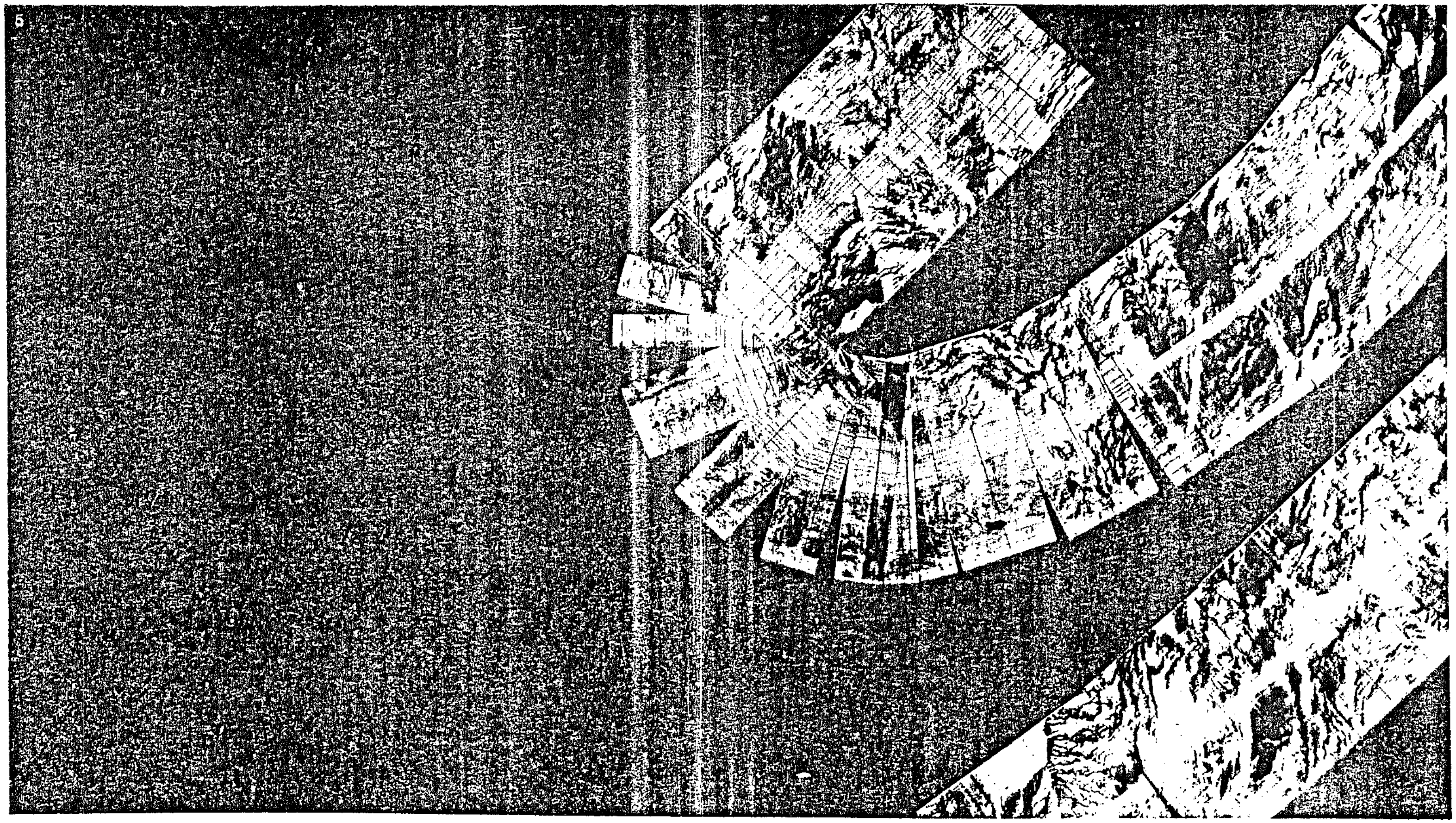

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PLATE 5

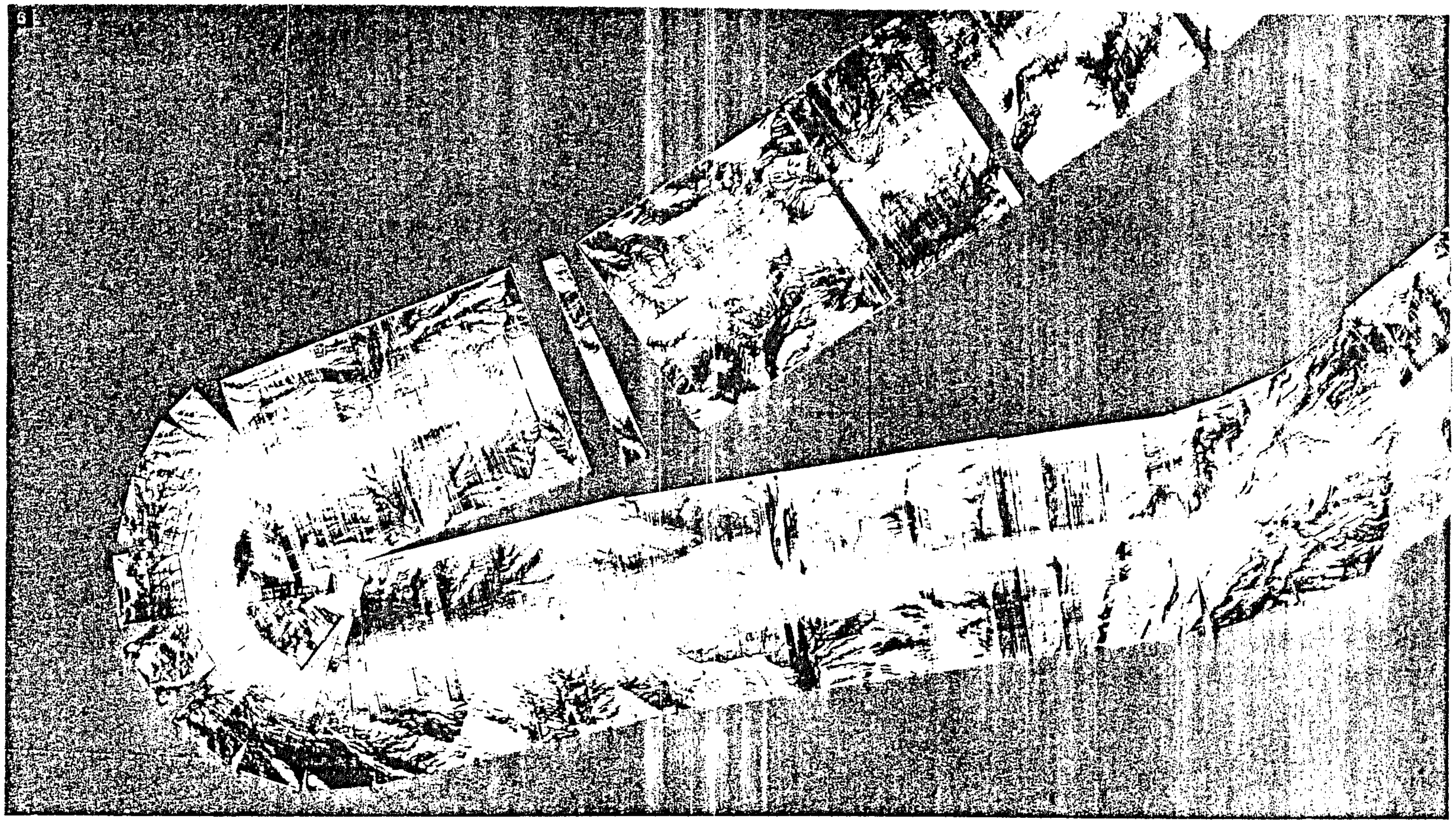

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PLATE 6

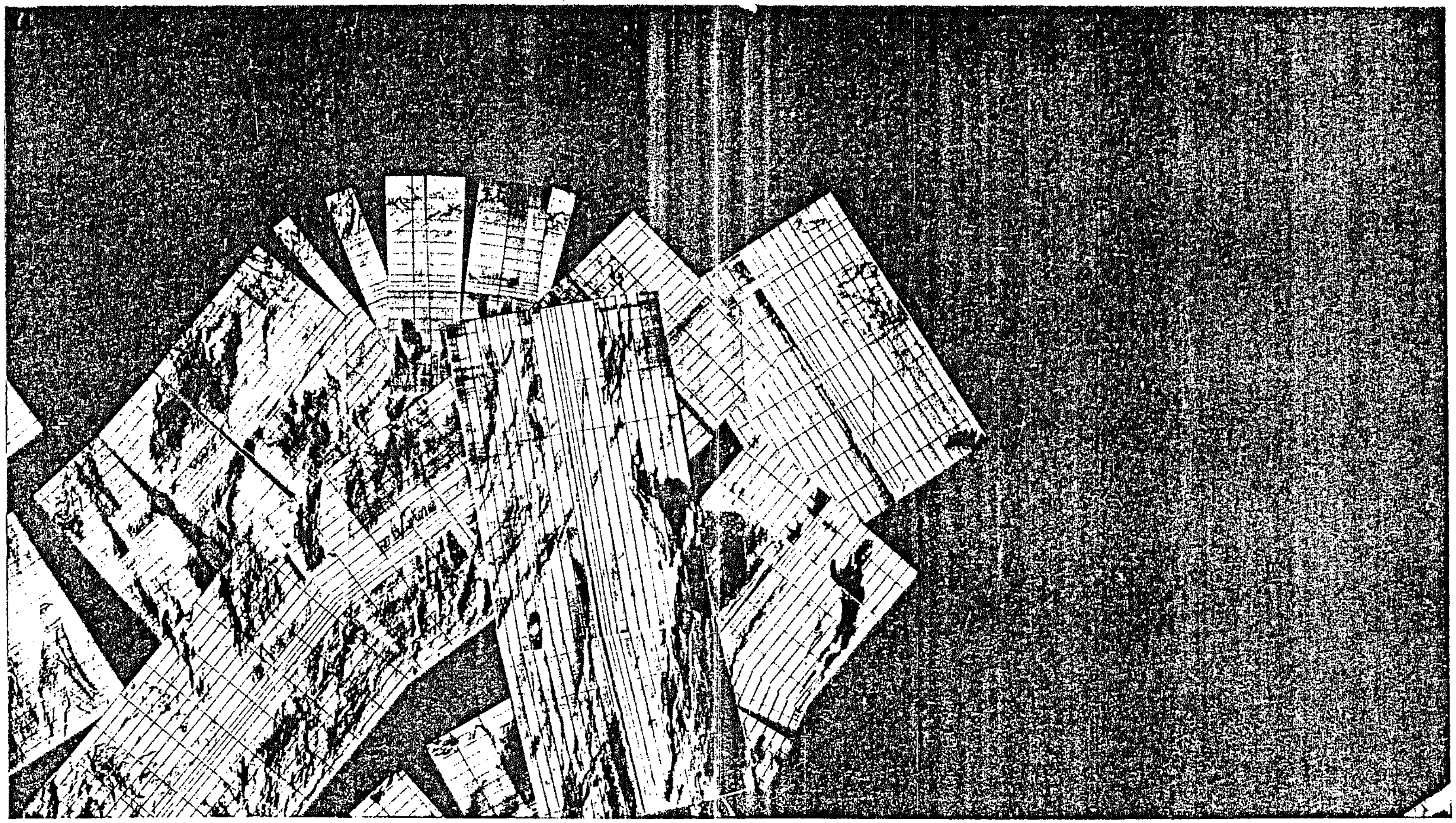

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PLATE 7

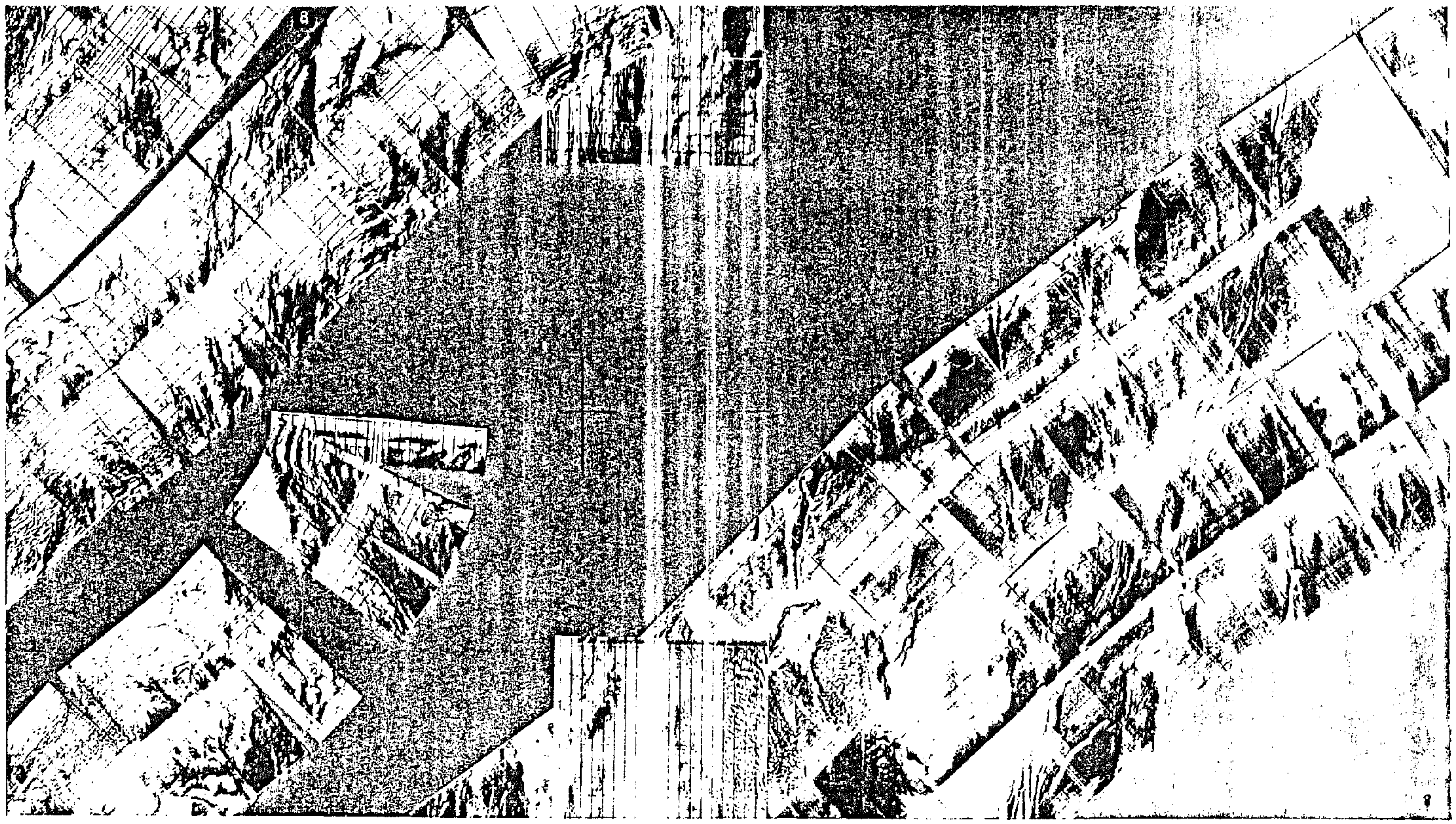

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PLATE 8

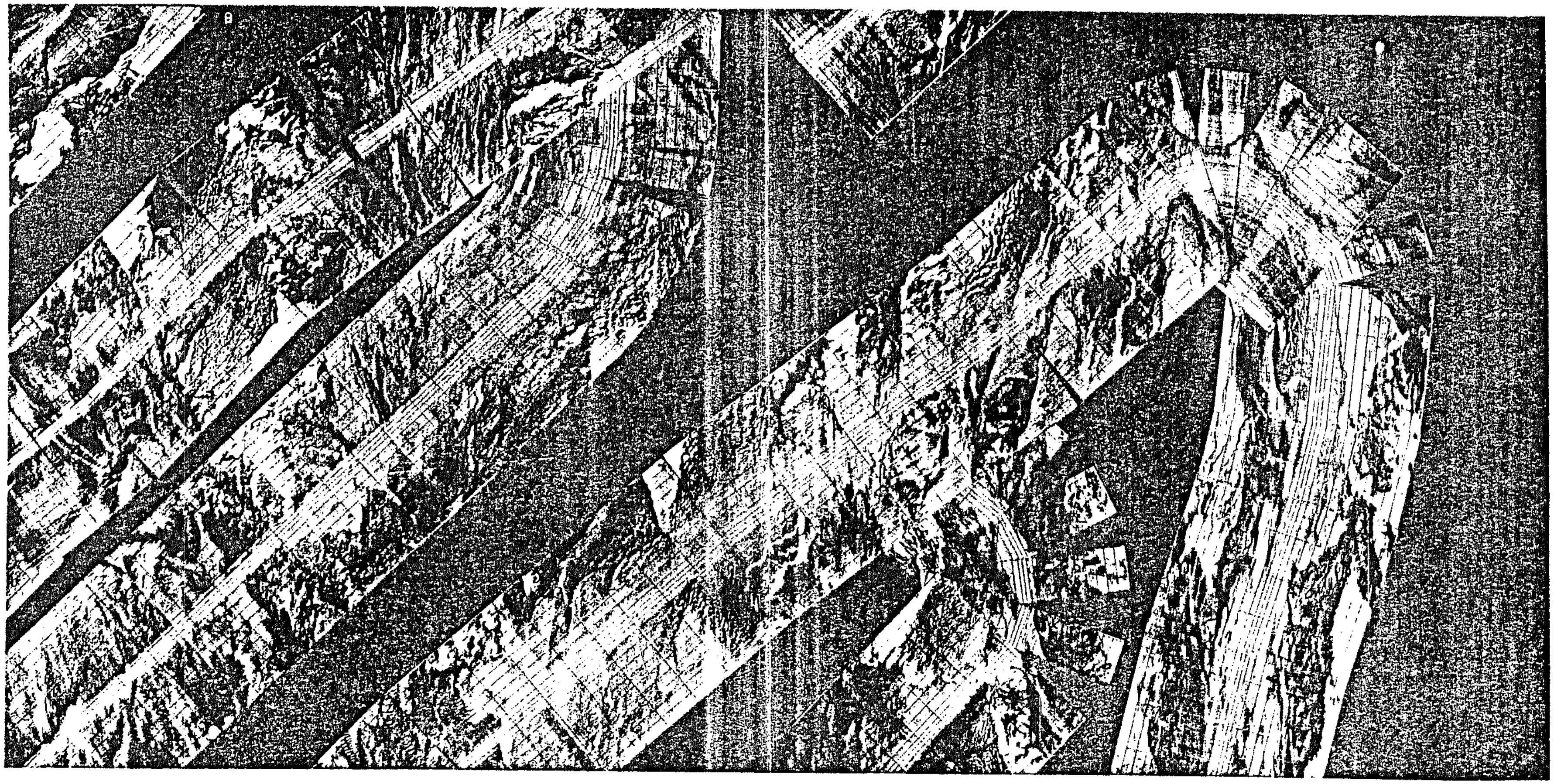

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PLATE 9

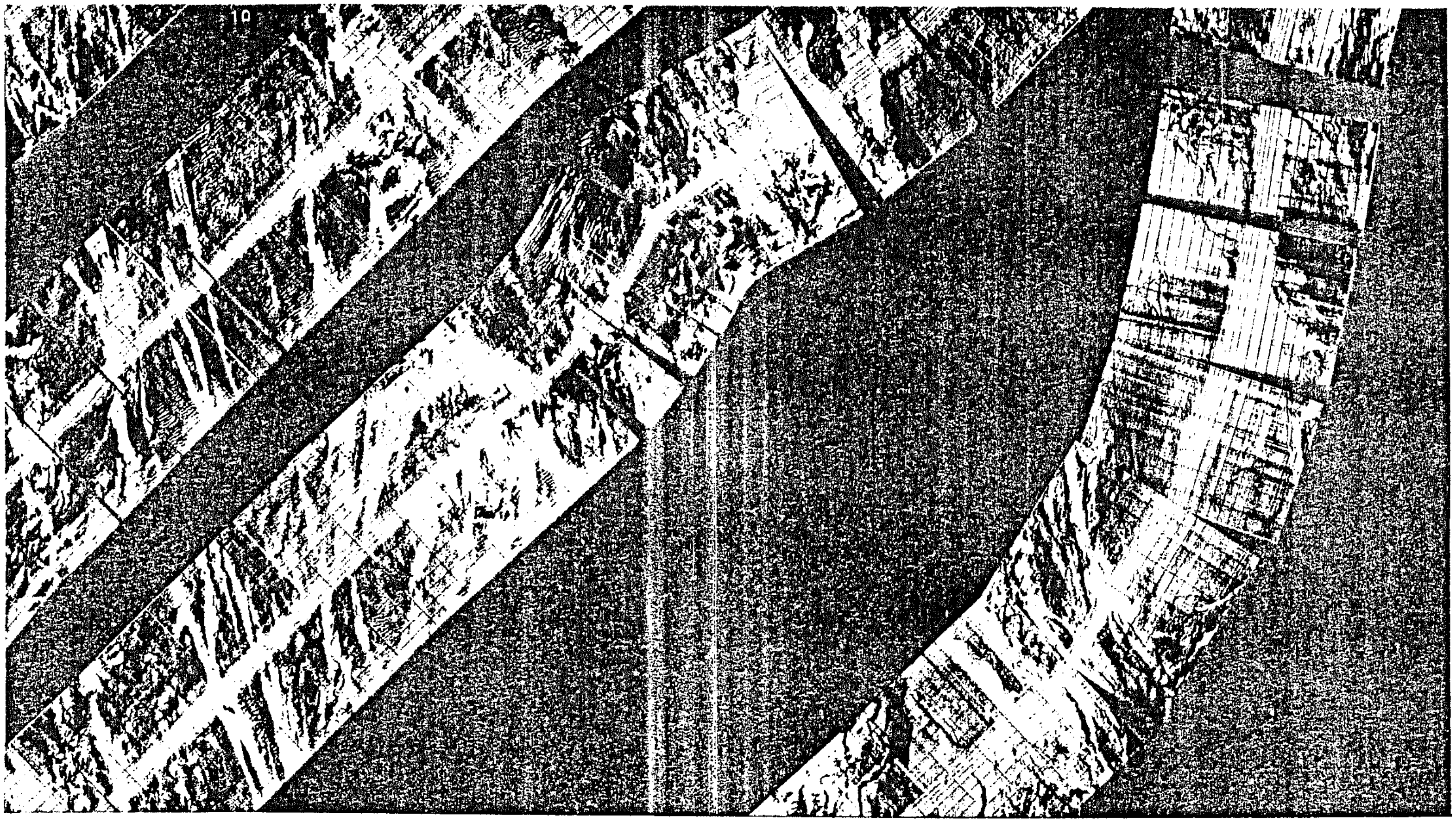

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PLATE 10

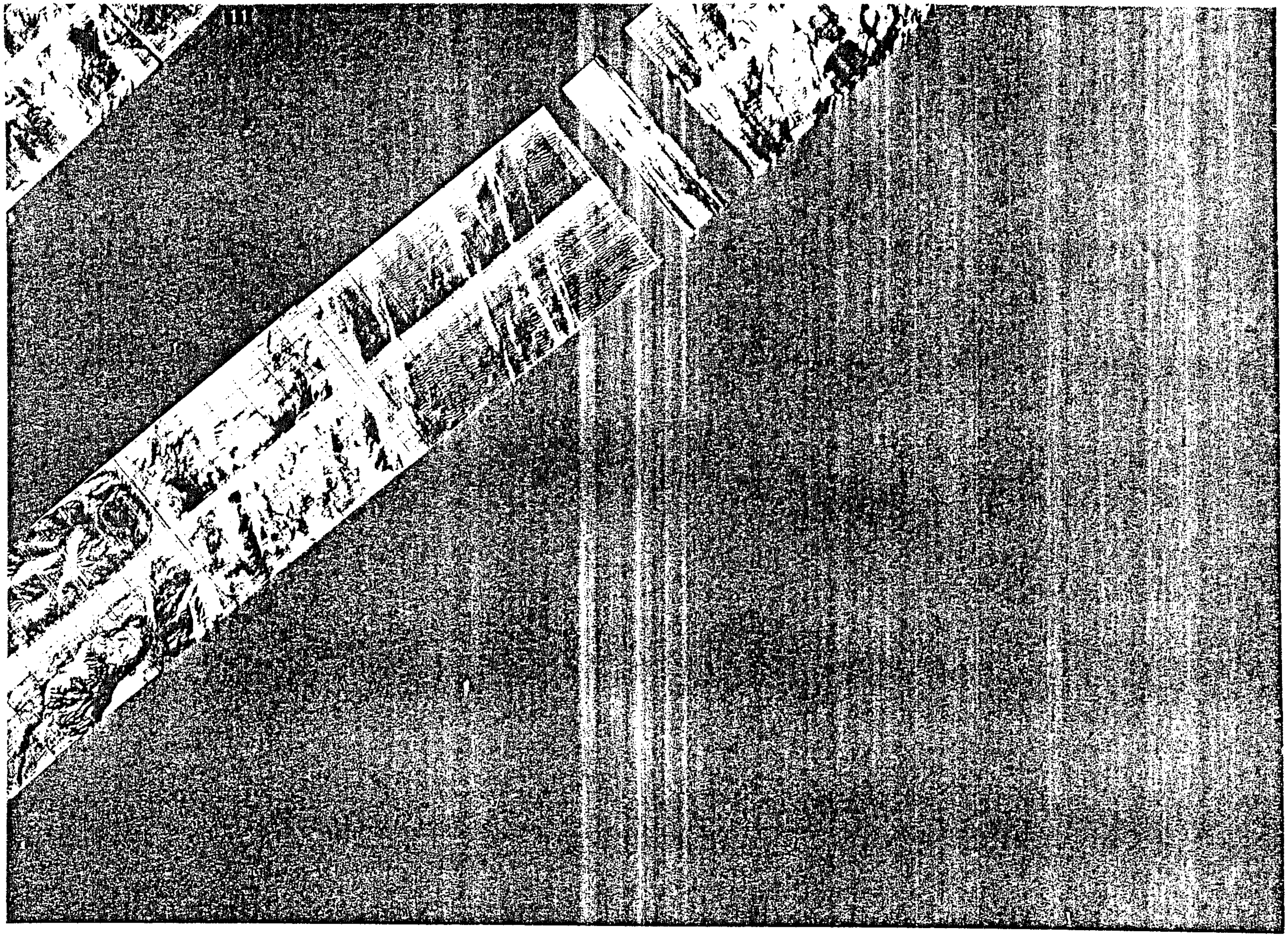

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PLATE 11

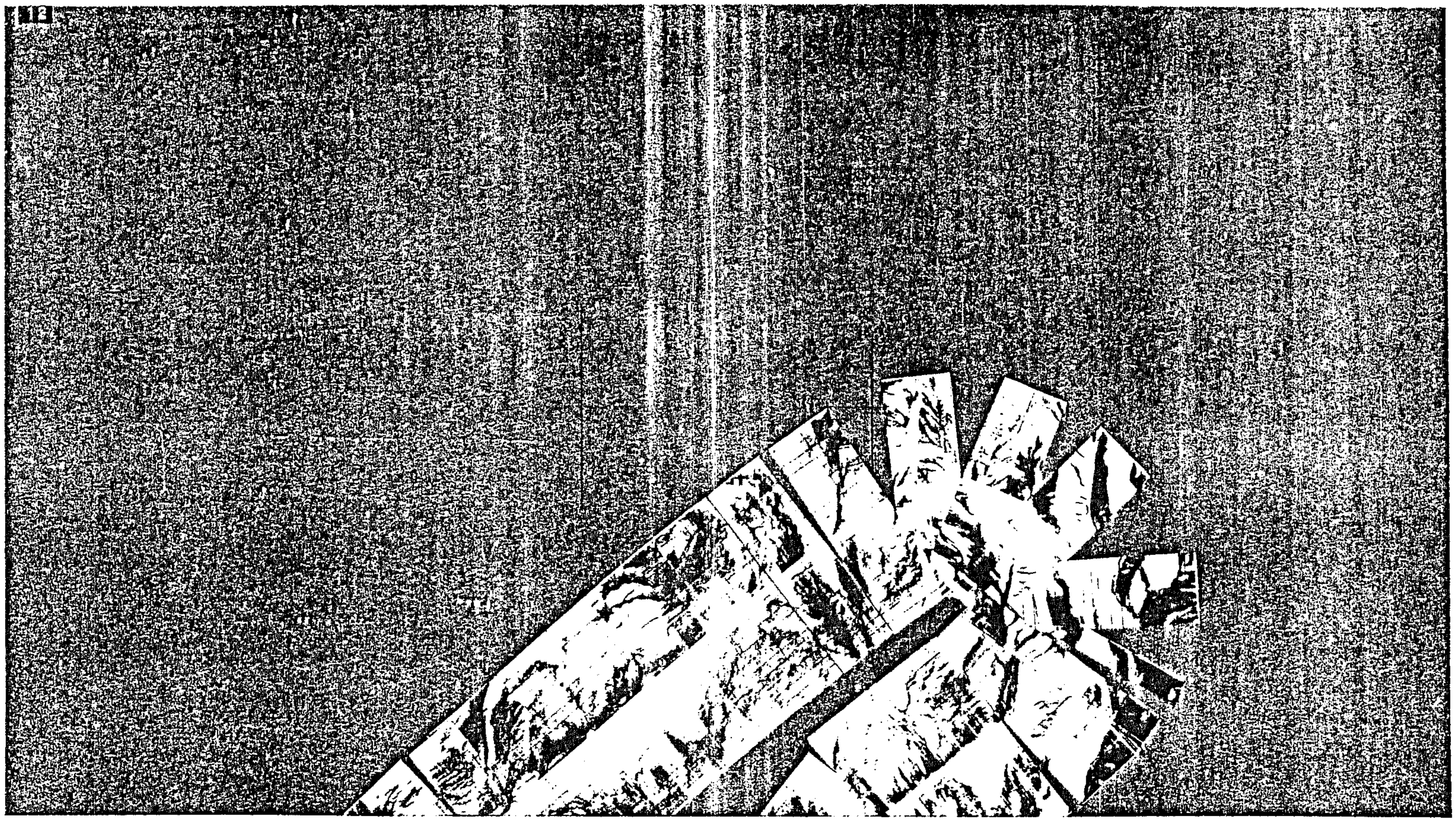

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PLATE 12

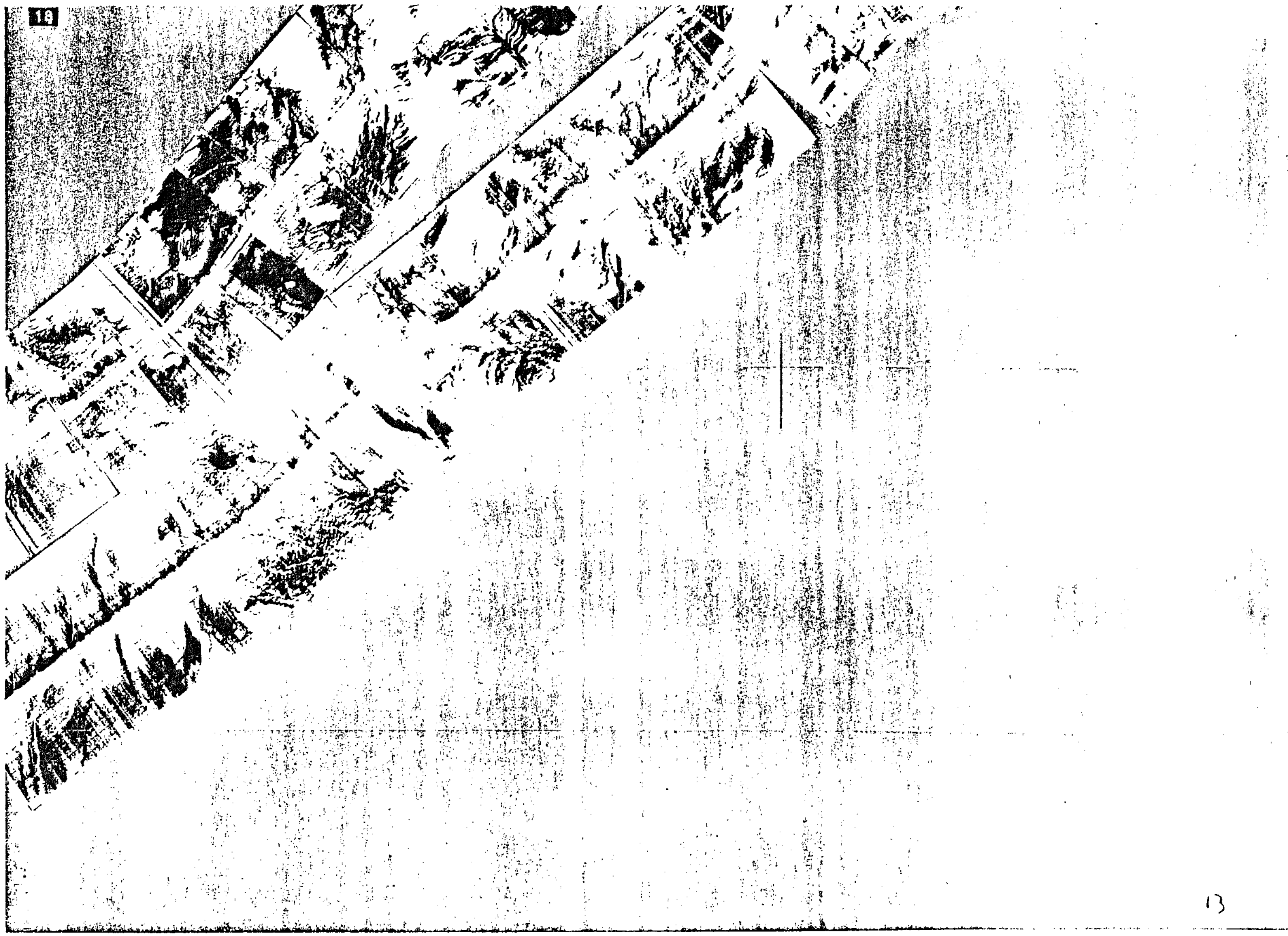

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PLATE 13