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SEABED FEATURES OF THE LABRADOR SLOPE AND RISE NEAR 55°N REVEALED BY SEAMARC I SIDESCAN SONAR IMAGERY

by

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ABSTRACT

Sidescan sonar imagery and accompanying seismic reflection profiles from the Labrador continental slope and rise provide geomorphologic information on 1600 km^2 of seabed between depths of 2000-3000 m. Three principal seabed features are recognized: channels, interchannel hills, and a large area of mass displacement. Channels and interchannel hills extend across the slope and rise; they generally converge downslope in a tributary pattern, but are locally distributary on the continental rise. Both features are <0.5-10 km (exceptionally 25 km) wide, with total relief of 10-150 m. Channels and hills are generally distinguished by lower and higher sidescan reflectivity, respectively, and by the loss of penetration on subbottom records across channels. Channels contain a variety of morphologic lineations 1-5 m in relief; their reflective characteristics may be due to incoherent scatter by widespread smaller relief.

Seismic profiles and cores show that interchannel hills are accumulations of fine sediment, which are discontinuous across the continental slope where channels have eroded into older underlying sediments, and continuous across the continental rise where superimposed channels are non-erosive. On the continental rise, hill surfaces are capped by slope-parallel sediment waves which appear to be migrating upslope; some of these waves contain distributary channels in their troughs. The downslope transition from erosive channels between hills, to depositional channels among wave fields, corresponds to the transition from slope to rise gradients. Isobaths and seismic surveys suggest that the sediment waves and channels of the rise extend seaward 350 km to the North Atlantic Mid-Ocean Channel (NAMOC). The channel/hill system along this part of the Labrador margin is of glaciomarine origin, formed when ice sheets grounded on the continental shelf supplied large volumes of sediment to the continental margin. Alongslope variations in channel size and relief may be related to adjacent shelf morphology (troughs vs banks).

A large mass displacement is observed on the flanks of a structurally controlled interchannel ridge, in the upper part of a layer of acoustically stratified sediments equivalent to those of the interchannel hills. The displacement takes the form of irregular seabed relief associated with unstratified subbottom sediment, bounded by seabed scarps. The displacement extends over an area of 250-300 km^2 in depths of 2050-2650 m on the east flank of the scarp, and a similar feature is suggested for the west flank.

The geomorphic character of this part of the Labrador continental slope and rise is dominated by the channels and intervening sediment accumulations (hills). There is no geomorphic evidence for the alongslope influence of the Western Boundary Undercurrent (WBUC), although current meter measurements, seabed sample textures and bottom photographs taken in 2400-2500 m depths indicate its effects. A Quaternary history of alternating downslope/alongslope influence is proposed: downslope processes have dominated during the greater sediment flux of glacial periods, when WBUC intensities were reduced, while alongslope transport by the WBUC has controlled sedimentation patterns during interglacials.

CONTENTS

1.0 INTRODUCTION

In 1984, the Atlantic Geoscience Centre contracted the midrange SeaMARC I sidescan sonar system to examine selected seabed areas in the eastern Canadian offshore, from Nova Scotia to southern Baffin Island (Piper et. al., 1985; Pereira et. al., 1985; Praeg et. al., 1987). One area surveyed was the Labrador continental slope and rise near 55°N latitude (Fig. 1). This report presents and evaluates 350 line-km of SeaMARC I imagery collected from the Labrador lower slope and upper rise, in water depths of 2000-3000 m (Figs. 2A; 2B, cover pocket). The sidescan imagery is presented both as page-sized (5 x10 km) reproductions at a scale of 1:50,000 (Appendix 1, Figs. A1- A35), and as a mosaic at a scale of 1:150,000 (Fig. 9, cover pocket). An interpretation is also presented at a scale of 1:150,000 (Figs. 10A and 10B, cover pocket).

Bathymetric contours show that this part of the Labrador margin is dissected by a system of 'slope gullies' (Piper, 1988) or channels (Fig. 1). This configuration is similar to the western Scotian Slope where these features have been related to downslope sediment transport adjacent to ice sheets grounded on the continental shelf (Piper and Sparkes, 1987). Seabed current measurements and sediment textures show that the Northeast Newfoundland and Labrador margins are presently influenced at a depth of about 2400-2500 m by the south-flowing Western Boundary Undercurrent (Schafer and Carter, 1985; Carter and Schafer, 1983; Schafer and Asprey, 1982). Contour currents have long been proposed as an important influence on the morphology of continental margins (Heezen et al., 1966), and features related to them have been reported from many areas (e.g. Flood, 1988; Hollister et al., 1974). However, recent studies on the Atlantic Canadian slope and rise suggest that, on formerly glaciated margins, the predominant seabed features are related to downslope sediment transport (Hughes Clarke, pers. comm., 1988; Piper and Sparkes, 1987; Schafer et al., 1985; Swift, 1985). The SeaMARC I sidescan imagery presented here provides a window on a part of the Labrador margin where both downslope and alongslope sediment transport processes are believed to have been active during the Quaternary.

2.0 REGIONAL SETTING

The survey area is located on the Labrador slope and rise adjacent to Hamilton Bank, and Cartwright Saddle of the Labrador Shelf (Fig. 1). The shelf break in this area occurs at about 300 m depth, below which average gradients decrease from $\approx 3°$ above 2000 m depth, to $\approx 1.5°$ between 2000-2500 m depth, to less than 0.5° below 2500 m depth. The slope/rise transition depth varies from 2500 m in the western part of the survey area to 2800 m in the east, and overall bathymetric gradients increase from west to east. Channels extend across the continental slope and rise below ≈ 1000 m depth, decreasing in number downslope because of convergence or as a result of a loss of definition. Several prominent channels extend to 3000 m depth, and one axis can be traced to the North Atlantic Mid-Ocean Channel (NAMOC) at 3700 m depth, 350 km to the east (Fig. 1).

Quaternary sediments of the Labrador margin were discussed by Myers (1986) and Myers and Piper (1988) in the course of a regional seismo-stratigraphic analysis of the Labrador Sea. Their study suggests that early Quaternary sediments are dominated by bottom current deposits (i.e. contourites), whereas mid to late Quaternary sediments contain evidence of shelf edge progradation, continental slope and rise channel incision, and turbidite accumulation as part of widespread activity which contributed to the development of the NAMOC system. Myers and Piper (1988) related this increased turbidite deposition in the mid to late Quaternary to the presence of glacial ice sheets on the Labrador shelf and upper slope.

The Labrador Shelf is characterized by a marginal trough and a series of transverse troughs, or saddles (Fig. 1). The troughs are incised into Tertiary sedimentary strata, and are attributed generally to Pleistocene glacial modification of fluvial channels and/or grabens (Grant, 1972). Tertiary and older bedrock strata of the shelf are overlain unconformably by Quaternary sediments, up to 100 m thick in Cartwright Saddle, which include 3 units interpreted as glacial tills (Josenhans, 1983; Josenhans et al., 1986). The older tills extend across the shelf to depths of 600 m on the continental slope, while the youngest till is less extensive, suggesting that the last glacial advance was confined to the transverse troughs. Deglaciation probably commenced ca. 20,000 B.P., and glacial marine conditions persisted until ca. 8,000 B.P. (Josenhans et al., 1986).

The WBUC affects the Labrador slope below a watermass "zone of minimum motion", centred at about 1500 m depth, which was described originally by Swallow and Worthington (1969). Current meter data from several sites along the Labrador slope from 49°30'N to 56°N, in depths of 2000-2500 m, suggest WBUC velocities on the order of 20 cm/sec (Rabinowitz and Eittreim, 1974; Allen and Huntley, 1977; Carter and Schafer, 1983). These results are in good agreement with values obtained from a current meter that was moored within the present study area at 2450 m depth (Fig. 2B), which indicated velocities of 10-28 cm/sec over a 304 day period (Schafer, unpublished data). Farther south on the Newfoundland slope at 49°30'N, Carter and Schafer (1983) recognized a 50 km wide zone of surficial sediments between 2500-2800 m depth characterized by greater proportions of sand and gravel, relatively high concentrations of foraminifera tests, and a more diverse foraminiferal assemblage. They related this zone to sediment reworking beneath the axial region of the WBUC. Such sediments probably reflect WBUC activity throughout much of the Holocene; during glacial intervals (i.e., before 12,500 B.P.), WBUC velocities appear to have been substantially reduced (Schnitker, 1979).

3.0 FIELD METHODS

The SeaMARC I (Sea-floor Mapping and Remote Characterization) system includes 27 and 30 kHz sidescan transducers, capable of generating 1, 2 or 5 km swaths, and a 4.5 kHz subbottom profiler. This hardware was towed 100-400 m above the seabed in a neutrally buoyant fish, coupled to an electro-mechanical tow cable up to 8 km long by an 80 - 100 m long umbilical. A depressor weight at the end of the umbilical was used in conjunction with the tow cable length and survey vessel speed to control the depth of the fish. Details of the SeaMARC I hardware configuration and handling can be found in Kosalos and Chayes (1983).

SeaMARC I data described here were collected between September 3-8, 1984, as part of Bedford Institute of Oceanography cruise 84-035. Three main survey lines were run, one parallel to the regional bathymetric contours, and the others at angles of 36° and 31° (Fig. 2A). The fish was towed at an average survey speed of 3.9 km/hr, up to 4 km behind the ship. A 5 km sidescan swath width was used throughout the survey, except for a 10 km interval where a 2 km swath was used (Fig. 9).

In addition to SeaMARC I data, single channel subbottom seismic reflection profiles were collected from the survey vessel using (1) a Bolt Associates 655 cm^3 air gun source with a Nova Scotia Research Foundation hydrophone, and (2) 3.5 kHz and 12 kHz transducers. Two Van Veen grab stations, one Lehigh core station and recovery of an Aanderaa current meter mooring were completed at the eastern margin of the survey area (Fig. 2B). Additional seabed sediment data were obtained at the western margin of the area (56°W) in 1986 during BIO cruise 86-040, when two piston core and one bottom photograph station were completed (Fig. 2B).

Ship's navigation was recorded each minute from an Internav LC408 Loran C receiver operating on the Labrador Sea Chain (7930). These positions were corrected and verified using fixes from SatNav and Austron Range-Range Loran C, which were recorded using the Bedford Institute's BIONAV system. Navigational accuracy varied across the survey area, from 200 m in the east to within 1 km in the west. Due to problems encountered with an Oceano short-baseline acoustic navigation system, the SeaMARC I fish was positioned relative to the ship using horizontal ranges calculated from a wire-out indicator.

4.0 DATA PRESENTATION AND INTERPRETATION

SeaMARC I sidescan sonar data were recorded digitally and processed in real time to produce slant-range corrected records with approximate orthorectifiction. Half-tone photographs of these records were taken at a scale of 1:40,000, and manually compiled on cardboard bases. The photographs were cut and either spaced or overlapped where paper speed variations were insufficient to correct for tow speed variations, or where changes in course produced relative distortion between channels. Reproductions of the resulting seabed imagery are presented at two scales, as a 1:150,000 mosaic (Fig. 9, cover pocket), and as 1:50,000 page-sized (5 x10 km) figures (Appendix 1, Figs. A1-A35). The locations of Figs. A1-A35 are indicated on Fig. 2B.

The sidescan data presented in this report are conventional 'negative' acoustic images: dark tones represent strong echoes while lighter tones represent relatively weaker echoes, or silence. Echo strength is controlled by both large-scale (coherent) and small-scale (incoherent) seabed reflective properties. 'Scale' is a function of the resolution of the sidescan system. The SeaMARC I system has a height resolution close to the 5 cm wavelength of the 27/30 kHz signal in water. At the 5 km swath width, it has a down-range resolution limited by the 2.5 m pixel sampling rate, and an-along-track resolution limited to 4 m by the 4 s firing rate at the average survey speed of 3.9 km/hr. Similarly, at the 2 km swath width resolution is limited to 1.25 m down- range and 2 m along-track. In principle, features greater than these dimensions will result in coherent reflections (dark) and shadows (light) on the sidescan imagery. Features at this scale or smaller in one or two dimensions (i.e. microrelief or sediment texture) will cause incoherent scatter and variations in overall seabed reflectivity. In practice, the resolution of features is influenced by other factors, such as their geometry and orientation relative to the sidescan line (features subparallel to the line are more readily resolved), distortions introduced by fish motion, and the scale and style of image reproduction (see Somers and Stubbs, 1984; DeMoustier, 1988). Consequently, minimum sizes are not so easily constrained.

Examination of the 1:50,000 images of Appendix 1 suggests an effective horizontal resolution of 10-30 metres.

An interpretation of the SeaMARC I sidescan imagery is presented as two 1:150,000 sheets (Fig. 10A and 10B, cover pocket). Principal seabed features are shown by stipple (Fig. 10B), while individual tonal lineations are traced (Fig. 10A). Lineations are interpreted as resulting from large- or small-scale reflectivity contrasts; the former are indicated as scarps where recognized from either bottom profiles or distinctive sidescan echo characteristics. Fig. 2B shows isobaths at a 500 m interval; ship's track, and the locations of seabed sample and current meter stations, in addition to the location of the 1:50,000 images.

5.0 SEABED FEATURES

The SeaMARC I sidescan imagery (Fig. 9; Figs. A1-A35, Appendix I) provides direct information on approximately 1600 km^2 of seabed on the continental slope and rise between 2000 m and 3000 m depth. Sidescan coverage is inhomogenous, but the slope and rise was observed almost continuously between 2500 m to 2800 m depth on one or more sidescan transects; in addition, at the western and eastern margins of the survey area, slope seafloor above depths of 2500 m to 2100 m were observed. In the central part of the area, the rise was observed below 2800 m to 3000 m (Fig. 2B).

Three principal seabed features are distinguished using the sidescan imagery in conjunction with 3.5 and 4.5 kHz subbottom records: (1) channels, (2) interchannel hills, and (3) a large area of mass displacement (Fig. 10B). Channels and interchannel hills are recognized across the continental slope/rise; the channels correspond to the bathymetric channel axes traced out on Figs. 2A and 10B, but also include features that are not resolved by the isobaths. The area of mass displacement is evident on the flanks of a large interchannel ridge at the western margin of the survey area. For ease of reference in the ensuing discussion, the channel axes on Figs. 2A and 10B are lettered A to O, from west to east across the survey area.

5.1 Channels

Channels are characterized on the sidescan imagery by (1) morphologic lineations of varying size and orientation, and (2) generally lower overall reflectivity relative to interchannel hills (Fig. 9). Associated 3.5 kHz subbottom profiles show a loss of subbottom penetration relative to interchannel hills (Figs. 3,4) corresponding to Damuth's (1980) echo types IIB (very-prolonged with no sub-bottoms), IIIB (regular single hyperbolae with varying vertices and conformable sub-bottoms) or IIIC (regular overlapping hyperbolae with varying vertex elevations).

Channel A at the western margin of the survey area is only observed locally; channels from B east to O are all crossed by one or more sidescan transect (Fig. 2A). The sidescan imagery shows that channels range in width from <500 m (branches of channels I, L and M) to 25 km (channel B), but are generally between 1 and 8 km wide (Fig. 10B). Channel widths tend to decrease from west to east across the survey area, although not systematically. Subbottom profiles and isobaths show that overall channel relief ranges from 10 m (branches of channels L and M) to over 200 m (channel-E), but is generally between 50 and 150 m. There is no pattern to this variability across the survey area, nor any apparent relationship to channel width.

Bathymetric channel axes decrease in number downslope (Fig. 2A), due either to convergence or to loss of definition. Sidescan imagery shows that channels either coalesce downslope to form larger features in a tributary pattern, or branch into smaller distributaries in places on the continental rise. Examples of coalescing channels are seen at channels B to D in western parts of the survey area seaward of Cartwright Saddle. For channel B, isobaths indicate the presence of several convergent channel axes above 2200 depth which lose definition downslope. The sidescan imagery in 2400-2700 m depth shows that these channels have coalesced to form a feature 25 km wide. The western margin of this large channel is not as distinct as the east, and sidescan shows evidence for a small adjacent subchannel in 2300-2400 m depth. Also, a small hill (0.7 x 2 km, 50 m high) with interchannel characteristics (see below) is observed within channel B in 2625 m depth, and is probably correlative to hills separating the channels upslope. These observations suggest that the smaller channels located upslope once extended below 2200 m depth, and that subsequent coalescing is incomplete. For adjacent channel C, isobaths indicate two tributary channel axes above 2500 m depth, which converge at 2600-2700 m and extend as a single feature to 3000 m depth. Sidescan imagery in 2650- 2750 m depth shows a corresponding single channel (2.5 km wide). Alternatively, isobaths show that the axes of adjacent channels D and E can both be traced from above 2500 m to about 3000 m depth where they converge, but the hill separating them appears much less distinct between 2600-2800 m depth. The sidescan imagery of these features shows a single channel (16 km wide) in 2700 m depth, which diverges downslope into two channels (5-7 km wide) in 2800-2900 m depth.

Further examples of coalescing are seen in channels J to O on the continental slope in the eastern part of the survey area. Isobaths indicate that these channels converge downslope on the continental rise. However, sidescan shows that channels L and M on the slope between 2300-2650 m depths are actually multiple features, composed of several smaller branches which appear to coalesce downslope. Channel L consists of two branches (0.5 km and 3 km wide), the larger of which contains complex tonal patterns that further broadly subdivide it into 3 indistinct branches (0.5 km wide) that may be in the process of merging. Channel M consists of four branches, from west to east: two <0.5 km wide, a third which widens downslope to 2 km, and a 2 km wide which is seen to result from the coalescing of two smaller features. It is likely that the multiple branches of both channels L and M all coalesce downslope to form larger single channels. In contrast, isobaths clearly indicate that channel O at the eastern margin of the survey area contains three converging branches which sidescan imagery in 2100-2350 m depth depicts as three 1 km wide features.

In the central part of the survey area, the sidescan imagery shows evidence of distributary channels on the continental rise. Isobaths indicate that the axes of channels F to I all lose definition below depths of 2500-2800 m; downslope below 2900 m a single prominent channel axis is indicated. Sidescan imagery from the continental slope in 2500-2700 m depth indicates downslope coalescing: channel F widens downslope (from 2 km to 3 km), and channel G has coalesced with channel H to form a feature that also widens downslope (from 6 km to 8 km). However, sidescan imagery from the continental rise shows a channel only 3 km wide in 2950-3000 m depth, which can be correlated with channel F in the west. The seabed to the east of channel F (downslope from channels G to I) consists of a subparallel series of channels 0.5-1.5 km wide that are oriented parallel to the isobaths (transverse to the axis of channel F). These transverse channels can be followed upslope to 2800 m depth, where they are seen to be western distributaries to channel I; eastern distributaries to channel I may also be present. A similar distributary pattern is inferred for channel G/H below 2800 m depth, although sidescan coverage is inadequate to verify this morphology.

The morphologic lineations that characterize the channels vary in style (height, spacing and orientation) across the survey area (Fig. 10A). Subbottom profiles show that, in general, channels B to H in the west have up to 5 m of relief, while channels I to O in the east appear smooth (<1 m relief). The sidescan imagery shows 3 groups of features: (1) distinctive subparallel features with relief of <1 m and spacings of 50-100 m, generally oriented approximately transverse to the channel axes; these occur in bands in many channels (e.g. channels D, K and O) or in fields (channel C, eastern channel B). In the latter case, the higher resolution 2 km sidescan swath across channels B and C shows that the fields contain alternating bands of differing orientation, resulting in a herrringbone pattern; (2) larger but similar subparallel features with relief up to 5 m and spacings up to 500 m are observed, generally with arcuate or wavy crests (western channel B, channels D, E and M); (3) chaotic or hummocky relief is observed in several channels, in one case with relief up to 5 m (channel G/H in 2600-2700 m depth), but otherwise with relief of <1 m (channels E, F, I and J in 2600-2800 m depth). It is important to note that preferential resolution of features subparallel to the sidescan transect is possible, and that additional lineations may be present but unresolved.

The lower overall sidescan reflectivity of channels relative to interchannel hills varies in degree across the survey area. Channels I to M in the eastern part of the survey area are more sharply distinguished by low reflectivity than other channels, some of which show almost no tonal contrast with adjacent interchannel hills (e.g. western side of channel B, channels D and O). Downslope variations in reflectivity do not appear significant, for example channel I is strikingly characterized by low reflectivity from 2500 m down to 3000 m depth. All channels are characterized by a similar loss of penetration on subbottom profiles (e.g., Fig. 9).

The lower reflectivity of channels compared to hills seen on the sidescan imagery, and the associated loss of penetration on subbottom records, is related to backscatter from small-scale (incoherent) seabed reflective properties (e.g., microrelief and/or sediment characteristics). Unfortunately, no samples are available from the channels. However, low sidescan reflectivity implies decreased echo strength (or finer sediment textures), while loss of subbottom penetration is associated with increased seabed reflectivity (or coarser sediment textures). These reflectivity characteristics could be accounted for by a veneer of fine sediment in the channels too thin to be resolved on subbottom profiles (<0.5 m) overlying coarse material which inhibits penetration.

Alternatively, scatter of reflected energy in the channels by microrelief could account for the observed reflectivity contrasts, and would also be consistent with the observed distribution of fine sediments on levees and coarse deposits in channels in other slope settings (e.g., Klaus and Ledbetter, 1988; Ivanov and Konyukhov, 1988). In theory, a perfectly smooth surface will reflect less energy than a rough one, which in this case would imply that the channels are smoother than the interchannel hills. However, little is known about sidescan reflectivity contrasts between areas of differing styles of microrelief, which can vary in height, down-range, and along-range dimensions. The association of microrelief with channel reflectivity is substantiated by two observations: (1) a 5 km sidescan swath across channels B and C shows low reflectivity areas with some morphologic lineations (<1 m relief), whereas a higher resolution 2 km sidescan swath reveals a dense pattern of lineations across these low reflectivity channel floors; (2) channels I to L all contain 'pepperings' of sublinear to point-source reflections suggestive of incidental echoes from small-scale features, possibly similar to those observed in channels B and C.

5.2 Interchannel Hills

Interchannel hills are characterized on the sidescan imagery by: (1) fairly uniform reflectivity, which is generally higher than that of the channels, and (2) often by broadly spaced (>0.5 km) isobath parallel morphologic lineations. Subbottom profiles across the hills show penetration of up to 20 m (Figs. 3, 4), corresponding to 3.5 kHz echo types IB (sharp continuous with numerous parallel subbottoms) or IIA (semi-prolonged with intermittent parallel sub-bottoms) as described in Damuth (1980). Similar sidescan and subbottom reflection characteristics are evident in parts of the large area between channels A and B at the western margin of the survey area, but this feature is not truly a hill and is considered separately below (see Section 5.4 below).

Sidescan imagery shows that the interchannel hills range in width from 0.5-1 km (isolated hill in channel B in 2625 m depth, hills between branches of channels L and M) to 10 km (hills between channels E and F, H and I), and are generally greater than 4 km wide (Fig. 10B). There is no apparent pattern to the variability in hill width across the survey area, although those in the east are often narrower (2 km or less). This association reflects primarily the multiple characters of channels L, M and O. Subbottom profiles and isobaths show that the overall relief of hills relative to the channels varies from 10 m (branches of channels L and M) to over 200 m (hill between channels E and F), and is generally greater than 50 m. There is no pattern to the variability in hill relief across the survey area, nor any apparent association in regard to hill width.

The penetration observed on subbottom profiles across interchannel ridges (Figs. 3, 4) indicates fine-grained or muddy sediment textures. Grab and core samples collected from the ridge between channels L and M (Fig. 2B), show that surficial deposits to depths of about 8 m are composed primarily of muddy turbidites. AMS C^{14} dating for foraminifera collected from cores of this sediment suggest that they are of pre-late Wisconsinan age (Schafer, unpublished data).

Subbottom profiles indicate that interchannel hills vary from features with wavy relief on the continental rise (Fig. 5) to features that appear relatively smooth on the continental slope (Fig. 6). Hills with wavy relief are observed on the continental rise between channels B to D (2650-2750 m depths) and between channels D to F on the deeper sidescan transect (2800- 2900 m depths). The waves are 10-30 m in relief, locally up to 55 m between channels E and F. Sidescan imagery shows that the waves are arcuate and sometimes complex, but in general broadly spaced (0.5-3 km) and oriented approximately parallel to the isobaths (i.e., normal to the hill axes). The waves are asymmetrical, with the steeper side facing downslope.

On the continental rise (2800-3000 m depths), hill features that separate distributary channels are also isobath parallel and asymmetrical, with spacings of 1-4 km and relief of 10-30 m. They are larger but equivalent waves, with distributary channels occupying their troughs. Their presence over a large area east of channel F reflects the downslope coalescing of adjacent hills as channels G to I become distributary downslope.

Hills on the lower continental slope between channels E to I (2500- 2700 m depth) do not have wavy relief. Instead they show local increases in gradient on subbottom profiles (Fig. 6) that appear as broad scarps on the sidescan imagery. These scarps often appear discontinuous, but in general they are broadly spaced (0.5-2 km) with relief of 5-20 m, and locally up to 50 m between channels E and F. The scarp features appear to be muted equivalents of the wavy relief observed downslope and to the west.

Hills on the continental slope east of channel I (2800 m up to 2100 m depth) appear smooth on subbottom profiles (Fig. 4), and are generally featureless on the sidescan imagery. An exception is the hill between channels I and J, which has relief of up to 5 m and contains arcuate, isobath-parallel morphologic lineations with 0.5-1 km spacing. Also, the two hills between channels M to O contain a few low morphologic lineations on the upslope side of the sidescan imagery.

5.3 Channel/Hill Reflection Seismic Character

Airgun seismic profiles show that interchannel hills are acoustically stratified sediment accumulations that are discontinuous across channels on the continental slope (Fig. 6) but continuous beneath them on the continental rise (Figs. 5, 7). These stratified deposits appear to correspond to material lying above the Ra seismic reflector described by Myers (1986). He concluded that this reflector underlies sediments that have been deposited since "Mid-Late Pleistocene" time.

On the continental slope, the channel floors are eroded into older underlying sediments (Fig. 6). Channel/interchannel relief is a combination of sediment thickness beneath the hills, and erosion beneath the channels. Relief east of channel M (2100-2400 m depth) is dominated by channel erosion, with sediment thicknesses in the hills (at 1.5 km s^{-1}) of less than 40 m versus relief of up to 80 m. Relief between and within channels I to M on the slope in the eastern part of the survey area (2300-2800 m depth) is less strongly influenced by erosion, with hill sediment thicknesses of 40-80 m versus channel relief of 40-130 m (Fig. 4). Relief between channels D to H on the slope in the central part of the area (2500-2700 m depth) is dominated by sediment thickness, which ranges from 50-80 m, up to 140 m between channels E and F.

On the continental rise, the stratified sediments of the interchannel hills extend beneath the intervening channel floors. Up to 20 m of stratified sediments are observed beneath channels B to E (Fig. 5), and up to 110 m beneath channel F (Fig. 7) and the adjacent distributary branches of channel

I. In these instances, the large- and small-scale sidescan reflectivity characteristics of the channels appear to be superimposed on the stratified sediments.

In smooth or broadly scarped hills on the continental slope, internal reflectors suggest that axial positions have remained stable across the slope over time (Fig. 6). In the wavy relief associated with continental rise hills, internal reflectors suggest an upslope migration of wave crests over time (Fig. 7).

5.4 Mass Displacement

A large-scale mass displacement of sediment is indicated on the flanks of the large ridge between channels A and B at the western margin of the study area. It is observed on sidescan transects along the axis and eastern flank of the ridge, in depths of 2050-2650 m (Fig. 10 A and B). Air gun profiles show that the ridge is mantled by stratified sediment up to 200 m thick (Fig. 8), and is a morphologic expression of the underlying sediment surface. The stratified sediment is similar in thickness and character to that underlying interchannel hills to the west (c.f. Figs. 6, 8), and has equivalent sidescan and subbottom reflectivity characteristics. The mass displacement is developed within the stratified sediment, and takes the form of irregular seabed relief associated with unstratified subbottom sediment (Fig. 8).

Sidescan imagery shows scarps on both the western and eastern flanks of the ridge (Fig. 9). The scarp on the western flank is only observed in 2050-2300 m depth, and extends beyond the sidescan swath in both upslope and downslope directions; the seabed below the scarp to the west is poorly resolved. The scarp on the eastern flank, however, is observed from up to 2050 m depth, down to 2550 m depth, where it extends towards the ridge axis and beyond the coverage of the sidescan record. Below the scarp, two types of irregular relief are observed. In 2050-2400 m depths, irregular morphologic lineations oriented subparallel to the scarp are indicated on the eastern edge of the sidescan imagery. These lineations are not crossed by subbottom profiles, but sidescan echo characteristics indicate they have relief of 10's of metres. Isobaths to the east of the sidescan swath are irregular, and may reflect the presence of similar irregular relief. Below 2400 m depth, these lineations give way to lower relief (up to 10 m) discontinuous linear mounds, with irregular spacing and density. The mounds form a distinctive suite along the eastern flank of the ridge, roughly describing an arc. They are generally subparallel, but vary in orientation across the area of observation. The area of the mounds is bounded downslope by a second scarp at 2600-2650 m depth. Air gun and subbottom profiles show that the upper and lower scarps each have relief of about 10 m. The area between them corresponds to unstratified subbottom sediment with irregular seabed relief up to 10 m (Fig. 8). These characteristics are similar to mass (debris) flows observed elsewhere (Nardin et al., 1979; Prior et al., 1984).

The mounds are morphologically comparable to crag-and-tail bedforms observed elsewhere on SeaMARC I records (S. Shor, pers. comm. 1984). Within the study area, these features were initially thought to reflect the influence of the WBUC due to their proximity to its axial zone at about 2500 m depth (Schafer and Carter, 1985). However, their areal distribution, association with scarps, and subbottom character indicates they are more likely a surface expression of the displaced underlying sediment.

The area of displaced sediment on the eastern flank of the ridge is only partly visible on the sidescan imagery, but extrapolation suggests it extends over a total area of perhaps 250-300 km^2, from 2050 m to at least 2650 m depth. In addition, the scarp that is partly observed along the western flank of the ridge suggests a similar feature along that side of the ridge. Displaced sediment extends west across the sidescan swath towards channel A in 2500-2600 m depth, suggesting that lobes of displaced sediment on the west and east flanks may coalesce downslope along the ridge axis.

6.0 DOWNSLOPE SEDIMENT TRANSPORT

The seabed features recognized in the survey area record the significance of downslope sediment processes in shaping the large scale geomorphology of the Labrador continental slope and rise.

6.1 Channels and Interchannel Hills

The survey area is dominated by the system of channels and interchannel hills that extends down the continental slope and rise (Fig. 10B). Channels contain a variety of morphologic lineations up to 5m in relief. Sidescan and subbottom reflective characteristics may be the result of incoherent scatter by microrelief. These varying scales of relief suggest mass flow down the channels. Interchannel hills are fine- grained sediment accumulations.

The Labrador margin has therefore been the site of both downslope mass transfer of sediment, and of sediment deposition between mass flow conduits. On the morphologically similar western Scotian Slope, an equivalent variability in slope character, that is especially prominent in relatively shallow environments, is interpreted to represent proglacial deposition from suspension combined with bypassing along slope gullies (Piper and Sparkes, 1987; Piper, 1988). Myers and Piper (1988) associated the channels of the Labrador margin with a mid to late Quaternary increase in turbidite activity resulting from glacial ice sheets crossing the Labrador Shelf. Josenhans et al. (1987) interpreted Wisconsinan ice to have reached to the Labrador upper continental slope. A glaciomarine origin for the channels in the survey area, similar to that proposed by Piper and Sparkes (1987) on the Scotian Slope, is therefore tenable.

Channels and interchannel hills show a downslope progression in character related to seabed gradients. As noted earlier, gradients increase both upslope, and from west to east across the survey area (Figs. 1, 2B). The continental rise was examined in the western and the deeper central parts of the survey area, while the continental slope was examined in the shallower central and the eastern parts of the survey area. The slope in the eastern part has steeper gradients and includes shallower depths than the slope to the west.

A downslope progression is observed from erosional channels between levees on the steeper gradients of the continental slope, to depositional channels among levees on the gentler continental rise. On the steeper continental slope in the eastern part of the survey area, overall channel/hill relief is dominated by erosion beneath the channels, and hills are generally smooth in profile (Fig. 3). On the gentler slope in the central part of the survey area, overall relief is a combination of hill-thickness and limited erosion of older sediments beneath channels, and hills have broad isobath-parallel scarps (Fig. 6). On the continental rise, channel characteristics are superimposed in a non-erosive style on stratified hill sediments, which extend beneath the intervening channels (Fig. 7); the isobath-parallel scarps have evolved into sediment waves, which appear to be building in an upslope direction (Fig. 7). Further, sidescan imagery shows that channels either coalesce downslope in tributary fashion to form wider features, or branch into distributaries on parts of the continental rise. These distributary channels occupy the troughs of interchannel sediment waves on the continental rise. As channels branch out, adjacent interchannel hills merge, and wave fields extend over large areas.

Normark et al. (1980) reviewed sediment waves in the deep ocean, and showed that they are most common on continental rises on slopes of $<1°$, typically have wavelengths of 0.5 to 6 km and amplitudes of 10 to 40 m, and commonly are reported to migrate upslope. They suggest that such features are probably antidune forms which originate from thick, low-velocity, low-concentration fine-grained turbid flows, although bottom current transport hypotheses have also been advanced (e.g. Klaus and Ledbetter, 1988; Flood, 1988). In the present survey area, the downslope transition from interchannel levees on the continental slope to levee wave fields on the continental rise supports an origin for sediment waves on the Labrador margin as turbidity current antidune forms.

Isobaths indicate that such distributary branching of channels and merging of adjacent hills corresponds to a downslope loss of resolution of channel axes. Regional isobaths show that the loss of channel axes continues seaward across the continental rise (Fig. 1), until only a single large channel reaches the NAMOC 350 km to the east. The continental rise in the survey area was characterized by Myers and Piper (1988) from seismic reflection profiles as part of their seabed wavy-stratified facies, which they show as a widespread feature along the Labrador rise and seaward toward the NAMOC . They related it to the alongslope influence of the WBUC in the mid to late Quaternary. However, the downslope relationships observed in the present survey area suggest that the wavy-stratified facies may in fact represent fields of sediment waves, related to downslope sediment transport and dispersal in the mid to late Quaternary.

Channels also contain variations in character along the continental slope and rise in the survey area. In general, channels in the western part are dominated by large-scale relief (up to 5 m), while channels in the east have lower relief (<1 m) and are more sharply distinguished by small-scale reflectivity contrasts related to microrelief. Channels are also generally narrower in the east, or are composed of several narrow subchannels. This variability appears to be independent of water depth or gradient. However, the continental shelf adjacent to the study area consists of Cartwright Saddle (deep) in the west, and Hamilton Bank (shallow) in the east (Fig. 1). Swift (1985) similarly noted lateral variability in the character of the Scotian Slope seaward of LaHave Channel and Emerald Bank, and suggested control of the glacial sediment supply to the slope by shelf morphology. Consequently, a greater net flux of glaciomarine sediment through Cartwright Saddle could account for the greater relief and width of channels in the western part of the Labrador survey area.

It is uncertain to what extent the glaciomarine channels of the slope and rise remain conduits for modern downslope sediment transport. The contrasting sidescan reflectivity of most interchannel hills and channels may represent either seabed microrelief, or a veneer of fine-grained post-glacial sediments. Pisces IV submersible observations at the head of a channel seaward of Makkovik Bank

(Fig. 1) in 750-1000 m depth recognized small- and large-scale mass failures at the seabed (Josenhans et al., 1987), suggesting that some modern channel activity is possible.

6.2 Mass Displacement

The interchannel ridge at the western margin of the survey area represents a structurally controlled high, blanketed by glaciomarine sediment equivalent to that which forms the interchannel hills to the east. The large-scale mass displacement developed within the upper part of these glaciomarine sediments represents downslope dislocation of up to 300 km^2 of sediment on the eastern flank of the ridge, and an unknown area of sediment on the western flank. The well-defined bounding scarps suggest that this feature may reflect a single event. Its occurrence at the seabed suggests it is a post-glacial event, and possibly quite recent.

7.0 DOWNSLOPE VS. ALONGSLOPE TRANSPORT

Carter and Schafer (1983) recognized a 50 km wide zone of relatively coarser surficial sediments between 2500-2800 m depth on the Newfoundland Slope at 49°30'N, which they related to reworking beneath the WBUC axial zone in late glacial to Holocene time. In our survey area, 3 surface samples collected from the hill between channels L and M in 2400-2500 m depth (Fig. 2B) have bulk textures comparable to those observed by Carter and Schafer (1983) beneath the WBUC axis. That these samples come from a similar zone of surficial reworking is supported by a 304 day current meter record from the same location (Fig. 2B), which indicates WBUC velocities of 10-28 cm/sec (Schafer, unpublished data). In addition, bottom photographs from the ridge mantled by levee sediments between channels A and B show evidence of sediment winnowing below the WBUC axis (Fig. 11). At station 86-040-007 in 2560 m depth, bottom sediment is a matrix of silty-sand patches and angular ice-rafted (?) cobbles and boulders that can exceed 80 cm in diameter. Some of the larger boulders display a tail of manganese-coated pebbles that points in the downcurrent direction. Attached algae and sponge species are often seen on the upcurrent side of these boulders. These bottom photograph, bulk texture and current meter data suggest that a belt of reworked sediment is continuous between the eastern and western limits of our survey area.

As noted earlier, the contrasting sidescan reflectivity between most channels and interchannel hills could be related to a veneer of relatively finer-grained sediment occupying the channels. Such a veneer might result from winnowing of exposed hill crests and deposition in intervening (sheltered) channels under the influence of the WBUC, a process similar to that presently active on the adjacent continental shelf under the influence of the Labrador Current (Josenhans et al., 1986). However, at present there are no sediment samples available to verify this, and sidescan reflective contrasts may alternately be explained by microrelief scattering. In addition, some channel/hill pairs are seen to have marked reflective contrasts across depth ranges of up to at least 500 m (e.g., channel I from 2500-3000 m), and to depths well below the proposed influence of the WBUC; sediment winnowed under the influence of the WBUC would be expected to form a widespread veneer across continental rise depths both above and below the WBUC axial zone (e.g., Carter et al., 1979), but this is not observed.

The survey provides no direct evidence for morphologic features, such as bedforms that can be related to WBUC activity. A sedimentary model of interacting downslope and alongslope transport processes on continental slopes and rises (Heezen et al., 1966) has been promoted by many workers. For example, Asquith (1979) examined "lower continental rise hills" off the east coast of the United States and proposed that they originated from a combination of turbidity current erosion of a distributary channel system and contour current entrainment of fine-grained sediment. These hills occur in depths of 4500-5000 m, but are generally similar in relief (46-137 m) and spacing (4-9 km) to the interchannel hills of the Labrador slope and rise. Migrating mud waves of similar scale were observed by Klaus and Ledbetter (1988) in the Argentine Basin and are also attributed to interacting down/alongslope processes. Interchannel sediment deposition on the Labrador slope and rise could have been similarly influenced by alongslope currents that entrained sediment mobilized during downslope transfer events. However, there is no apparent evidence for this process in either the sidescan imagery or seismic records of the interchannel hills: hill morphology is not significantly asymmetrical along slope, and is dominated by slope-parallel sediment waves on the continental rise.

During the present interglacial, slope/rise cores from offshore eastern Canada indicate a decrease in sedimentation rates of at least an order of magnitude since ca. 12,000 BP (Schafer et al., 1985; Hill, 1984). These data reflect primarily a decreased interglacial sediment flux, compounded by trapping of sediment in intrashelf basins due to the reestablished influence of the Labrador Current (Josenhans et al., 1986). Over the same time period, the intensity of WBUC velocities has increased (Schnitker, 1979; Streeter and Shackleton, 1979; Schafer et. al., 1985). Thus the WBUC appears to have had a lesser influence on the continental slope and rise during the last glacial, when high rates of sedimentation promoted downslope sediment transport as expressed by the channel/levee system (e.g. Mountain and Tucholke, 1985).

We propose a Quaternary history of alternating downslope and alongslope influences on sedimentation for the Labrador margin. Downslope sediment transfer has dominated during glacial periods, when large volumes of sediment were supplied to the continental margin by ice sheets; WBUC activity was reduced during this time. During interglacials, the alongslope influence of the WBUC has dominated the redistribution of available sediment. However, the much greater sediment flux of glacial periods has resulted in the associated channel/levee system dominating the geologic record, and the geomorphology of the slope and rise. This alternating sedimentation pattern may be applicable to the Quaternary history of most glaciated continental margins.

8.0 ACKNOWLEDGMENTS

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FIGURES

Figure 1 - Location of the SeaMARC I survey area in the Labrador Sea showing bathymetry of the continental margin and the names of major physiographic features. From GEBCO Chart # ________

Figure 2A - Map of the SeaMARC I survey area, showing ship's track, 500 m bathymetric contours, bathymetric channel axes from Fig. 2B, and locations of Figures 3-8. The position of Figure 11 is shown by the star symbol. See Figure 1 for location.

Figure 2B - 1:150,000 scale map (cover pocket) showing ship's track, location of current meter and sample stations.

Figure 3 - 3.5 kHz subbottom profile showing reduced penetration across a channel in comparison to the adjacent interchannel hills. See Figure 2A for location.

Figure 4 - 3.5 kHz subbottom profile showing reduced penetration across channels in comparison to interchannel hills. See Figure 2A for location.

Figure 5 - 655 cm^3 air gun seismic reflection profile showing two stratified interchannel hills with wavy relief flanking channel D. See Figure 2A for location.

Figure 6 - 655 cm^3 air gun seismic reflection record showing two stratified interchannel hills with smooth surfaces flanking a channel. See Figure 2A for location.

Figure 7 - 655 cm^3 air gun seismic reflection profile showing an interchannel hill with wavy relief, and associated stratified sediments extending beneath a channel. Note the upslope progradation of subsurface reflectors marking previous wave crests. See Figure 2A for location.

Figure 8 - 655 cm^3 air gun seismic reflection profile showing a thin, surface unstratified interval realted to mass displacement of adjacent stratified sediments.

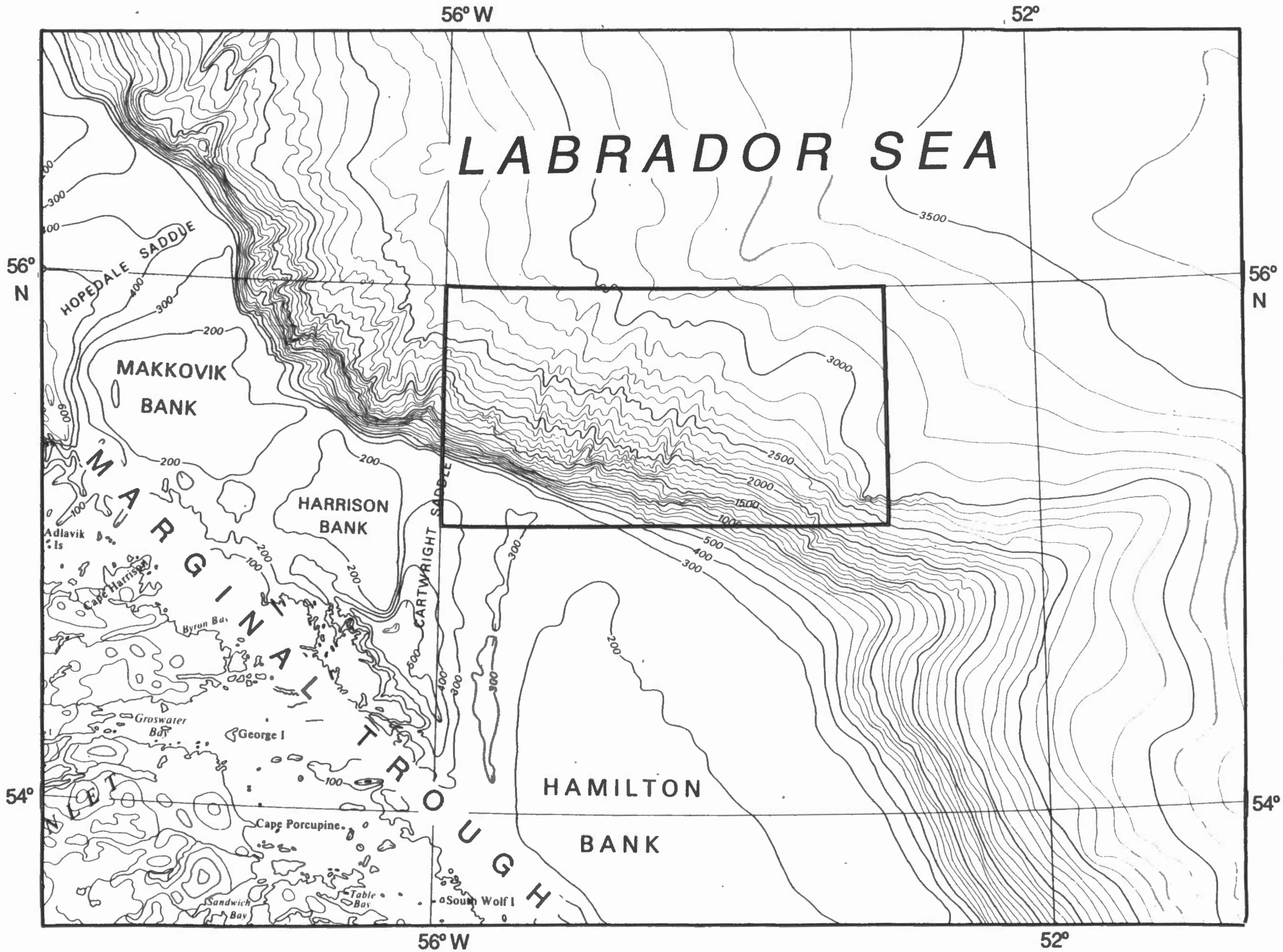
Figure 9 - 1:150,000 scale map (cover pocket) showing SeaMARC I sidescan sonar mosaic and bathymetry.

Figure 10A - 1:150,000 scale map (cover pocket) showing bathymetry, bathymetric channel axes, interpretation of sidescan tonal lineations, and position of Appendix Figures A1-A35.

Figure 10B - 1:150,000 scale map (cover pocket) showing bathymetry, bathymetric channel axes, and principal seabed features interpreted from SeaMARC I imagery and 3.5 kHz profiles.

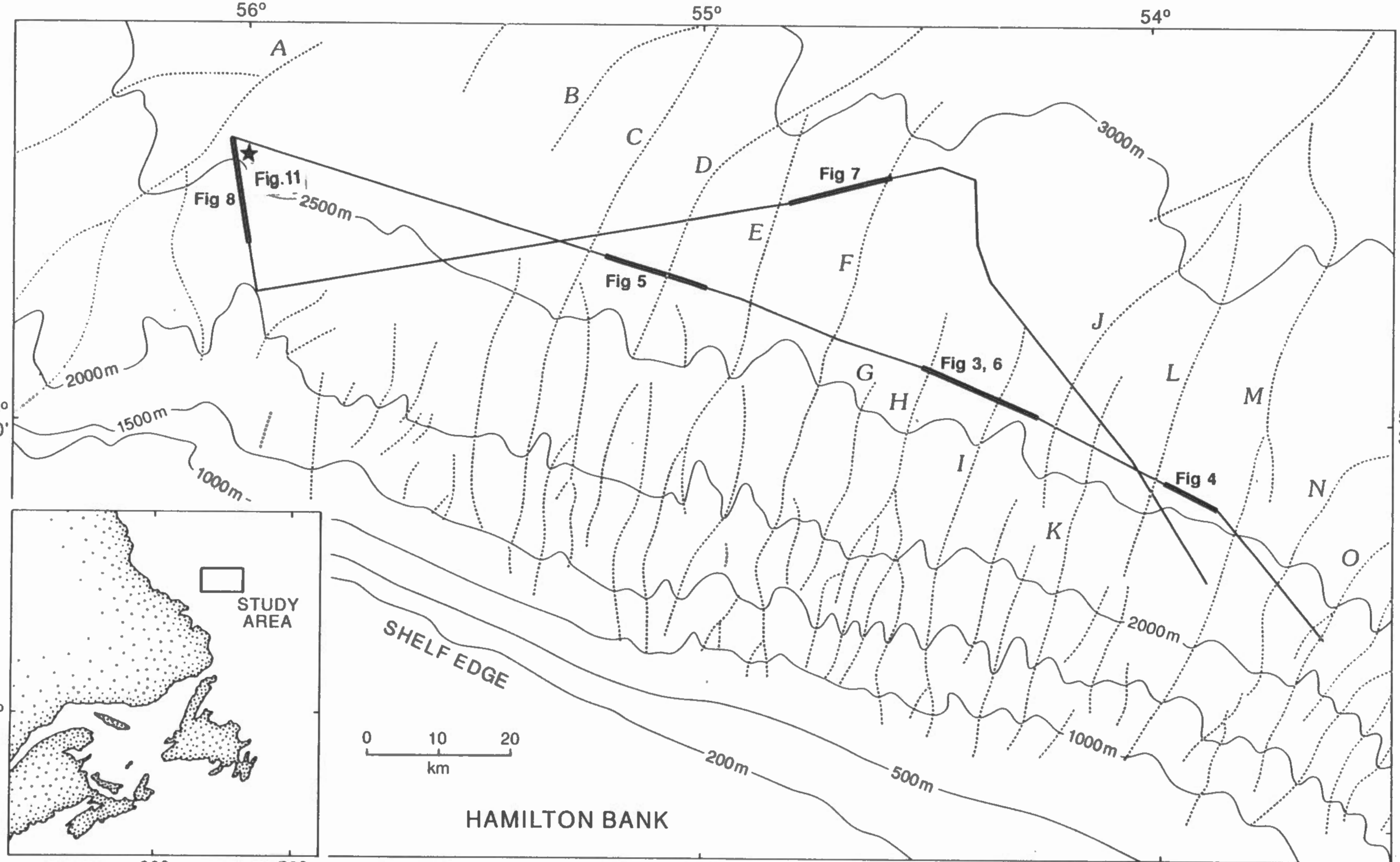
Figure 11 - Bottom photographs taken at 2560 m (Station 86-040-7) showing winnowing effects of the WBUC. The length of the compass and tailfin is 40 cm.

Appendix - Figs. A1-A37.



56° W
52°
LABRADOR SEA
3500
3000
2500
2000
1500
1000
500
400
300
200
100
600
56° N
HOPEDALE SADDLE
MAKKOVIK BANK
HARRISON BANK
CARTWRIGHT SADDLE
MARGINAL TROUGH
HAMILTON BANK
Adlavik Is
Cape Harrison
Byron Bay
Groswater Bay
George I
Cape Porcupine
Sandwich Bay
Table Bay
South Wolf I
54°

FIGURE 1



56°
55°
54°
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
Fig 8
Fig.11
Fig 5
Fig 7
Fig 3, 6
Fig 4
3000m
2500m
2000m
1500m
1000m
200m
500m
55° 30'
SHELF EDGE
HAMILTON BANK
0
10
20
km
STUDY AREA
50°
60°

FIGURE 2

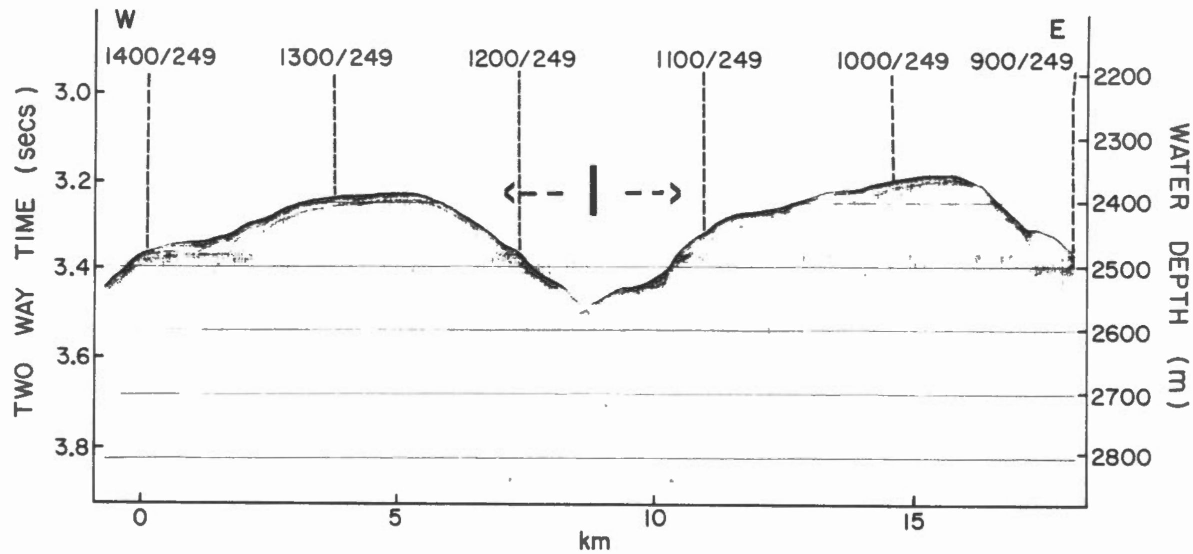


FIGURE 3

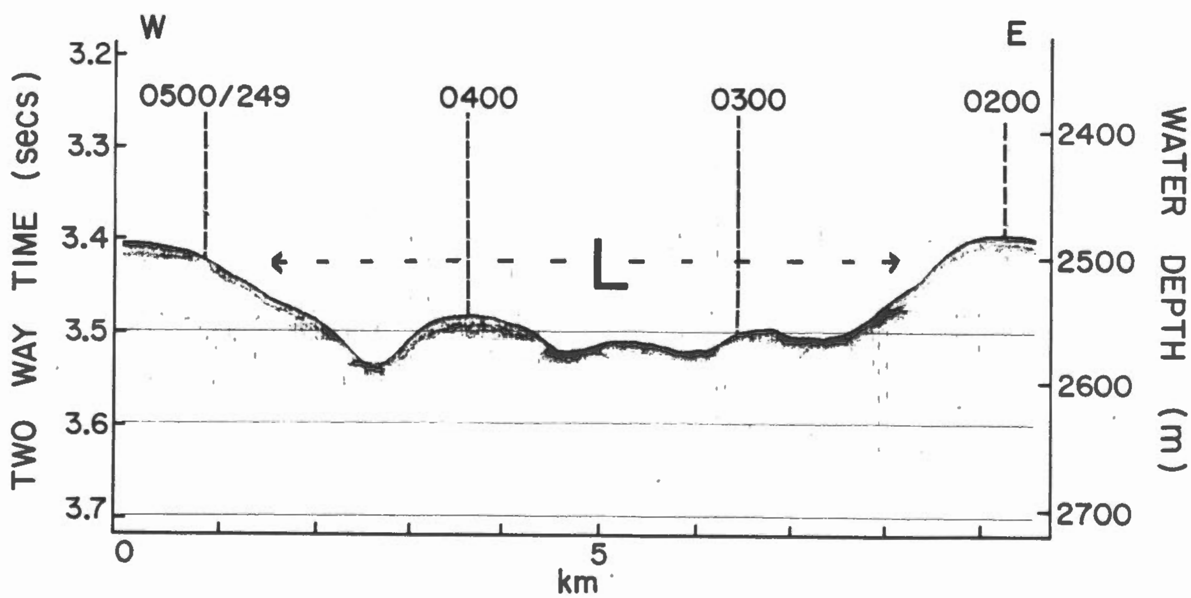
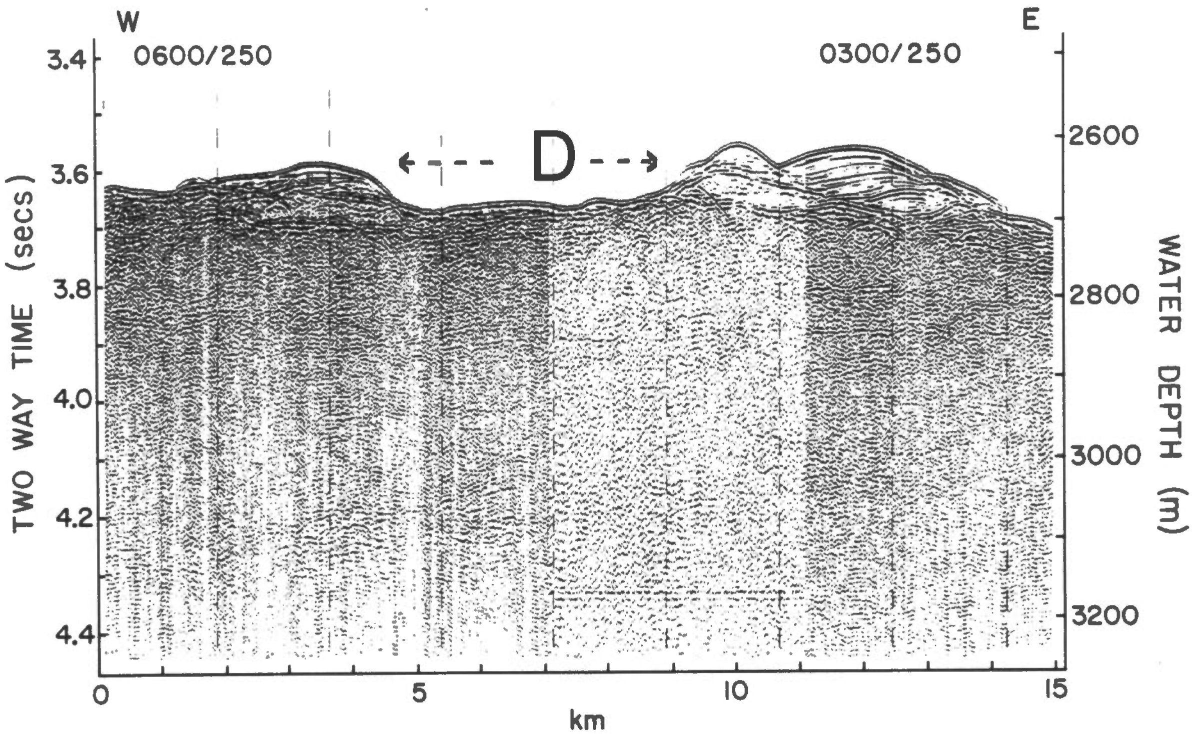


FIGURE 4

FIGURE 5



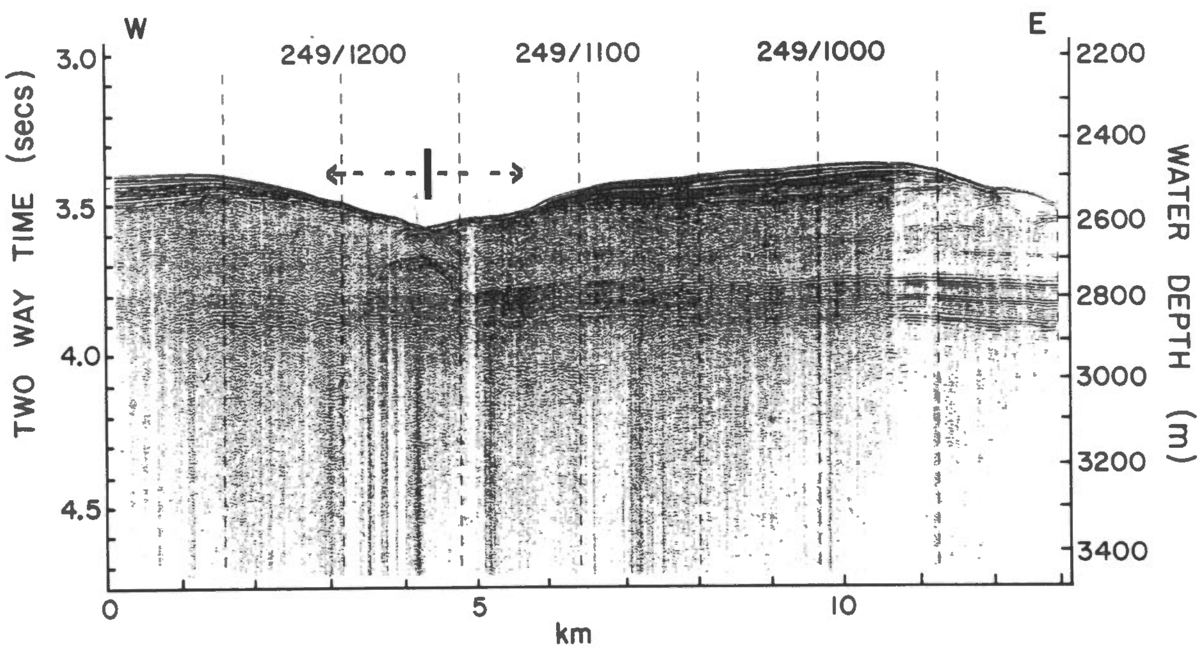


FIGURE 6

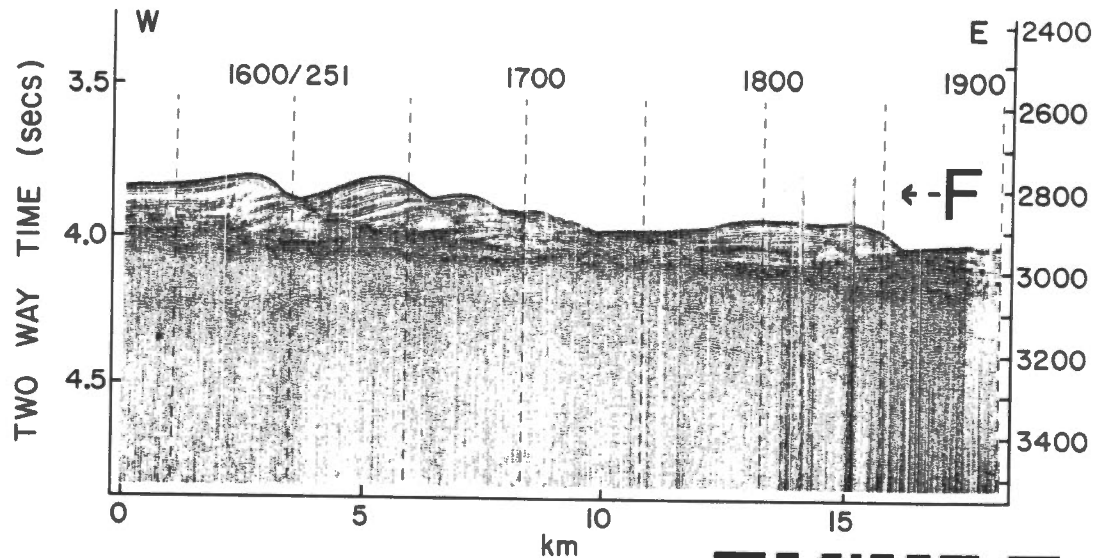


FIGURE 7

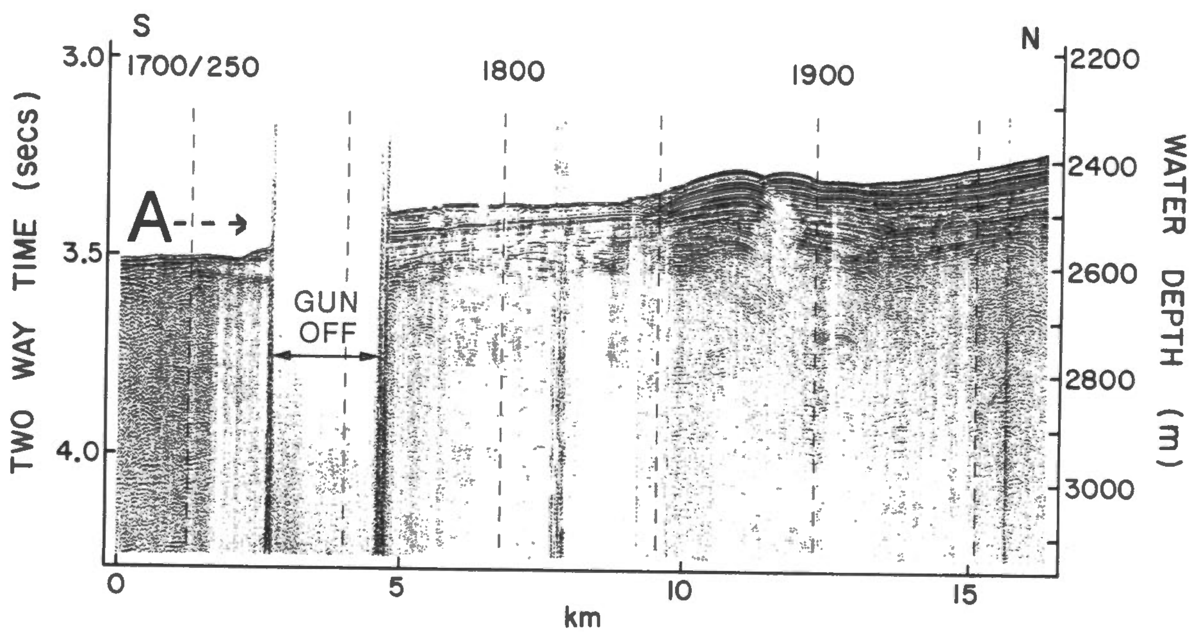
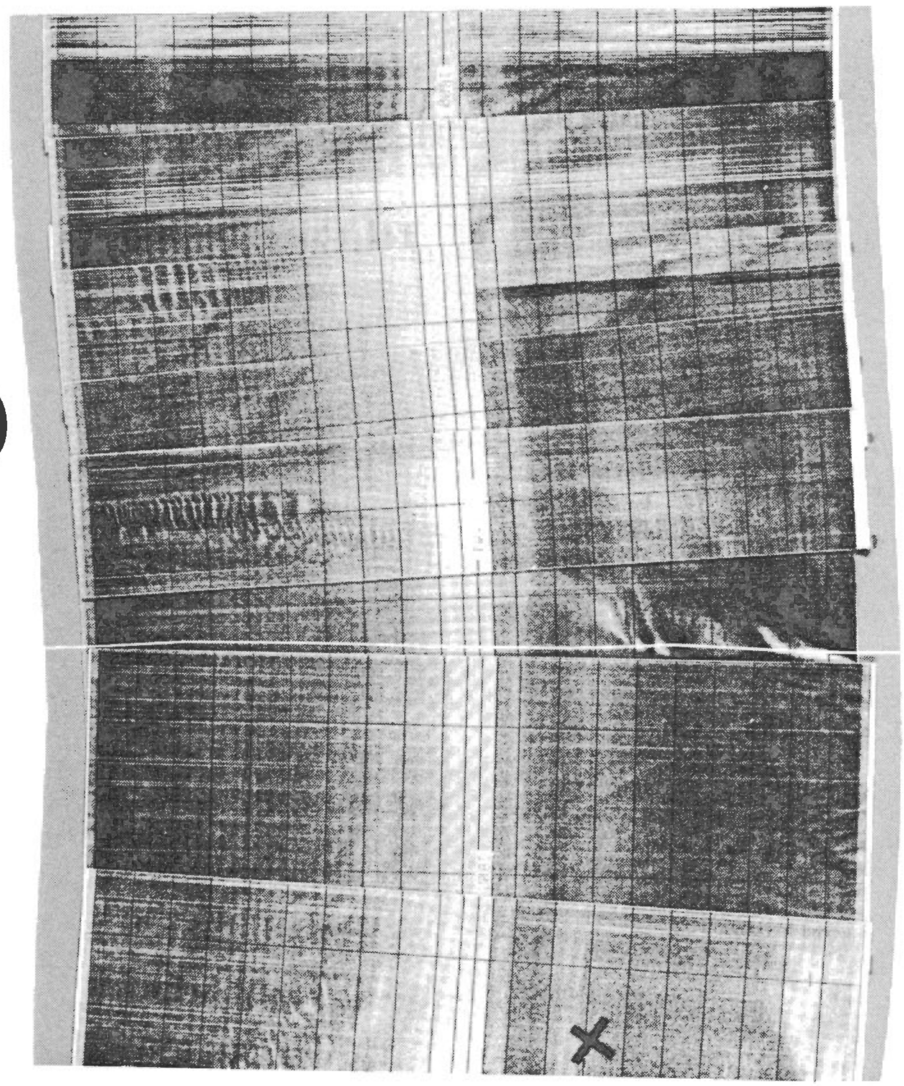
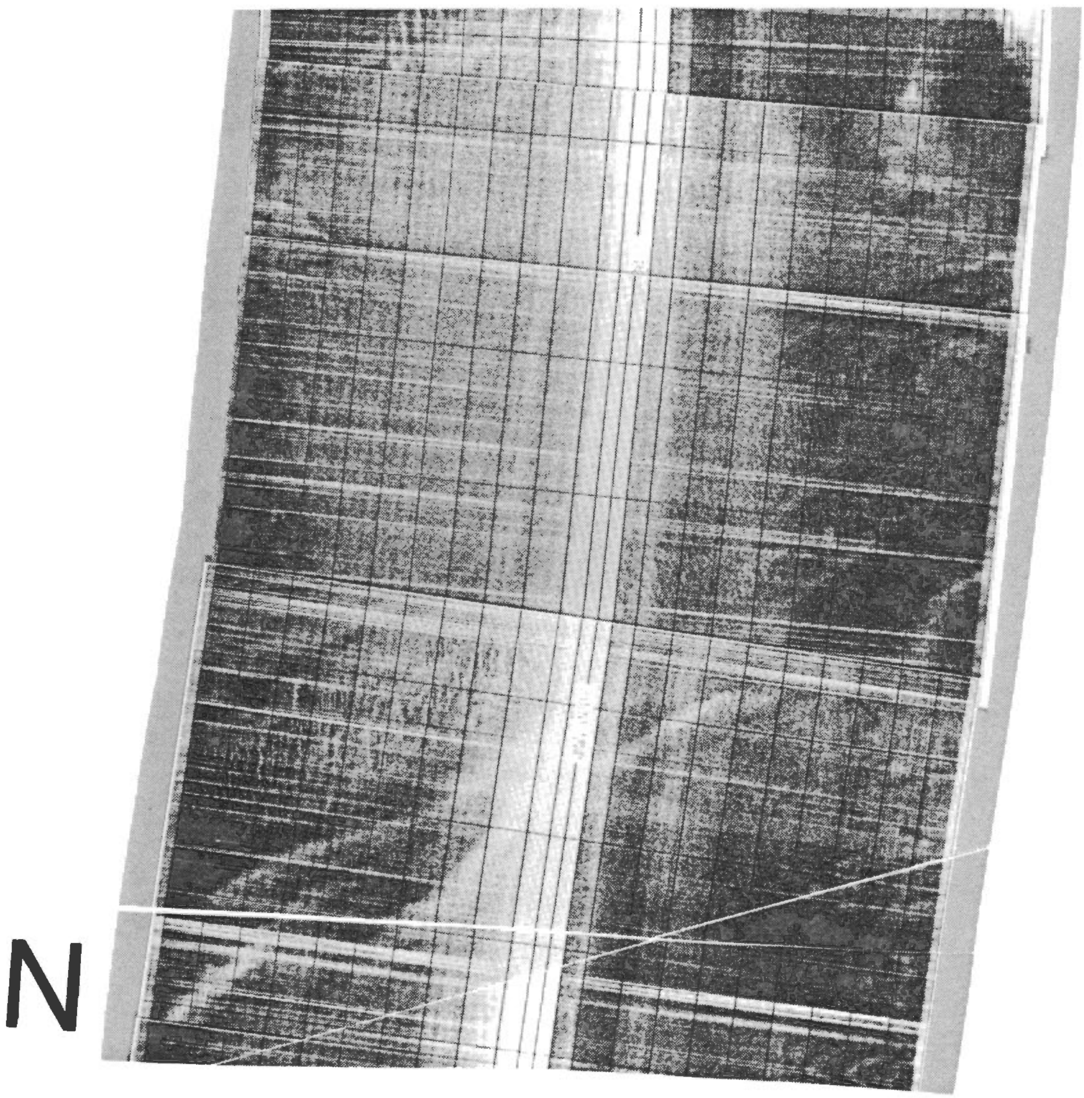
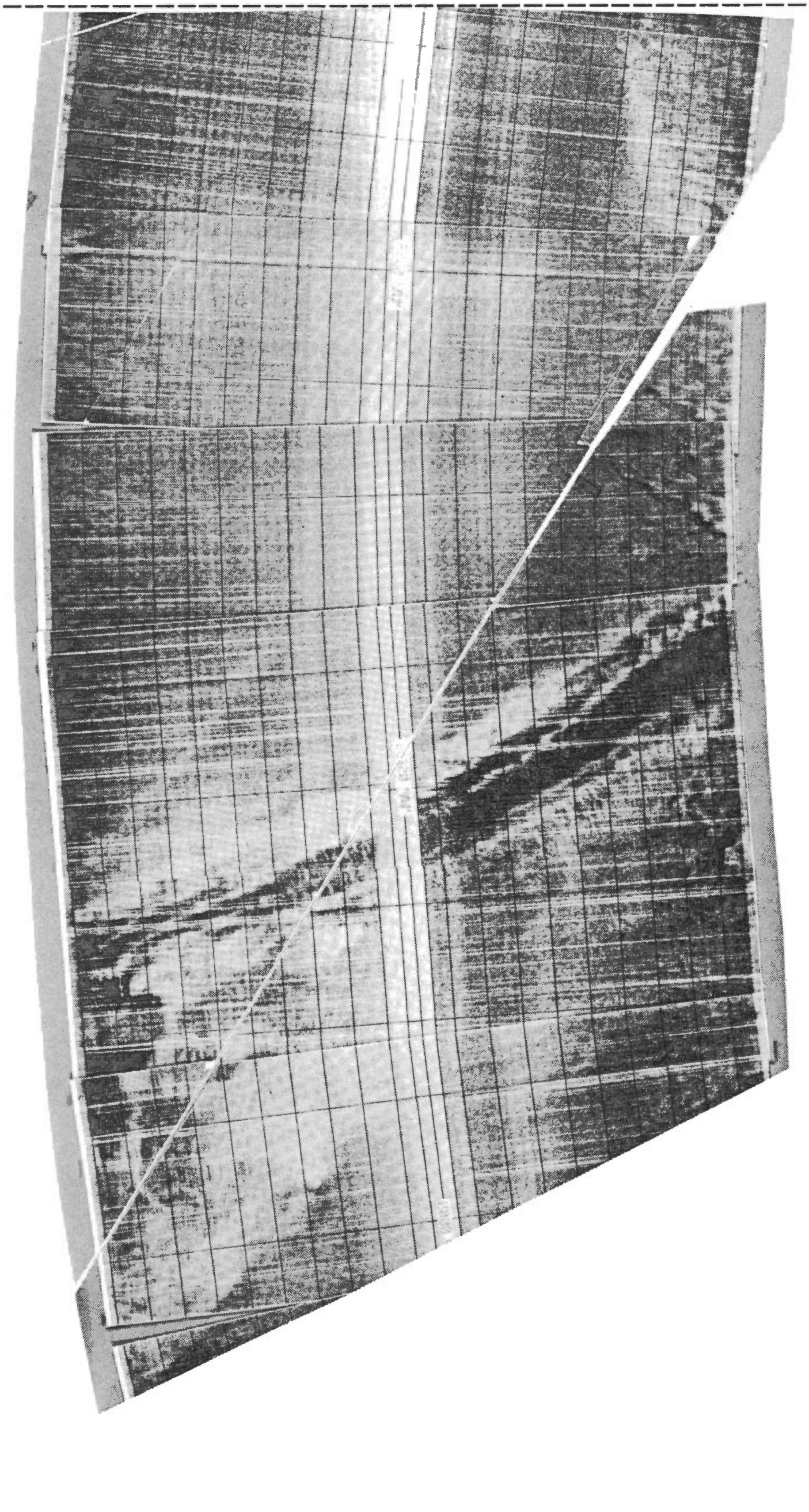


FIGURE 8

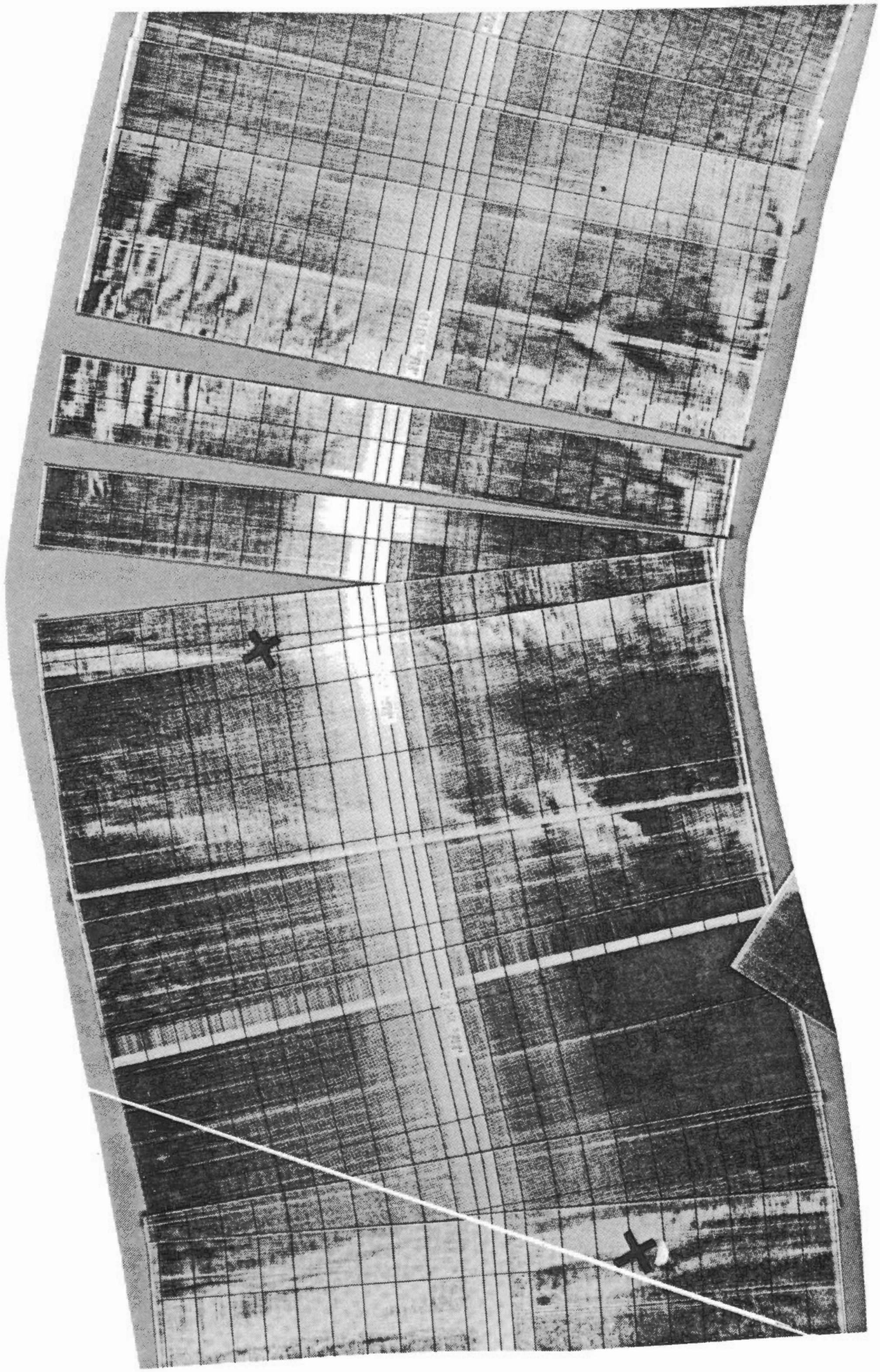
FIGURE 11







M



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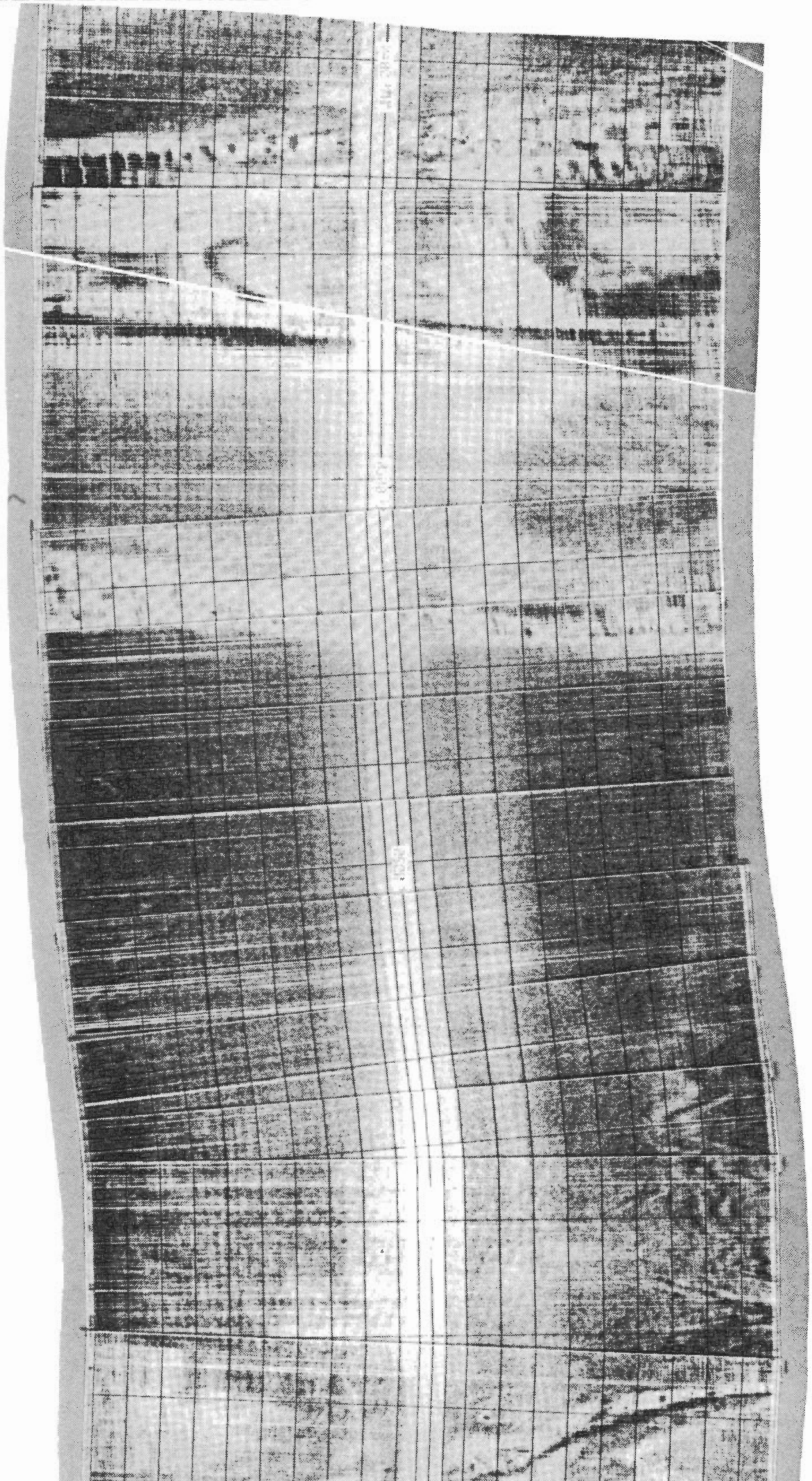

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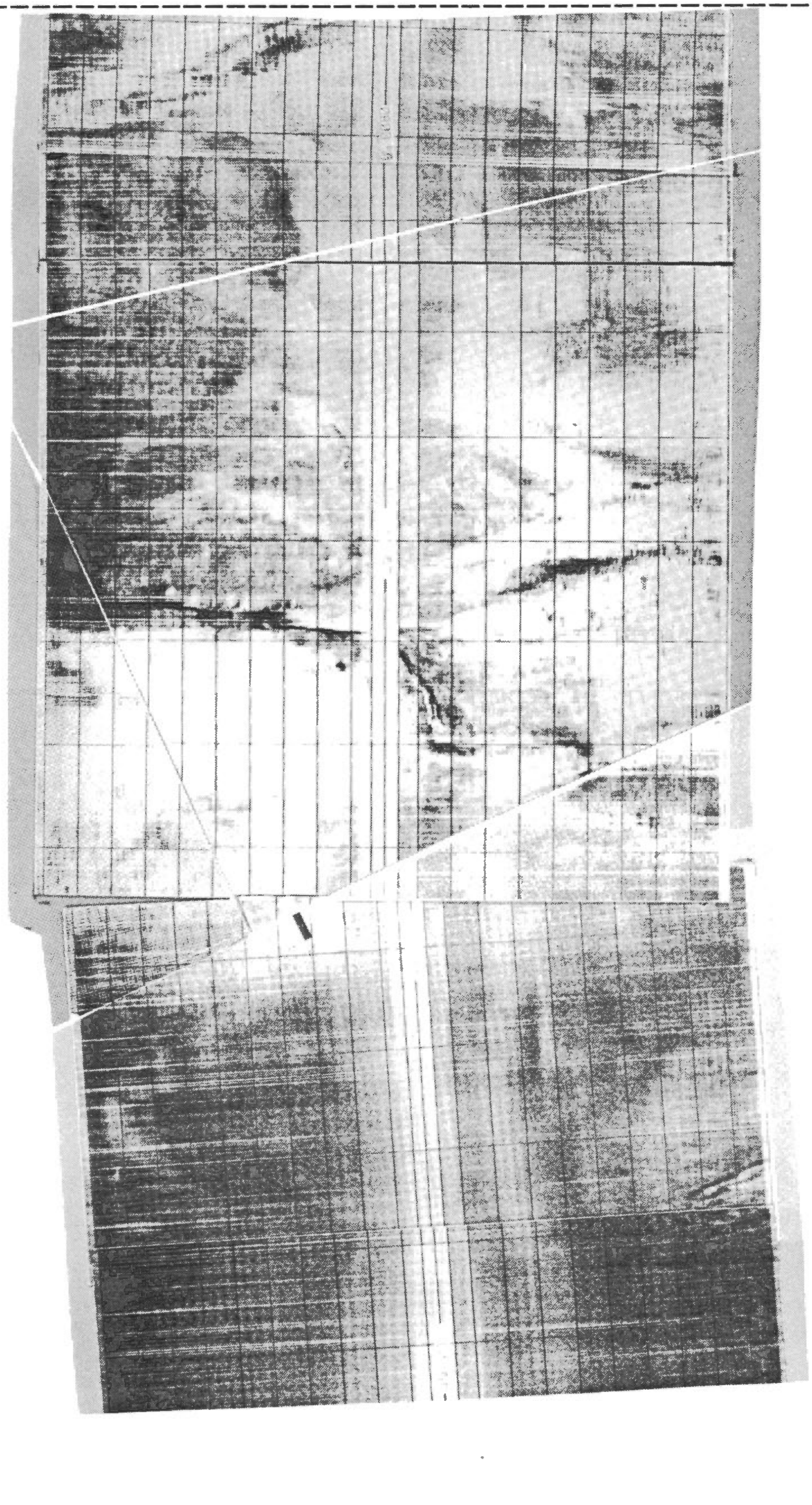

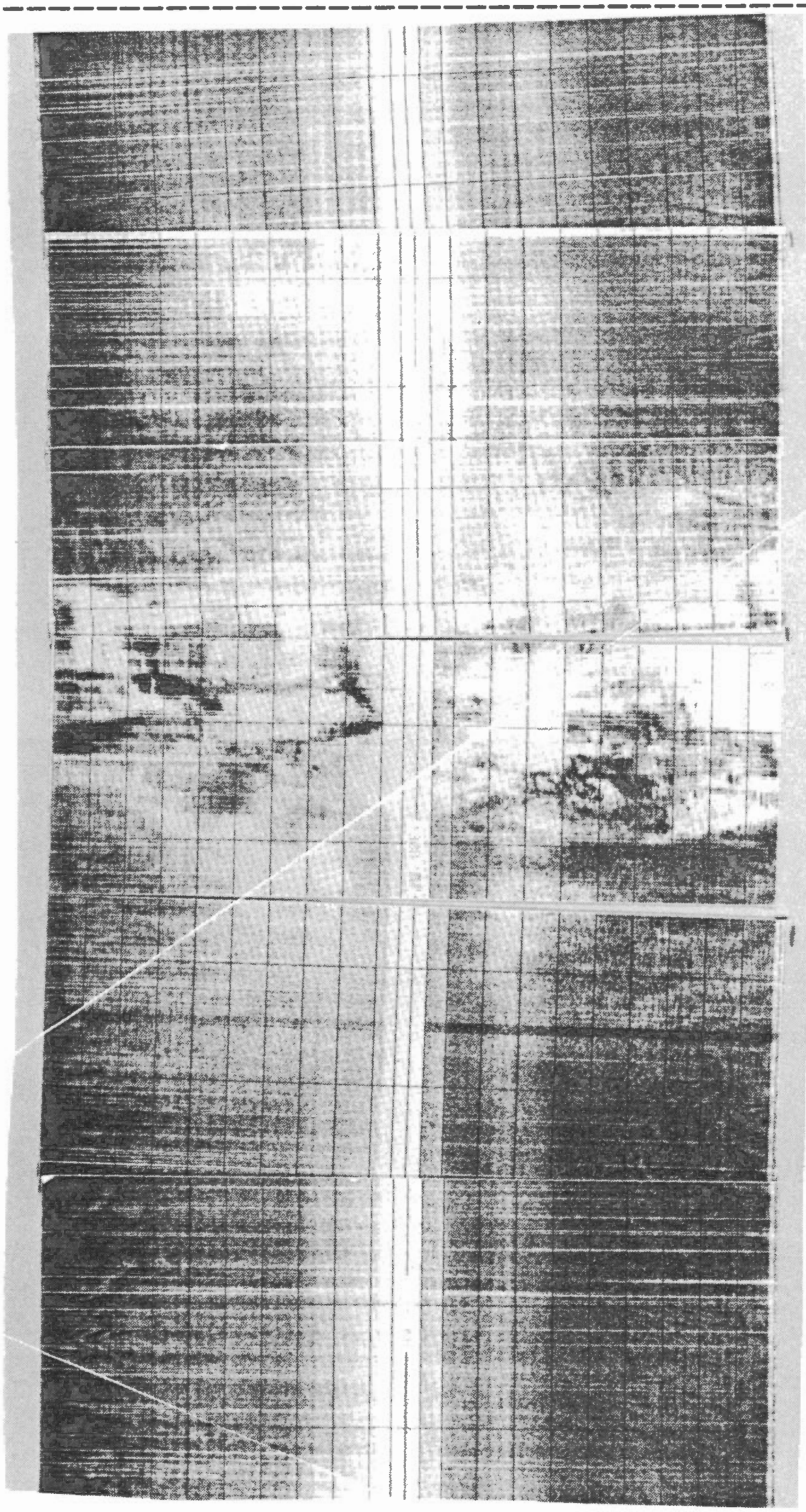

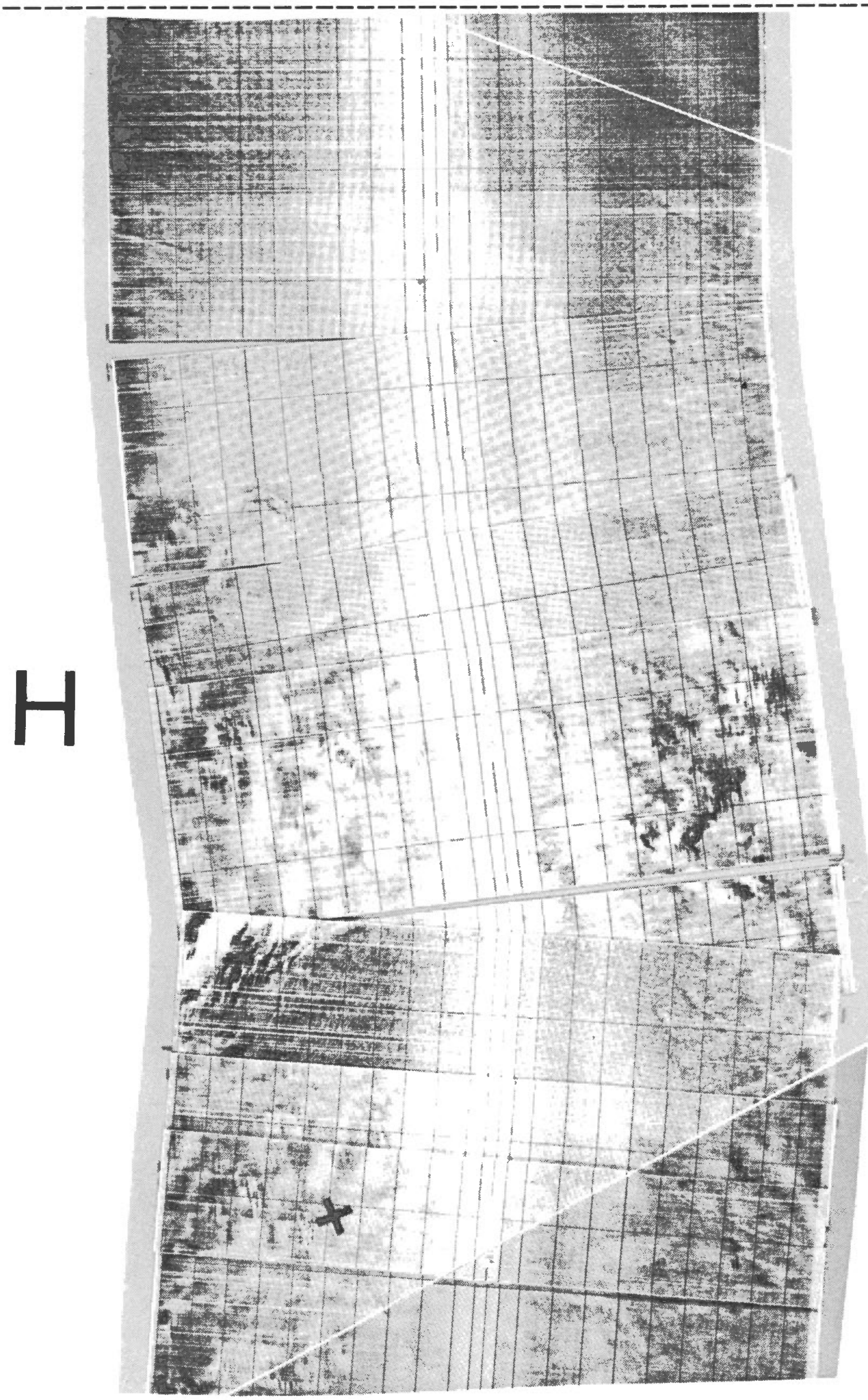
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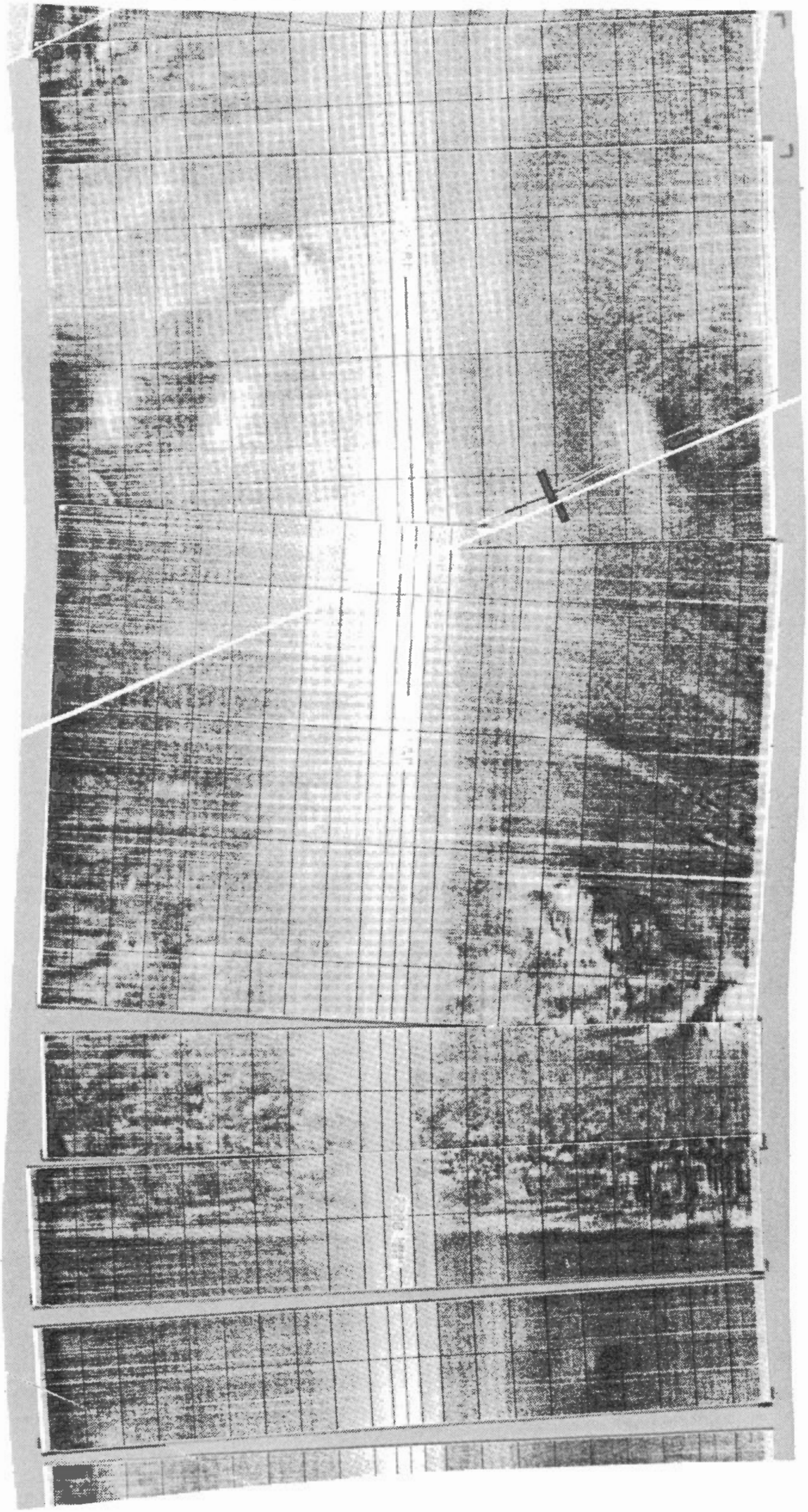

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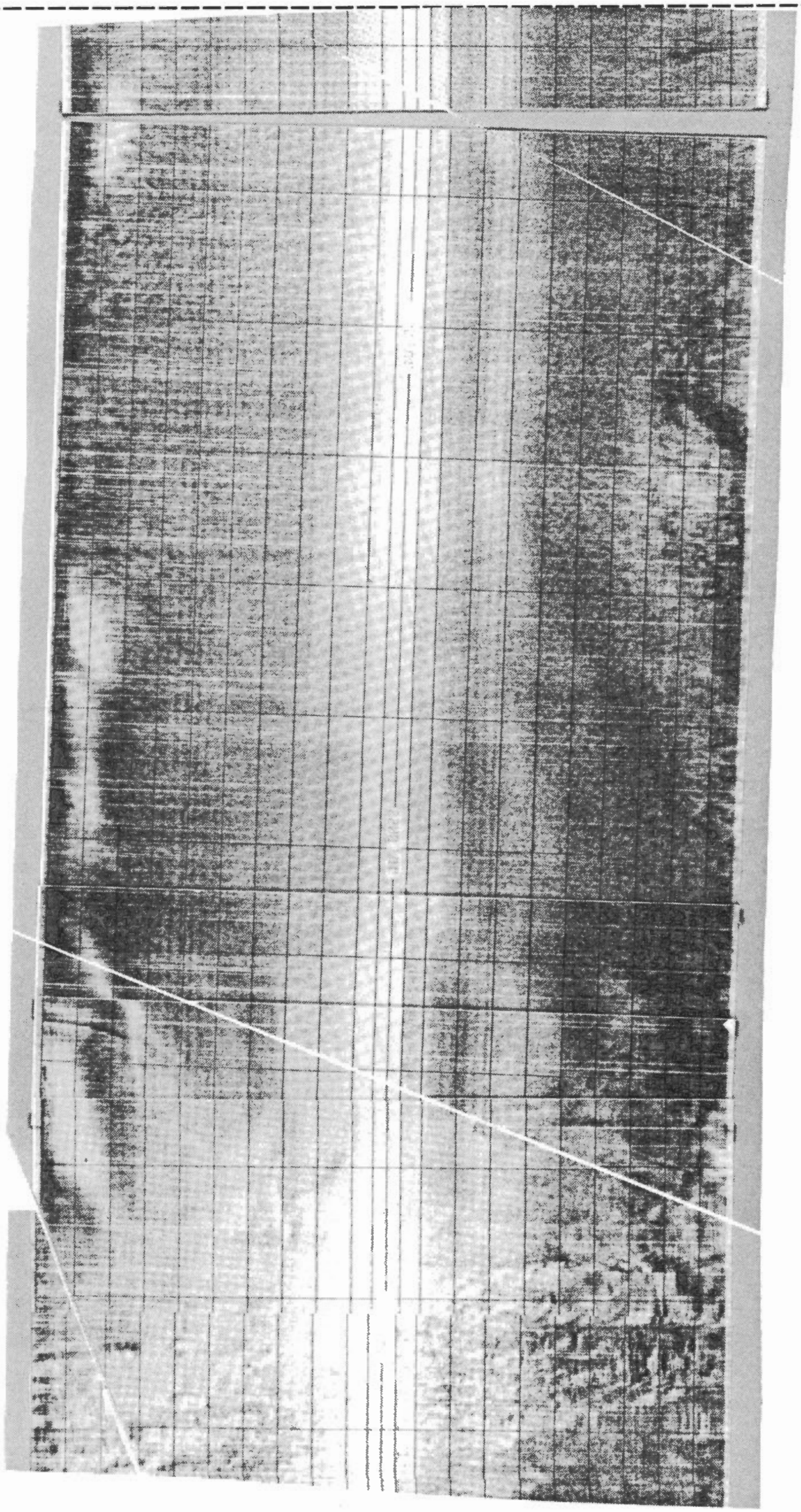

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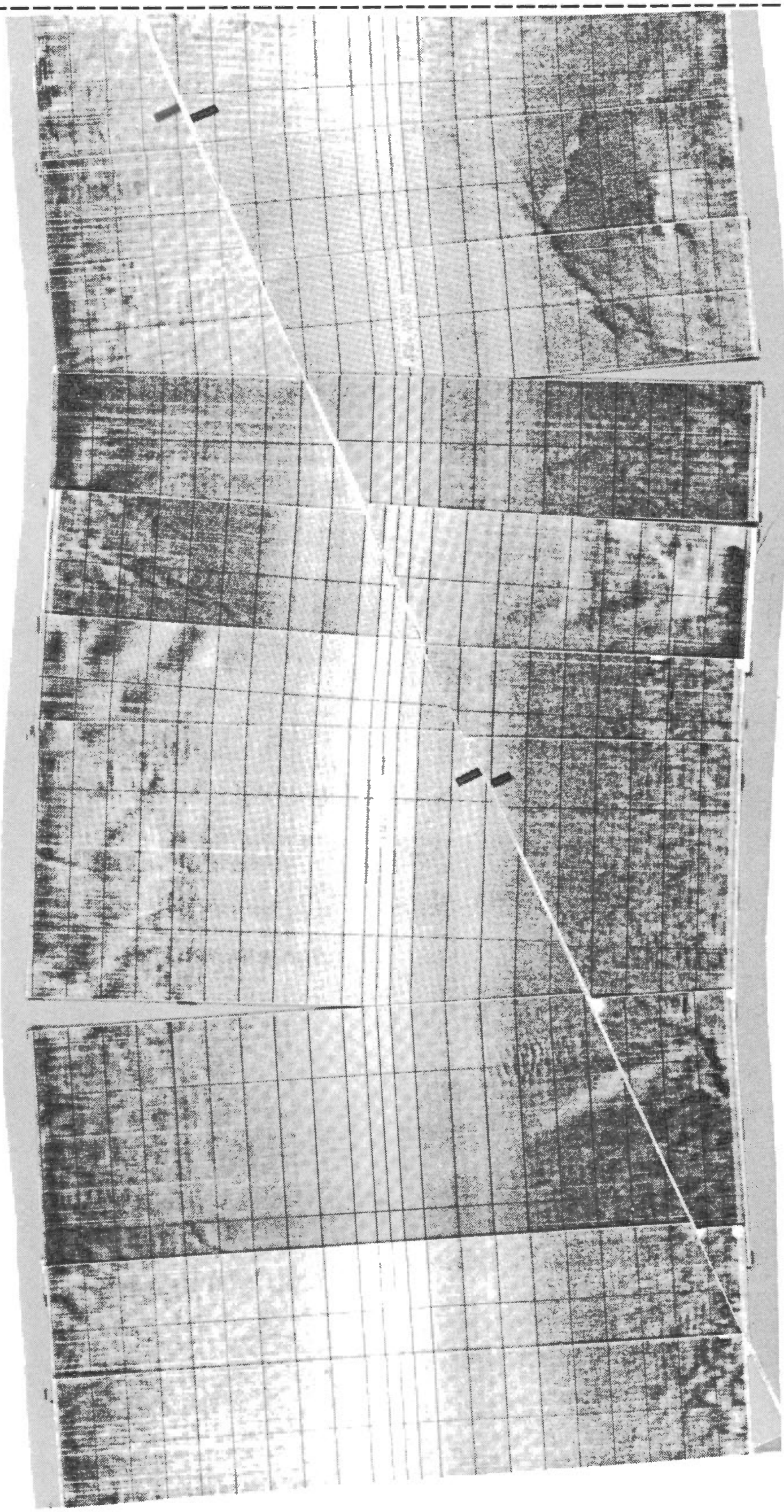

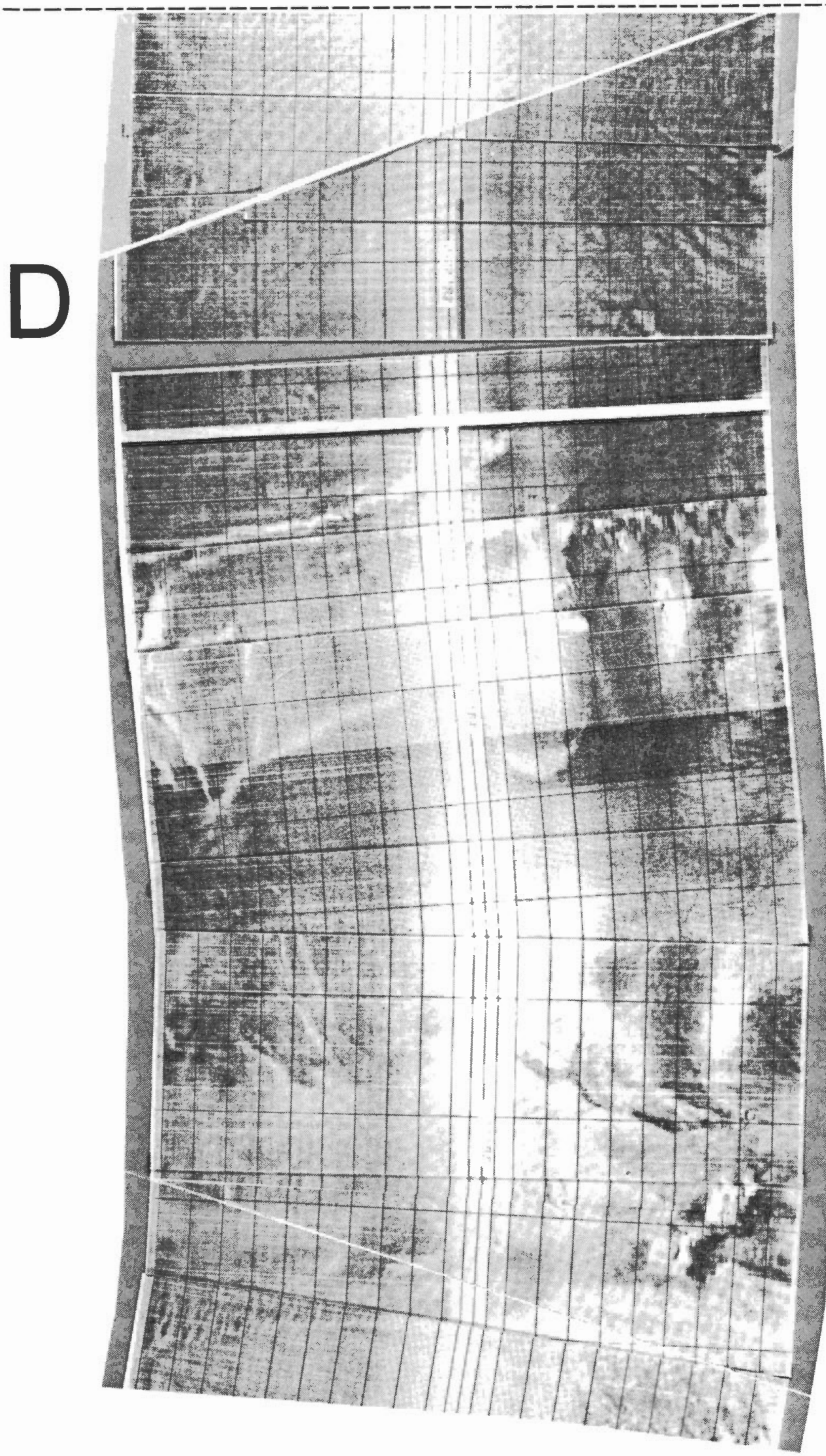
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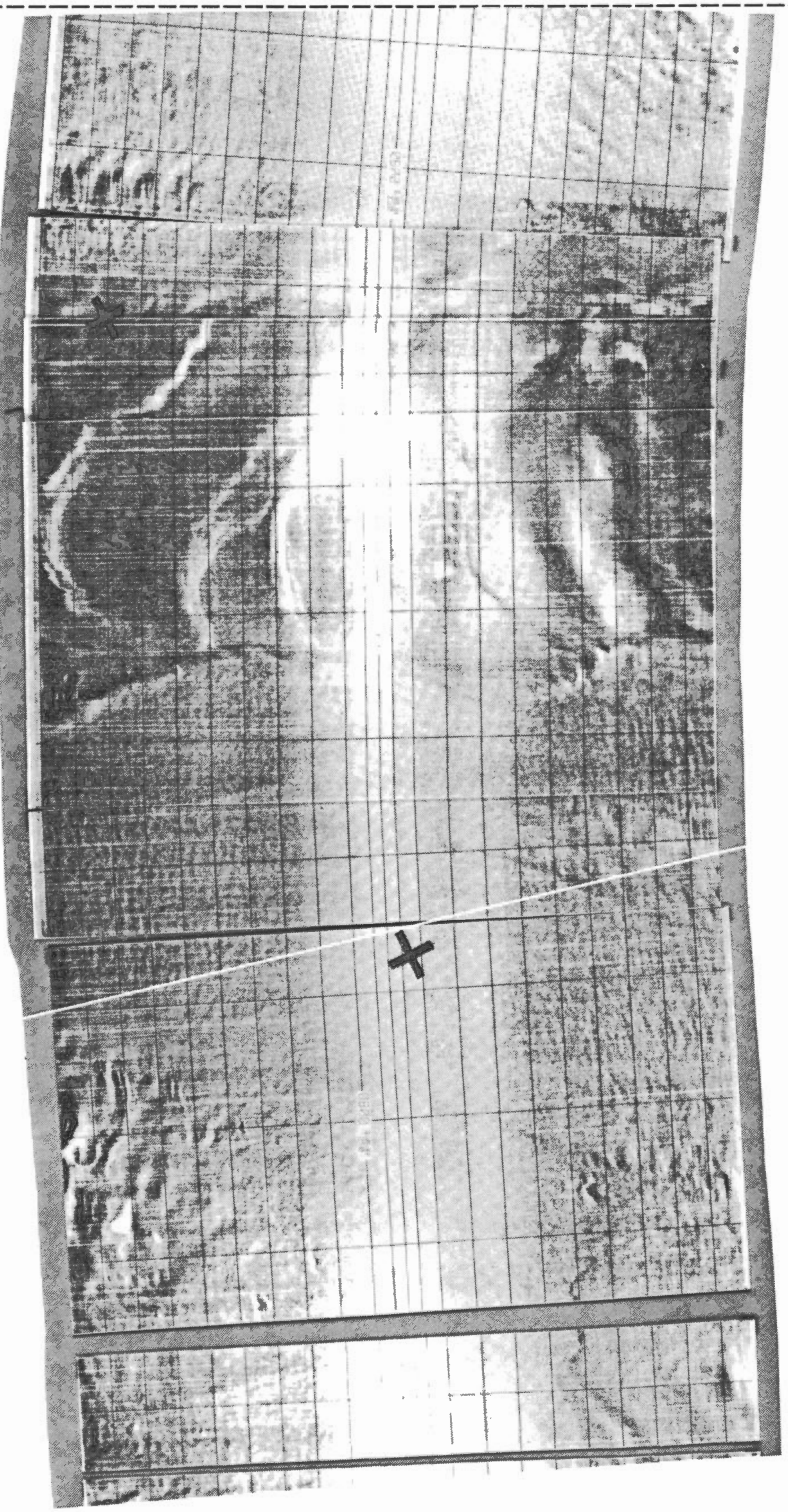

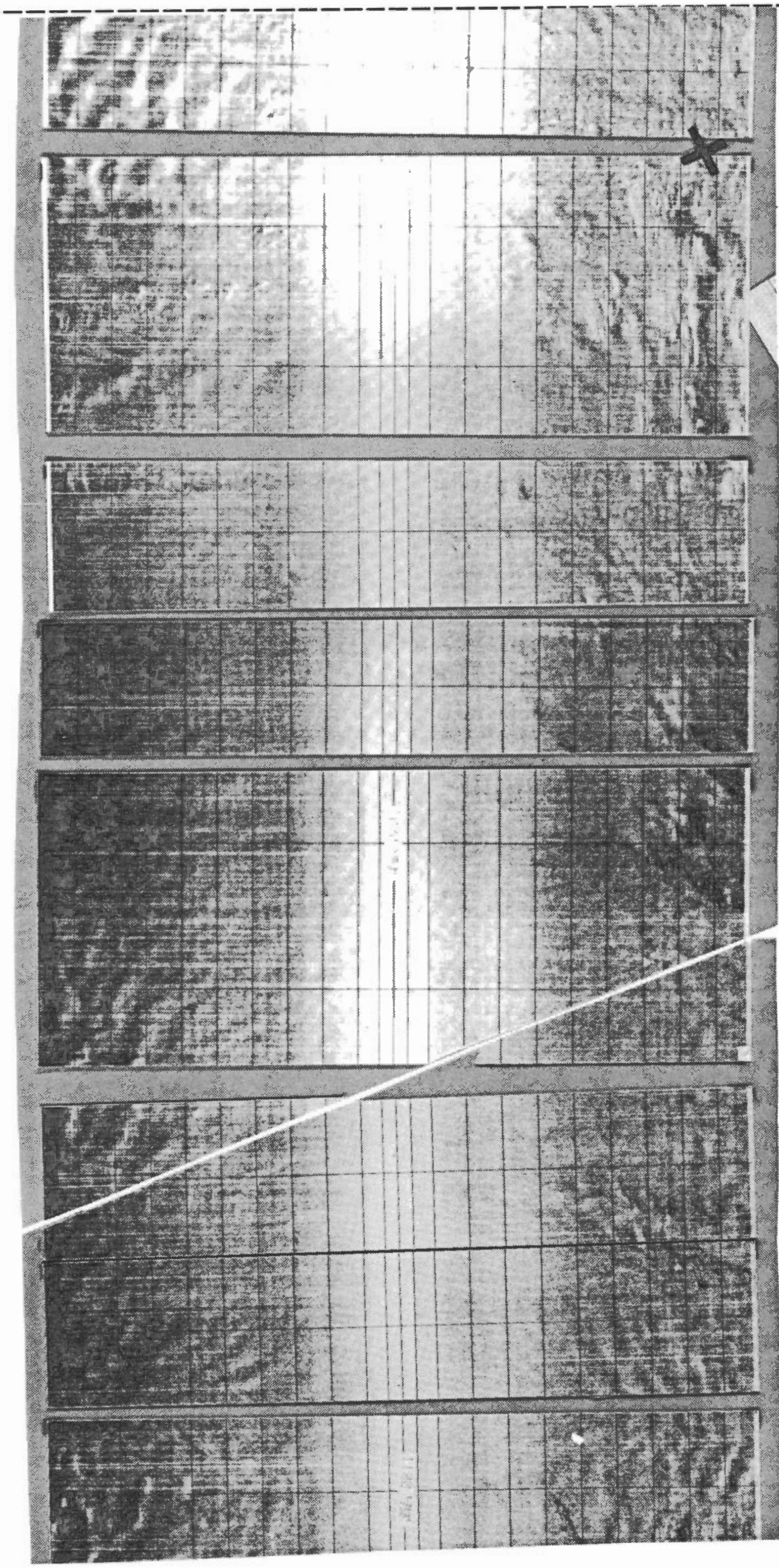

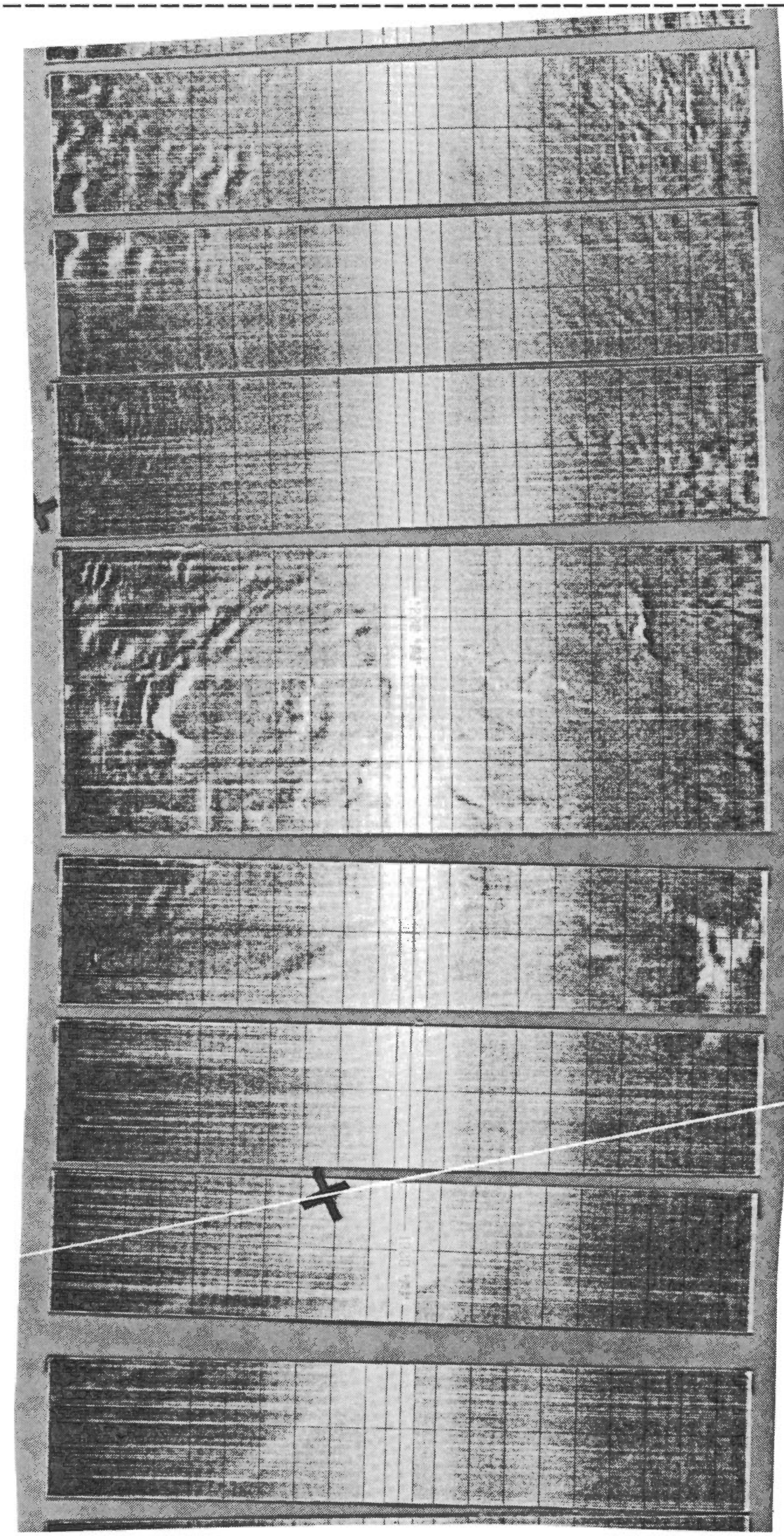

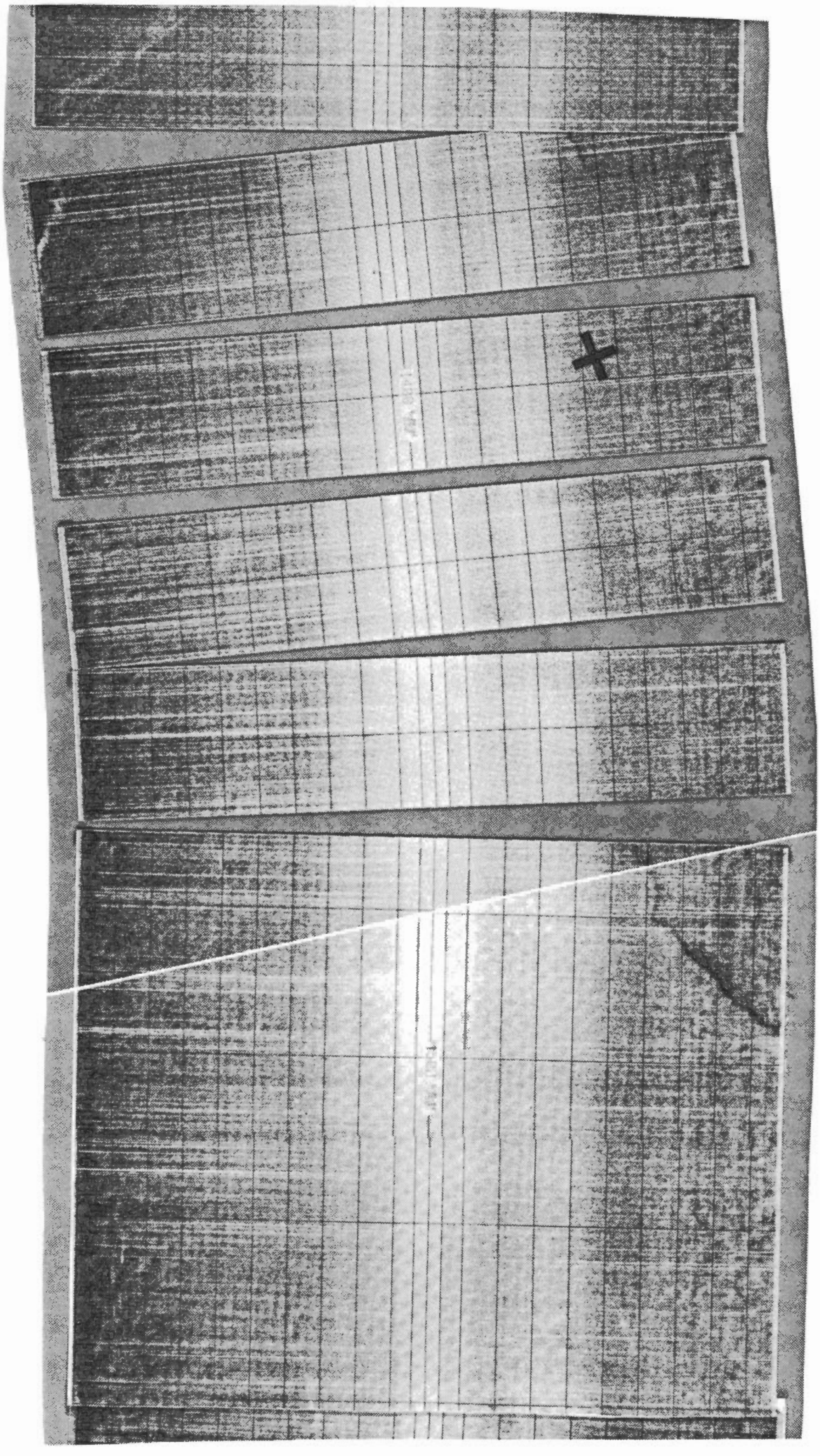

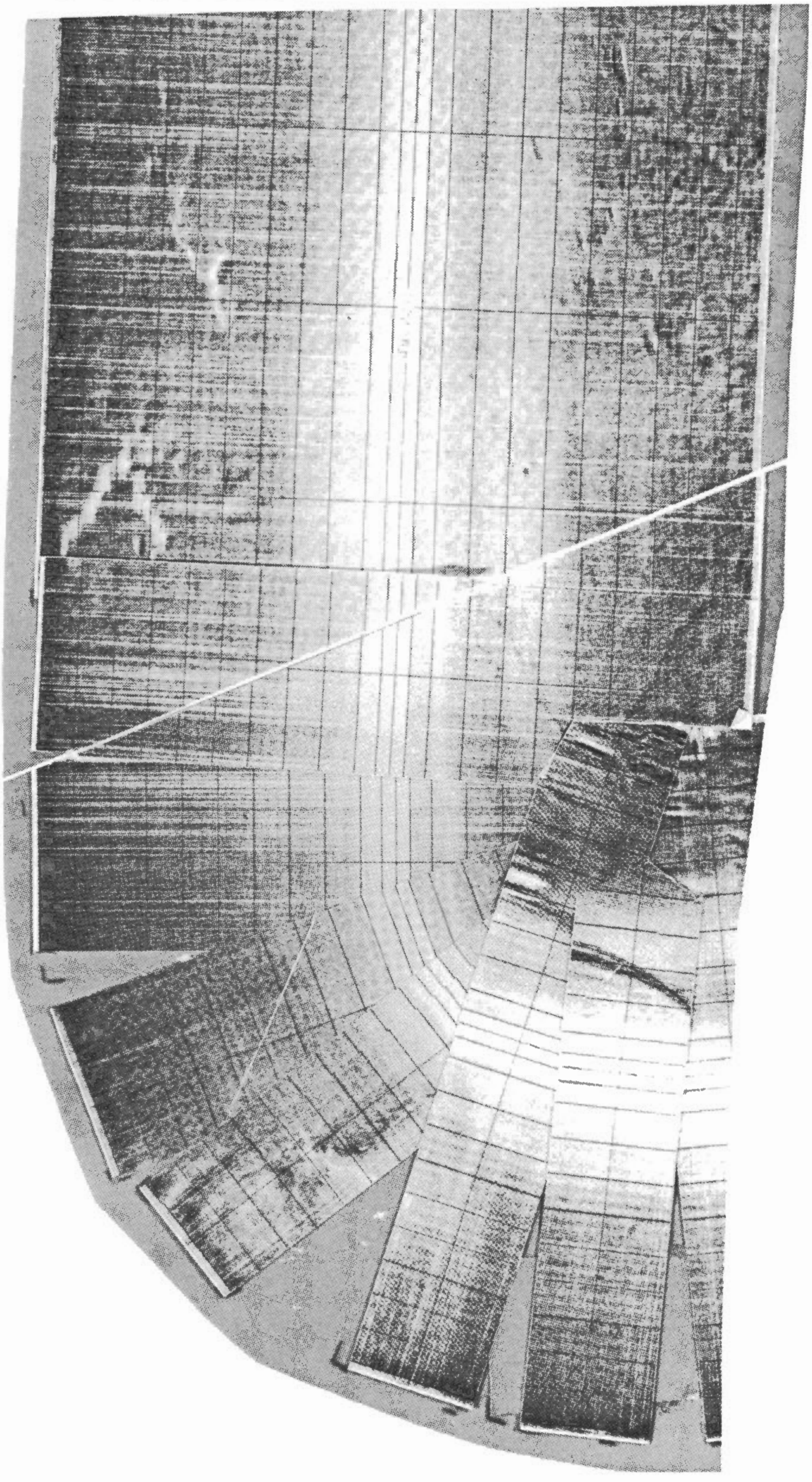

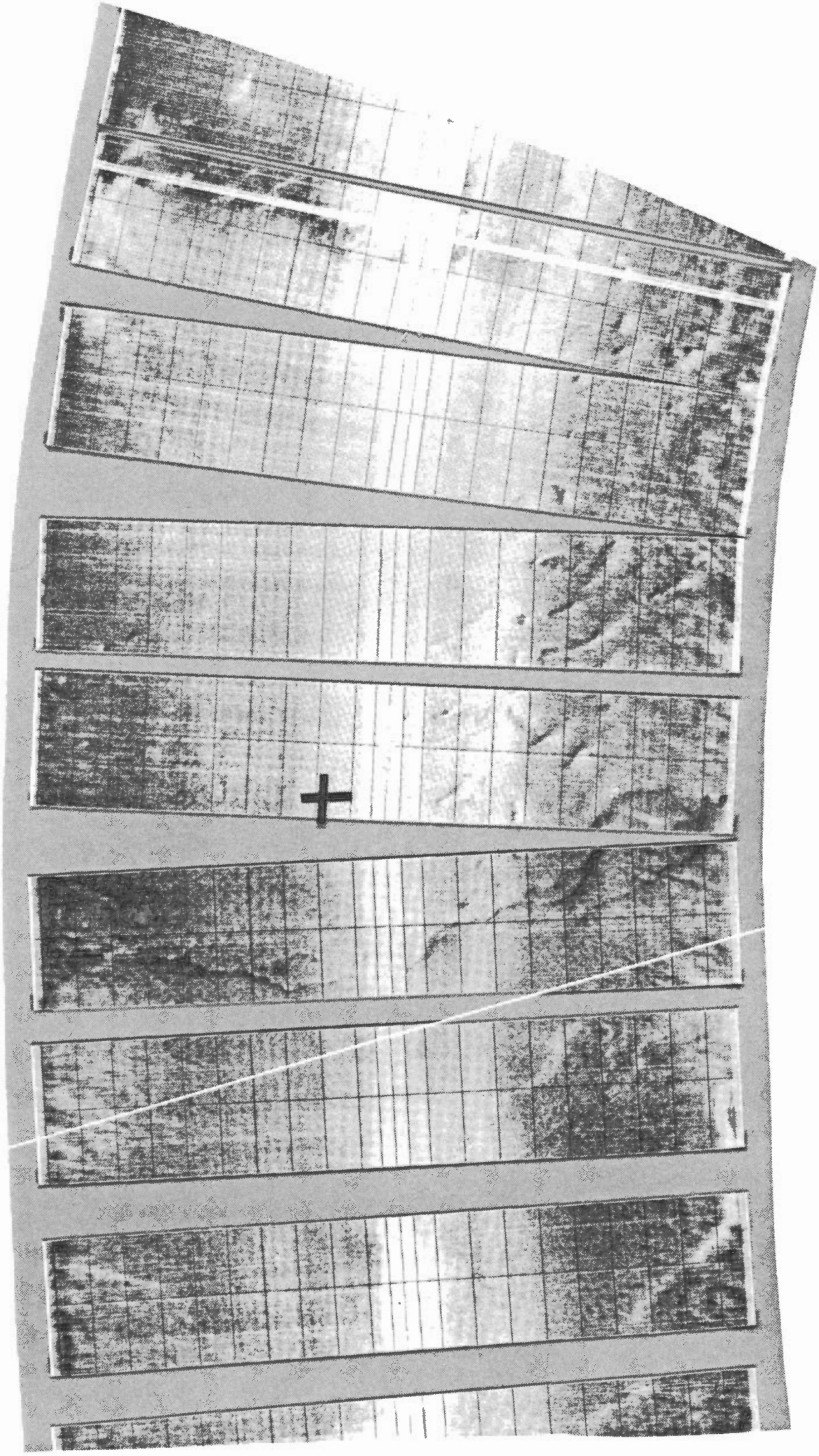

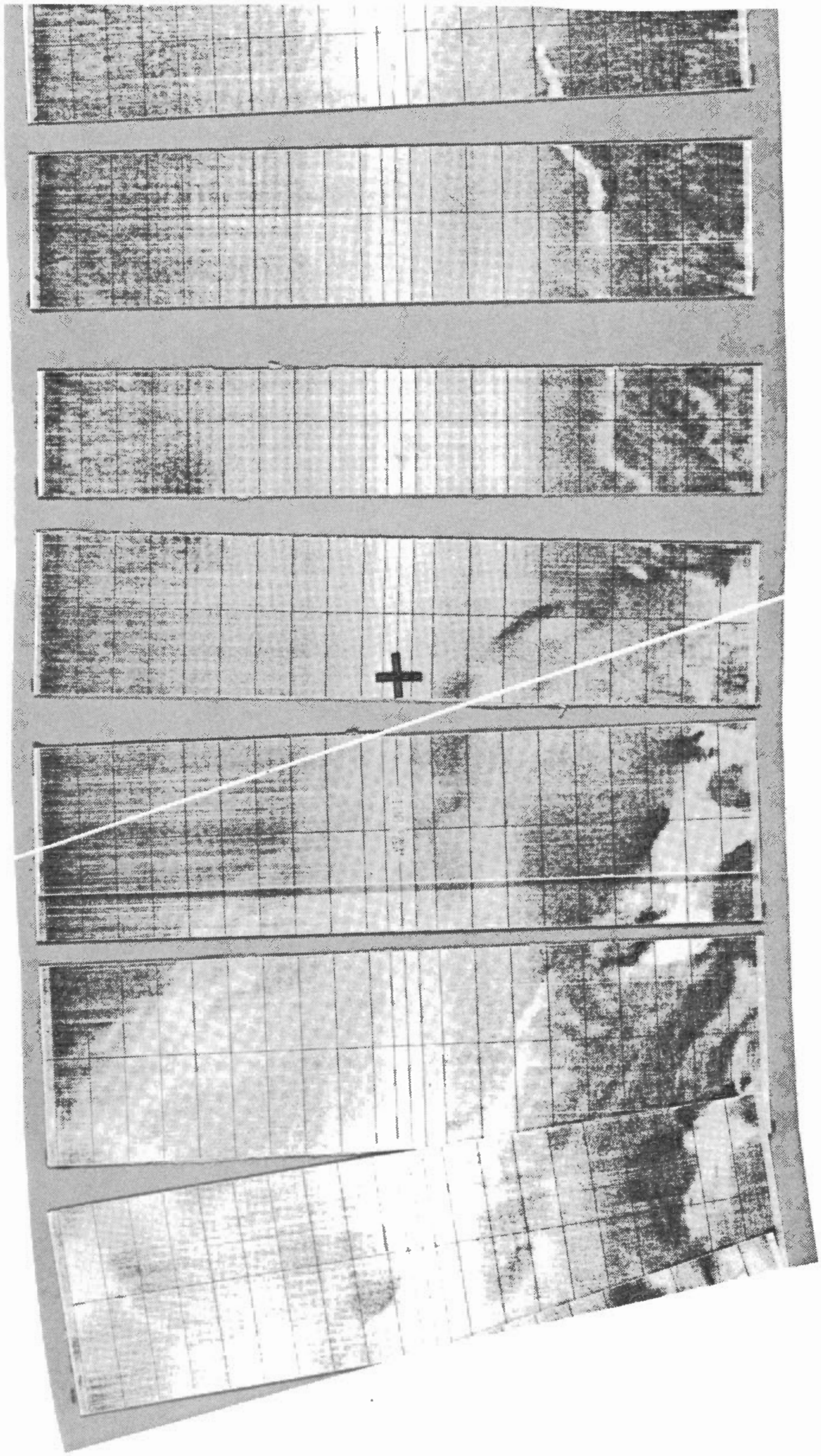

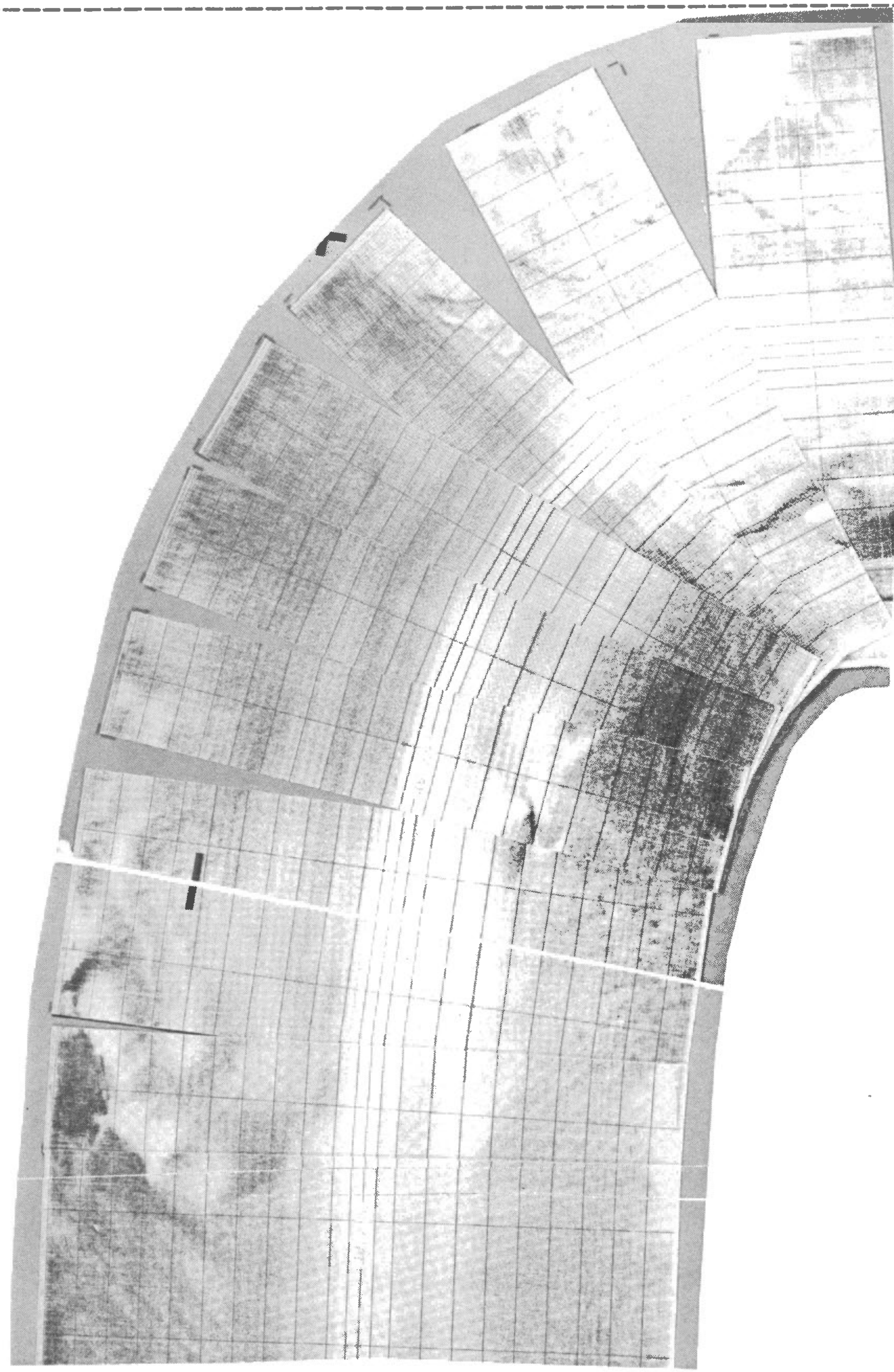

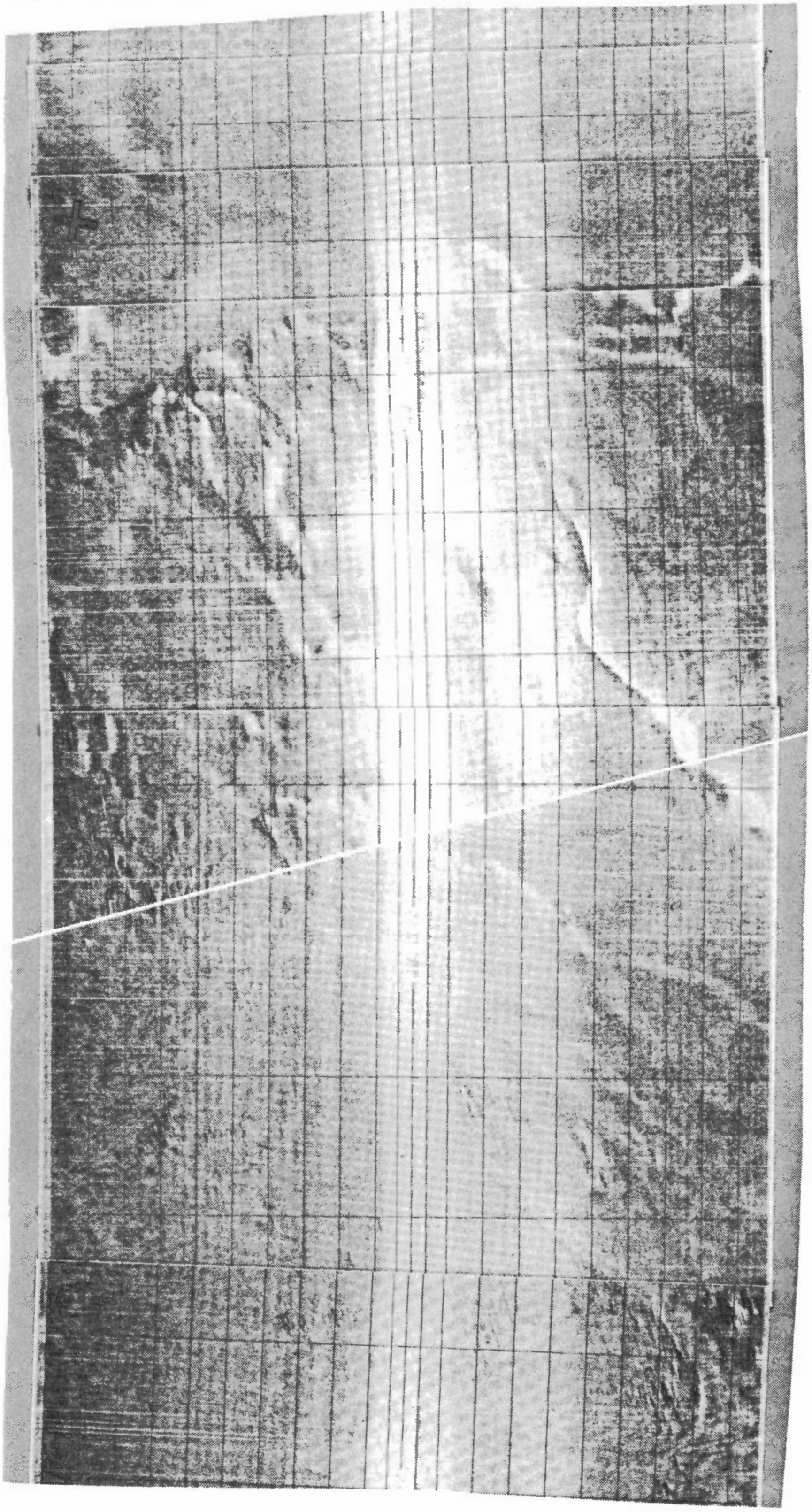

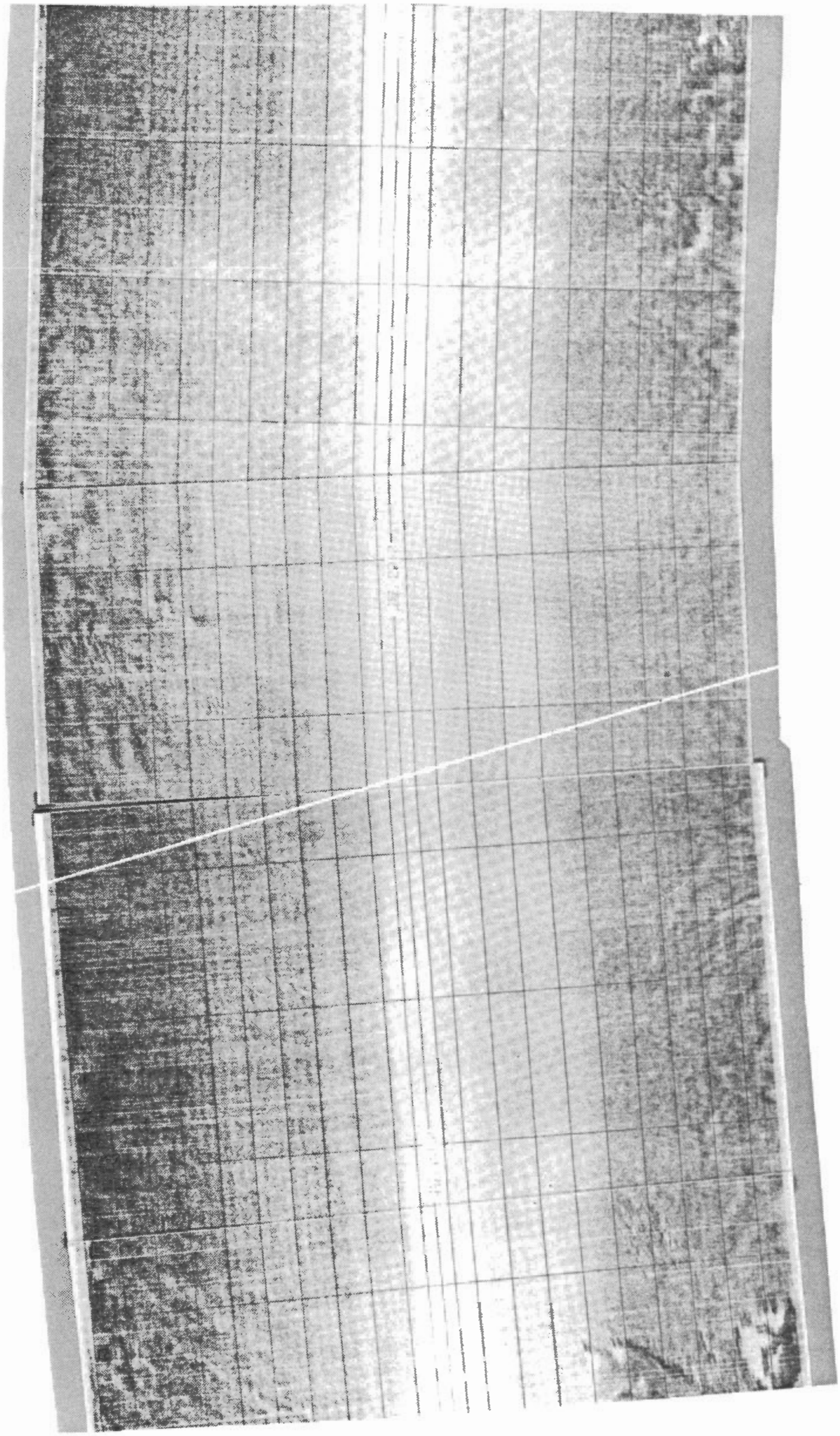

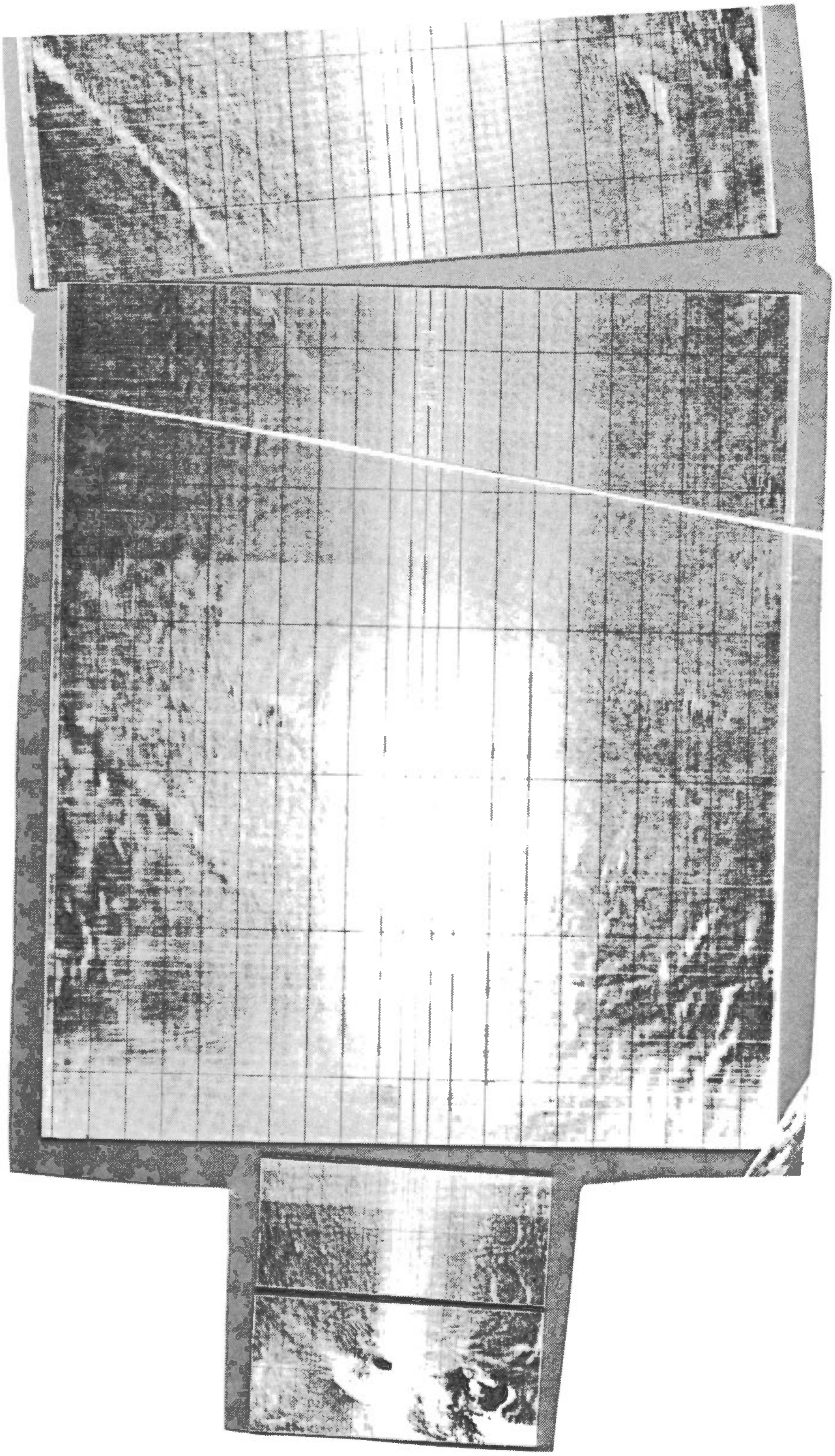

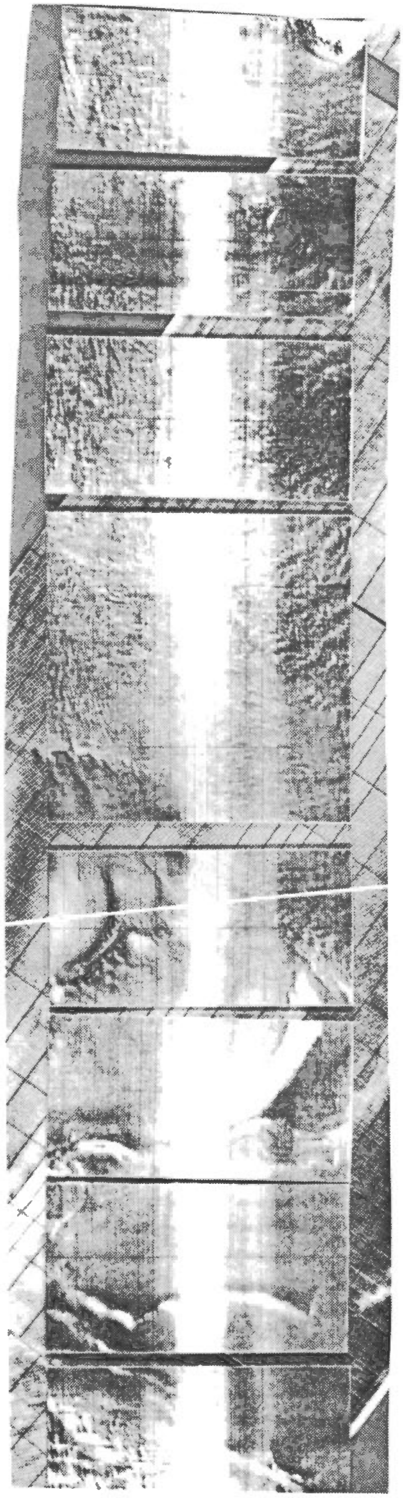

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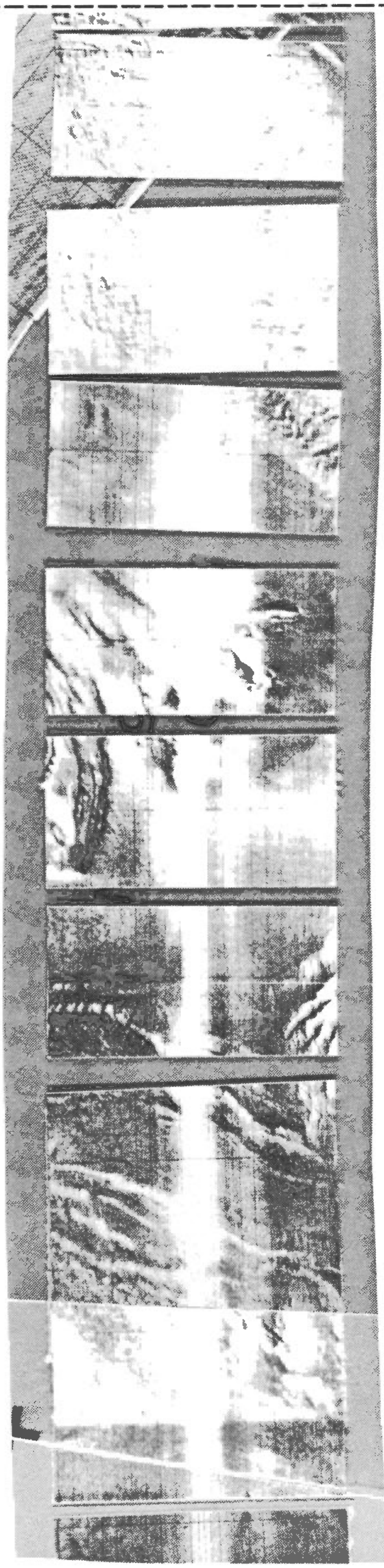

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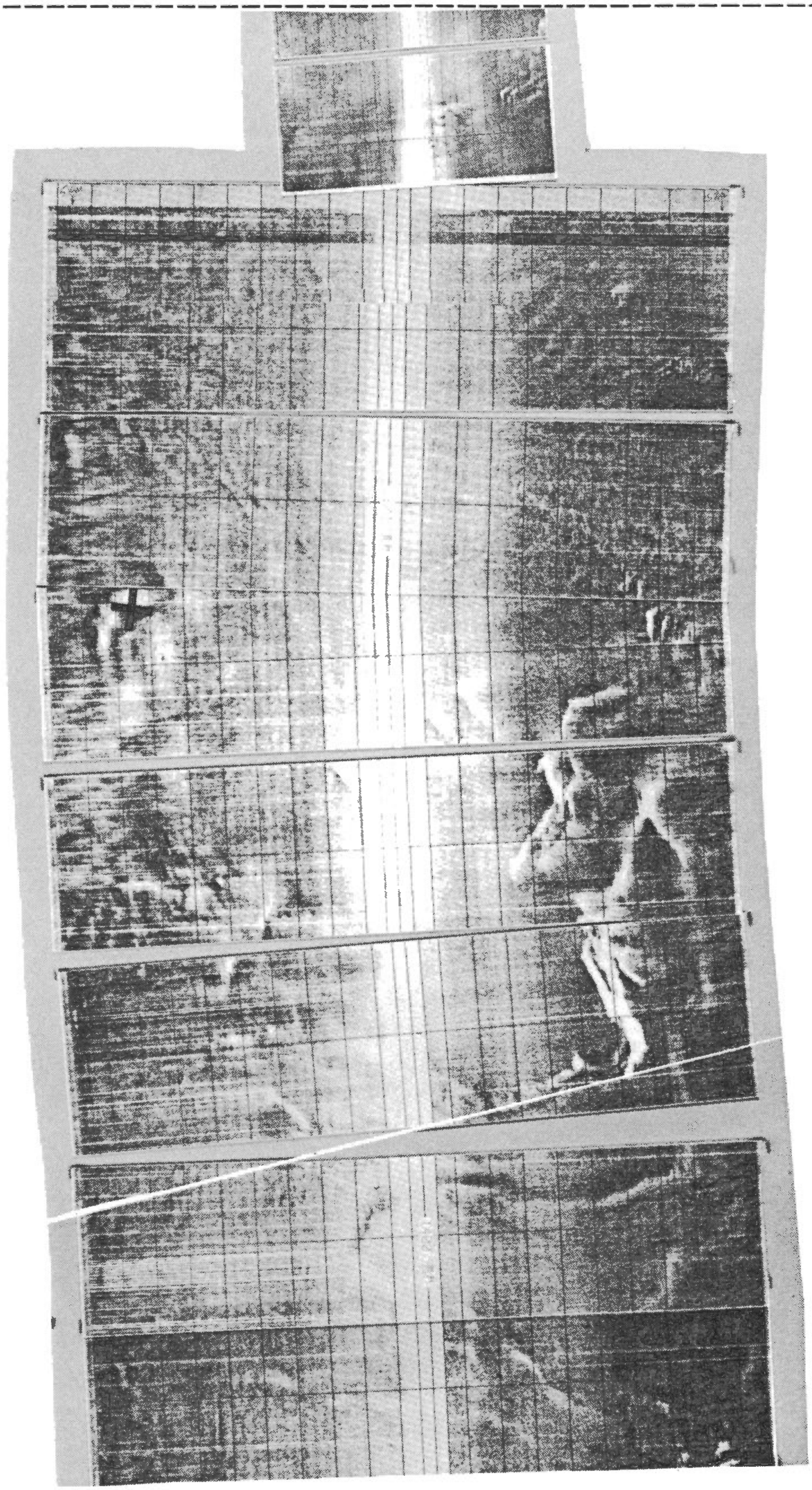

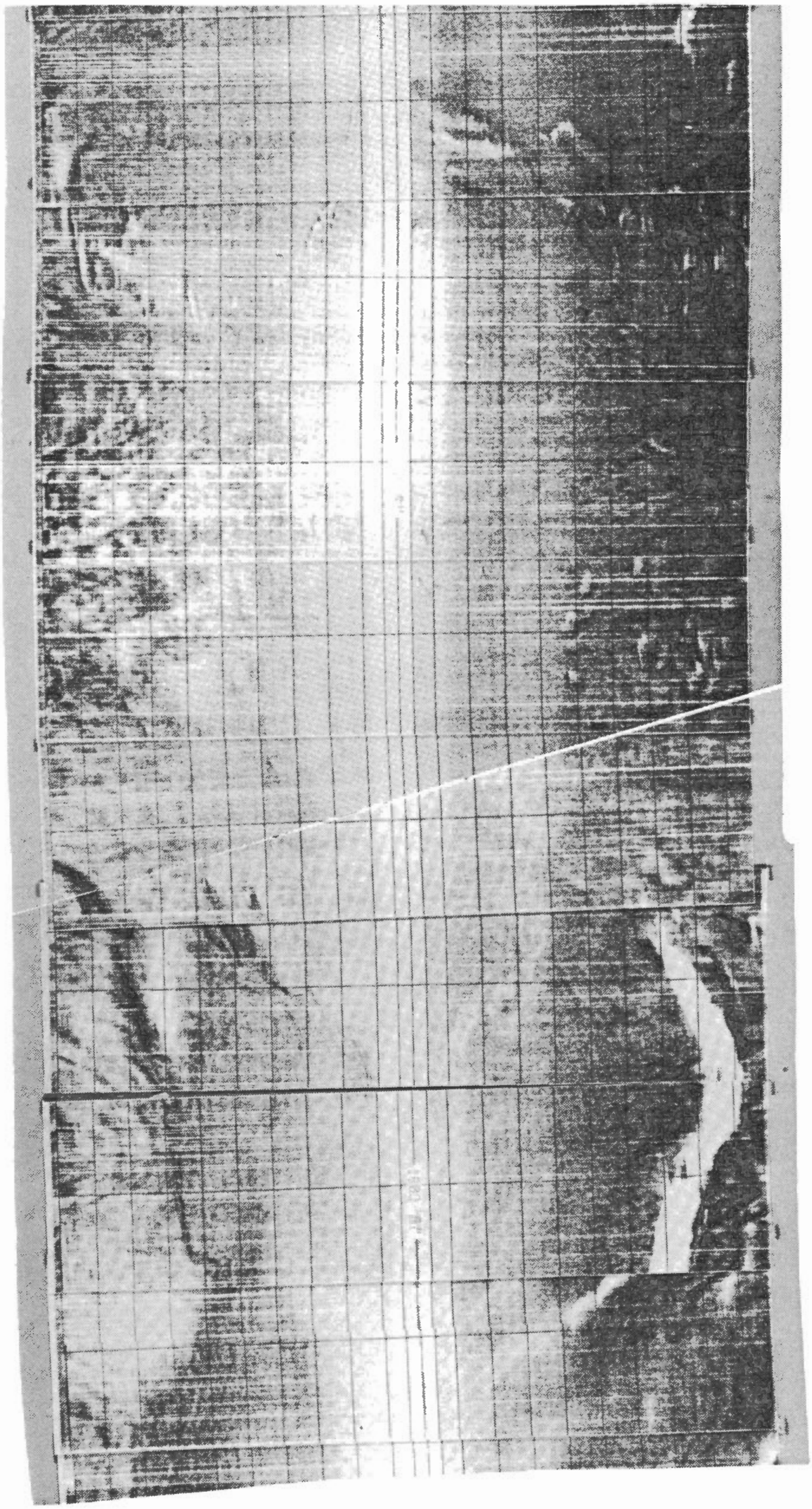

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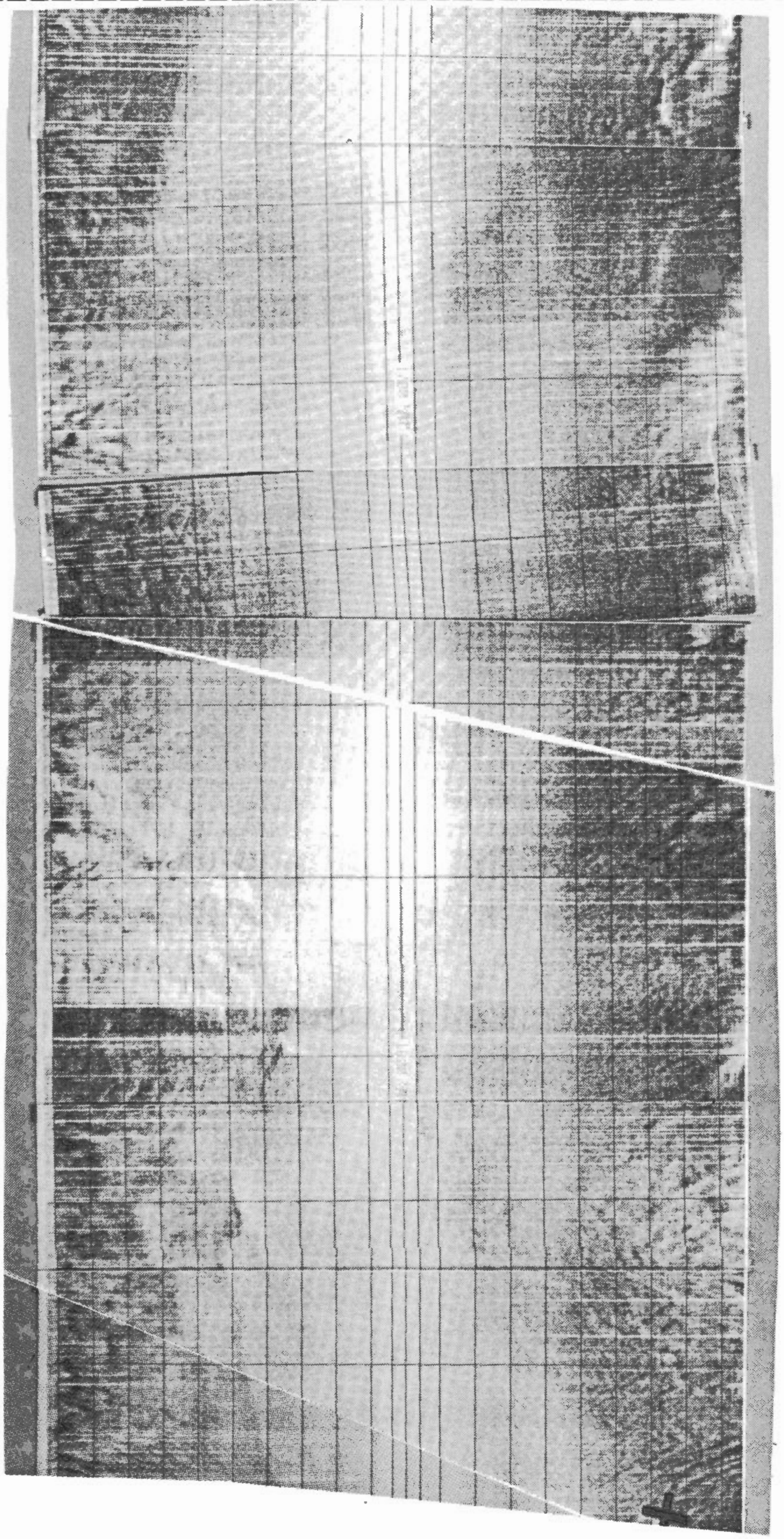

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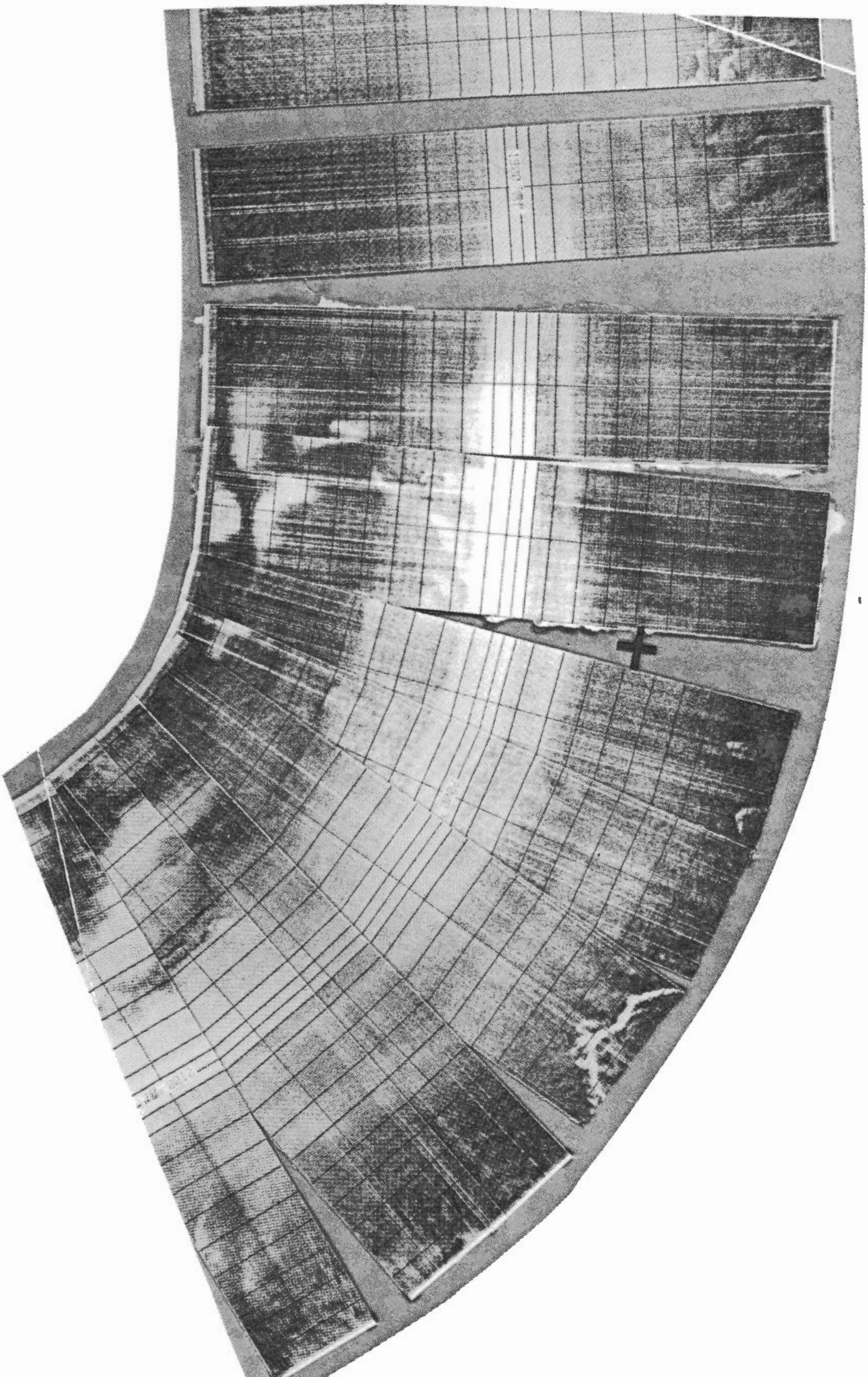

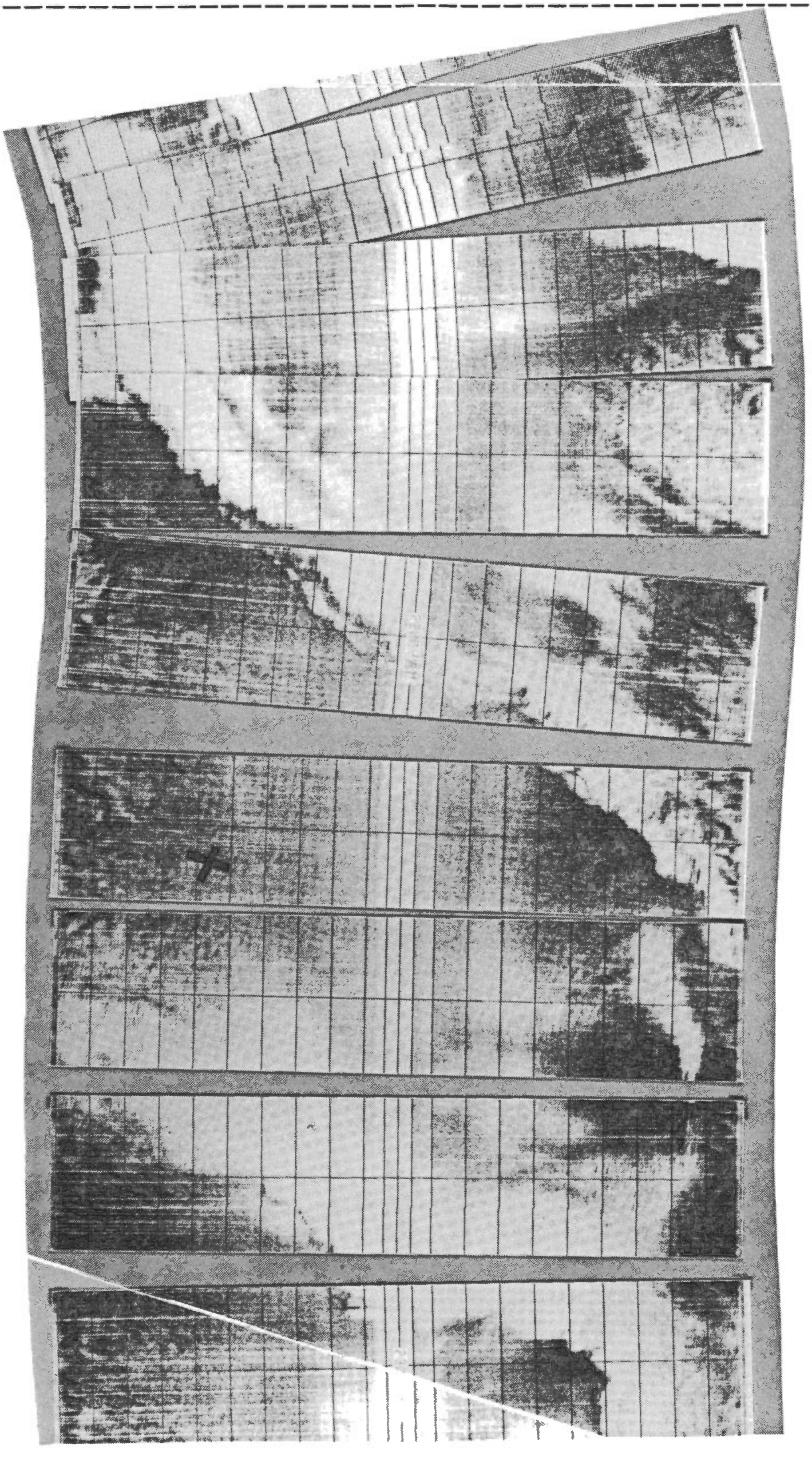

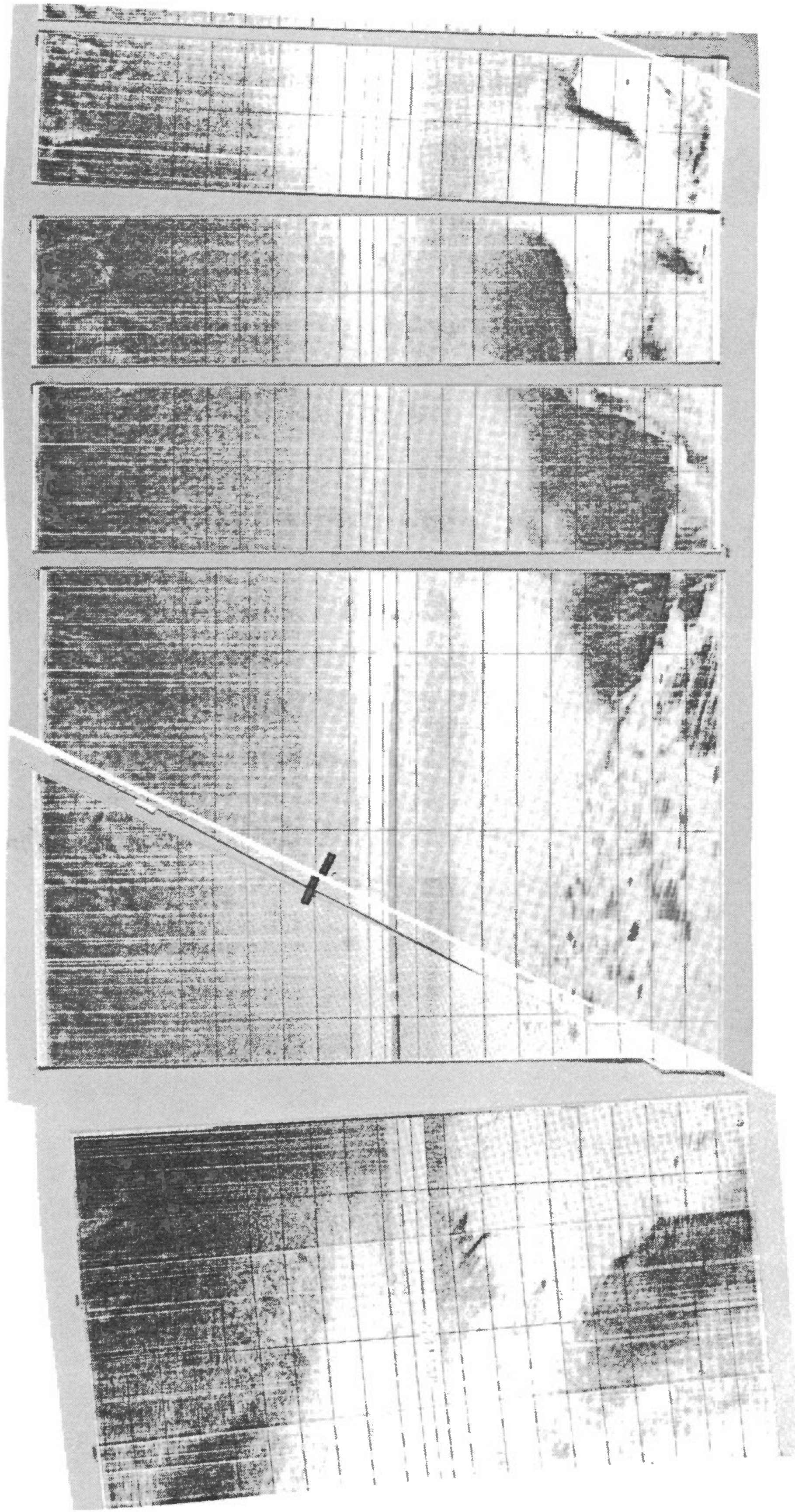

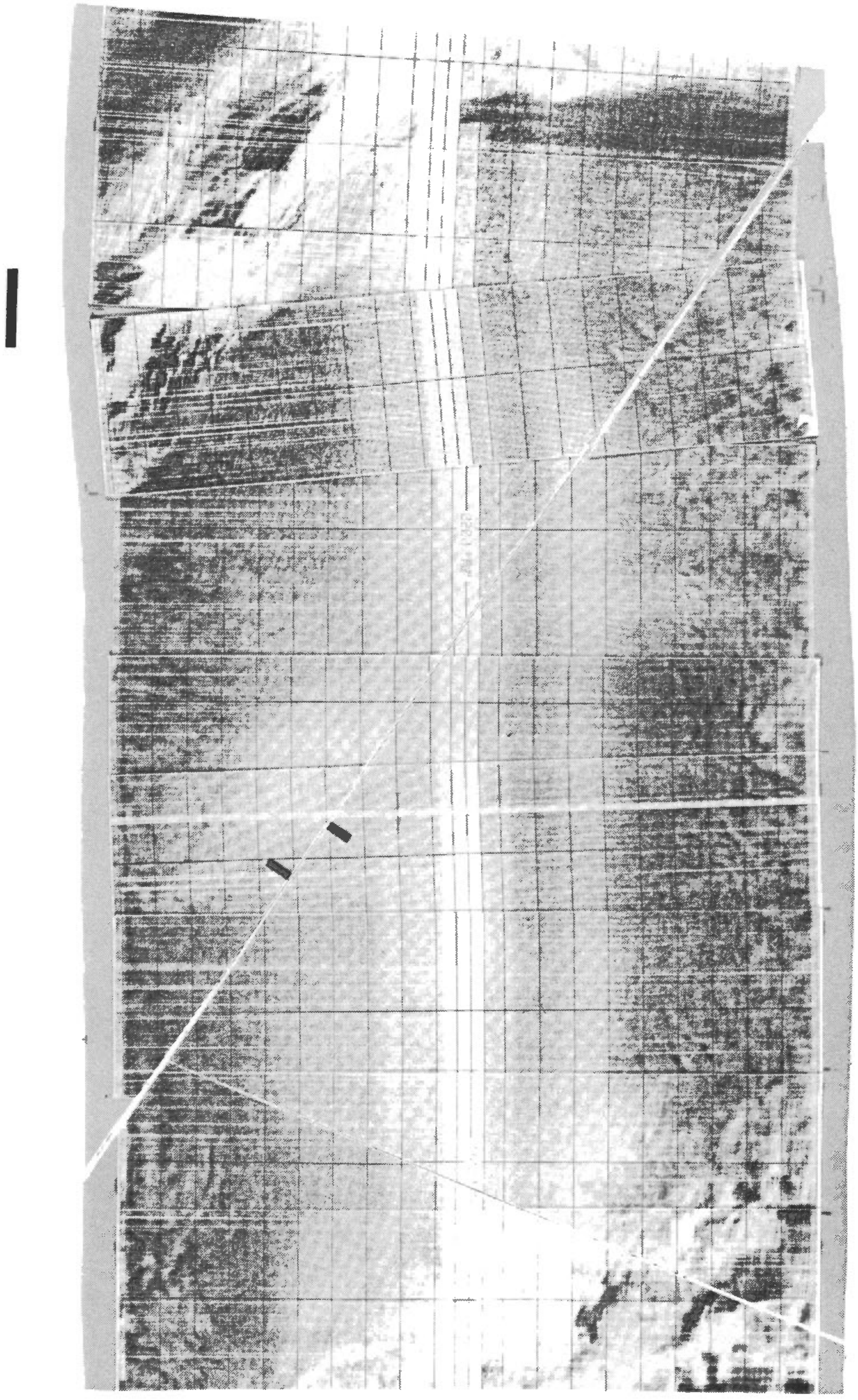

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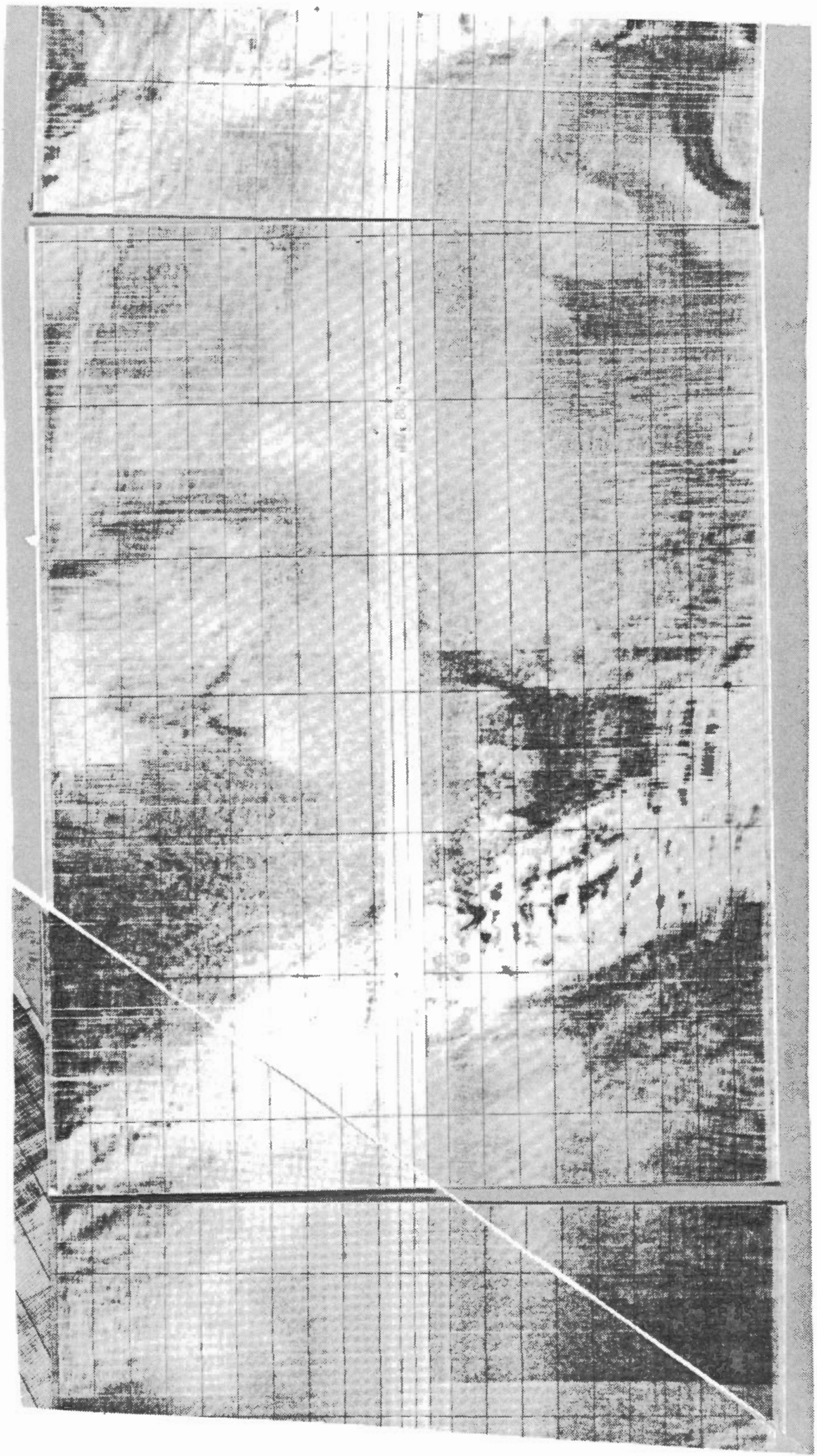

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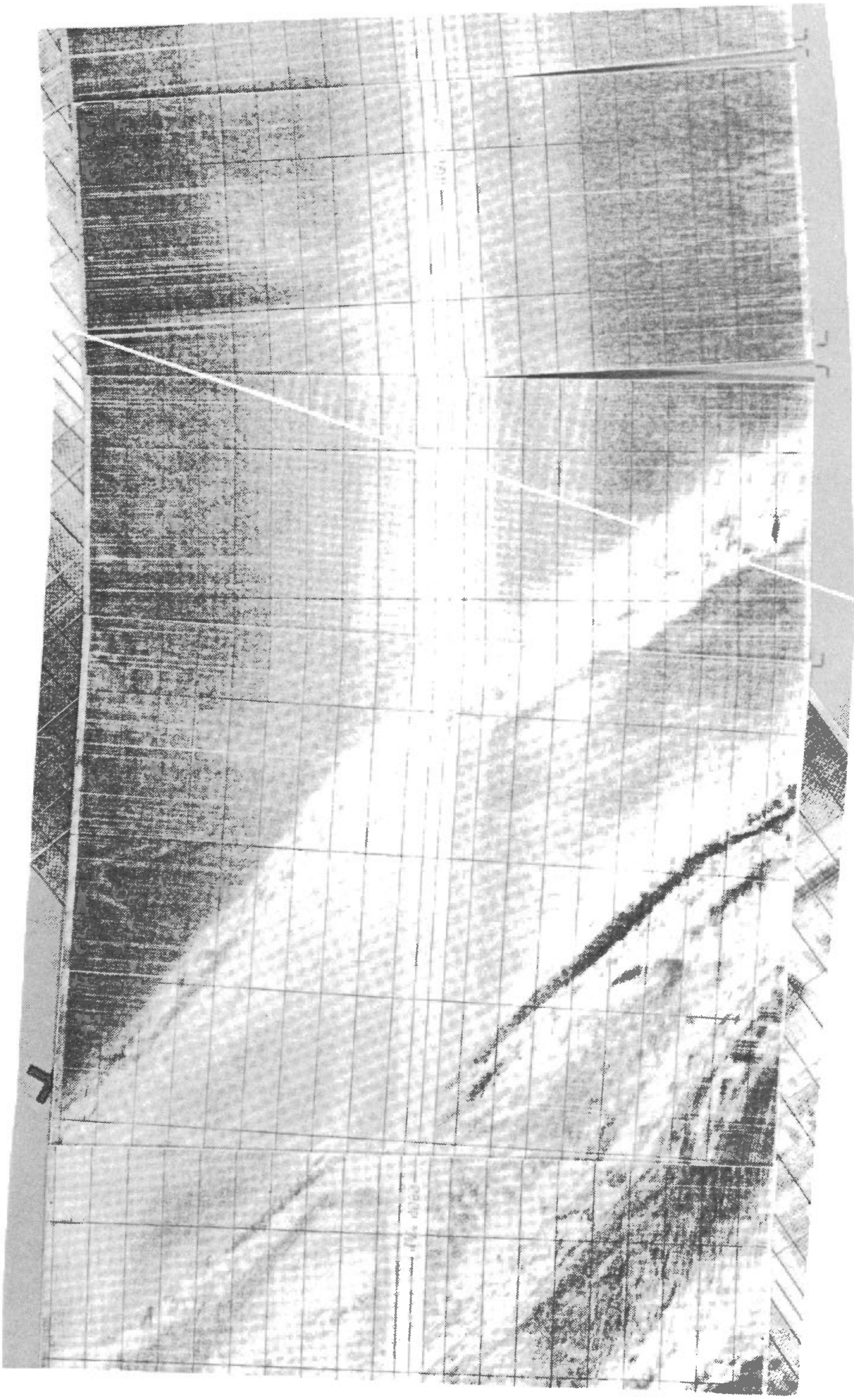

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