PALEOCEANOGRAPHIC MAPPING PROJECT
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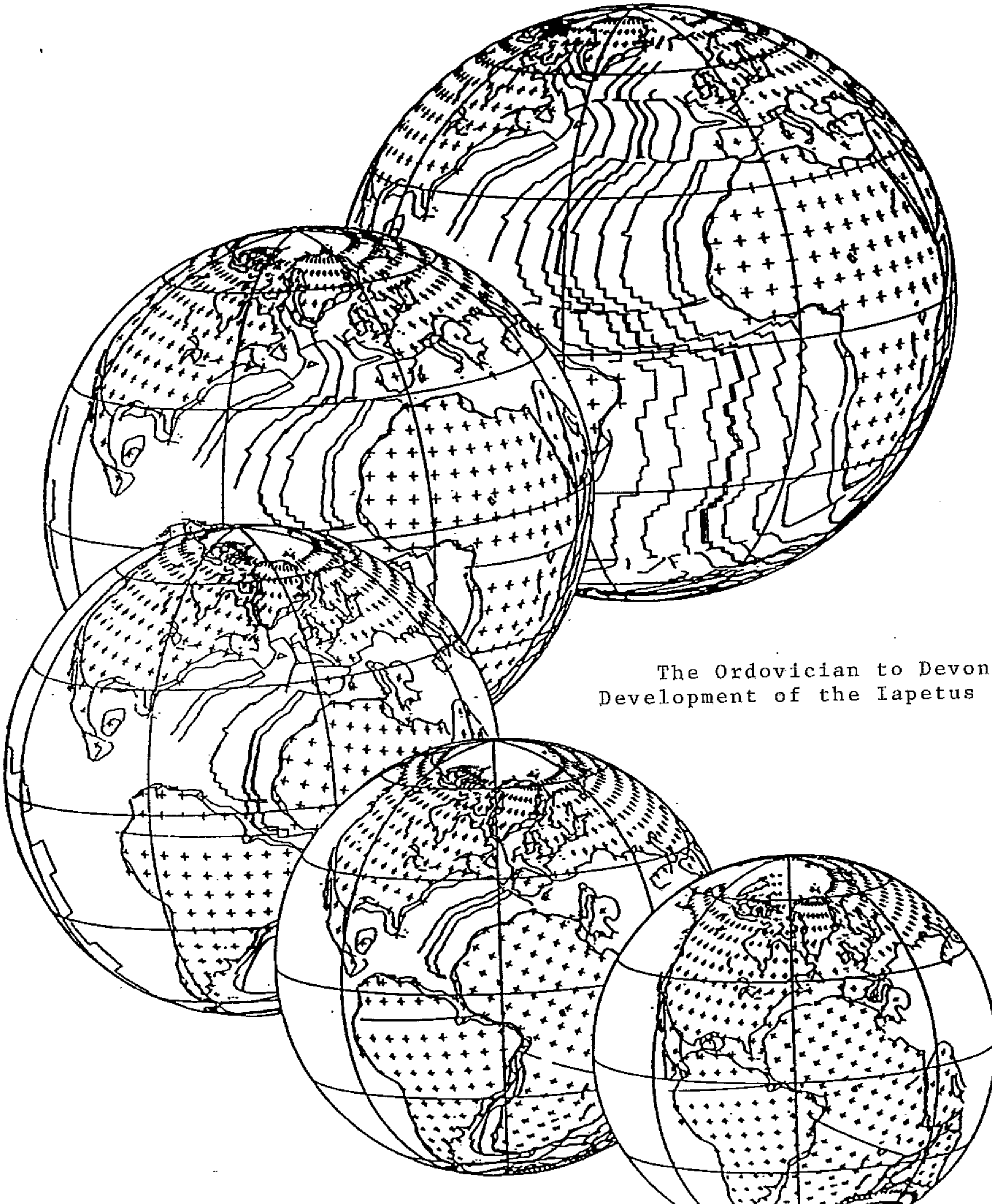

The Ordovician to Devonian Development of the Iapetus Ocean

by
W.S. McKerrow and
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University of Texas Institute for Geophysics Technical Report No. 55

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by *W. S. McKerrow and C. R. Scotese* 01/16/86

Introduction

The recognition of many small terranes bordering the Early Paleozoic Iapetus Ocean has entailed the revision of previous models, that only discussed the relations between the major continents. In this paper we illustrate the development of Iapetus through 100Ma by means of six maps drawn by computer graphics. In addition to paleomagnetic data, we have used biogeographic affinities, sedimentary facies, tectonic events and the distribution of igneous rocks to develop our assessment of continental and terrane distributions, and the positions of arcs and trenches. The tectonic model presented here is thus much more complex than the model first postulated by Wilson (1966) invoking the presence of a wide ocean in the Caledonides and Northern Appalachians, or the original plate tectonic model proposed by Dewey (1969). Subsequent models for the development of Iapetus have been proposed ( ) which we have taken into account in this review.

Following the recognition of exotic and displaced terranes in the western Cordillera (Coney et al., 1980), similar terranes are now recognized in the Northern Appalachian and Caledonide mountain belts (Williams and Hatcher, 1982; 1983; Zen, 1983). The Iapetus terranes are of three types: 1) fragments of exotic continental crust (like Avalonia) which have migrated independently of the larger continents, 2) parts of island arc systems which collided with the margins of continents at different times, and 3) small terranes that have been displaced laterally along the margins of the continents. (The recognition of displaced terranes has removed many of the difficulties that have arisen in previous models where arcs often appeared to be too close to trenches, or where opposing continents appeared to have collided at different times.)

Continents Bordering Iapetus

Faunal and facies distributions together with paleomagnetic data indicate that in the Early Paleozoic, there were three continents bordering the

Iapetus Ocean: Laurentia (North America, Greenland, northern Scotland and Svalbard), Baltica (Scandinavia), and Gondwana. The contemporary margins of the continents may be recognized by facies changes from shallow marine to deep water sediments (Rodgers, 1968) in those regions where no subsequent rifting has developed. Each continent was characterized by distinct shallow water benthic faunas, though deeper water benthos and many pelagic animals were capable of migrating between continents where similar climates prevailed (Cocks and Fortey, 1982; McKerrow and Cocks, 1986/J. Geol. Soc. London/). Also during the Early Paleozoic each continent was characterized by a distinct sequence of paleolatitudinal signatures. Evidence for these different latitudinal positions is given by the distinct apparent polar wander paths for each continent (ref) and by the distribution through time of climatically sensitive sedimentary facies (Ziegler et al., 1977; 1983?).

Laurentia.

The Cambrian and Early Ordovician margin of the continent can be recognized in the Appalachians by the transition from platform carbonates to deeper water slope and offshore deposits (Rodgers, 1968). In the British Isles and East Greenland, the continental margin is marked by the very thick (> 10km) sequences of Late Precambrian clastic sediments. In Scotland, the earlier parts of the Dalradian Supergroup below the Port Askaig Tillite (Harris et al., 1978) correlates with a similar thick sequence in East Greenland: the Eleonore Bay Group below the Tillite Group (Henriksen and Higgins, 1976) (in Escher and Watt). When the modern Atlantic is closed, these thick sediments mark the edge of Laurentia from Ireland, through Scotland as far north as the present latitude of 76 N.

Further to the north, the margin of East Greenland consists of old Precambrian metamorphic rocks overlain by Caledonian nappes. Though the thick marginal sequence of Late Precambrian sediments appears to be missing in this region, we believe that the Hecla Hoek Group of Svalbard (Harland, 1966) might be its continuation . The north coast of Greenland is characterized by a very different margin. Here the Early Paleozoic carbonates show a transition northwards into deeper water sediments (Hurst and Surlyk, 1983?) and the present coastline is along the line of the Early Paleozoicmargin of Laurentia.

Laurentia is characterised by endemic faunas which include bathyurid trilobites, nautiloids such as *Piloceras*, brachiopod genera including *Hesperomiella* , and the "mid-continent .conodont province" (Cocks and Fortey, 1982) .In the Early Paleozoic, warm water carbonates , with oolites, stromatolites and reefs, are the dominant shelf facies of North America;

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these persist throughout this time interval, suggesting that the continent straddled the Equator (Ziegler et al., 1979). Throughout the Early Paleozoic North America rotated counterclockwise as the east coast moved slowly northward (Scotese, 1984).

Baltica.

Baltica has a shallow water benthos distinct from North America (Cocks and Fortey,1982). The Ordovician sediments include nodular detrital limestones, however, these carbonates probably do not indicate a warm climate (Jaanusson, 1973); reefs are absent from Baltica until the Late Ordovician (Webby, 1984). Pelagic faunas show a mixture of North American and Gondwana forms. Scandinavia thus appears to have been situated in southerly mid-latitudes during the Early Ordovician, and moved steadily northwards during the Early Paleozoic

Gondwana

Paleomagnetic data from western France (Perroud et al., 1983), Spain (ref), are compatible with paleomagnetic data from northern Africa and South America(ref), indicating that these areas were adjacent to the northern margin of Gondwana during the Cambrian and Ordovician. Faunal evidence (Cocks and Fortey, 1982) supports the conclusion that these regions, together with Avalonia, formed the southern margin of the Iapetus Ocean. Further to the east, deeper water facies, marginal to the continent, are present in the Ardennes of northern France, and in Bohemia, showing that Europe south-east of the Tornquist Line, also lay along the margin of Gondwana (Cocks and Fortey, 1982). Unlike the carbonate facies from Laurentia and Baltica, the Early Paleozoic sequences of Morocco, Spain , France and Bohemia are dominated by clastic sediments; there are no warm-water limestones until the mid-Devonian. The Late Ordovician glacial deposits of North Africa (Bennacef et al., 1971), together with the paleomagnetic data, suggest that these regions of Gondwana lay at high latitudes near the South Pole.

_Terranes.

There is an accumulating body of data indicating that many smaller terranes moved independently of these Early Paleozoic continents. These terranes include: 1) exotic terranes composed of continental crust, like Avalonia, that through time appear to have been transferred from one continent to another, 2) island arcs that collided with the continents during the Early Paleozoic, and 3) some smaller displaced terranes that appear to have moved along continental margins by strike-slip (check spelling) faulting. Not all these terranes have yet been recognised, but some are shown on a Late Devonian reconstruction (Figure 1).

Exotic Terranes

Avalonia.

England, Wales, south-eastern Ireland, the Avalon Peninsula of eastern Newfoundland, parts of coastal New Brunswick and Nova Scotia and coastal New England, here collectively called Avalonia, are characterized by: 1) a basement that includes Late Precambrian arc rocks, 2) Cambrian and Early Ordovician faunas similar to the Iapetus margin of Gondwana, 3) and the absence of warm-water sediments. The Late Precambrian arc appears to have been formed on older continental crust along the Iapetus margin of Gondwana, but the precise location is uncertain. The sediments of Avalonia are generally of a deeper water facies than those of cratonic Gondwana, and they contain mixtures of pandemic fossils along with typical Gondwana forms (Cocks and Fortey, 1982).

In southern Nova Scotia, the very thick clastic sequence of the Meguma Group extends upwards to include Early Ordovician sediments. No comparable sequence is known in Avalonia, and it may be that the Meguma terrnae was originally separated from the rest of western Avalonia; it was, however, linked to the rest of Nova Scotia before the intrusion of the numerous Early Devonian plutons in the region.

NEW Meguma stuff(see above)

. ???Browns Mountain.

Island Arcs.

In New England and New Brunswick, the Bronson Hill and Tetagouche massifs consist of arc rocks lying, at least in part, on oceanic crust (Hall and Robinson, 1982; Hatch, 1982; Doolan et al. 1982). This arc appears to have developed above a south-eastward dipping subduction zone in the Iapetus Ocean. It collided with Laurentia in the Late Ordovician to produce the Taconic nappes. In Newfoundland, a similar suite of Early Ordovician arc rocks (the Lushs Bight Group) is present above ophiolites (Dean, 1978; Williams, 1979; Arnott et al., 1985) ; collision with Laurentia in the Llanvirn (in northern Newfoundland) and in the Llandeilo (in southwestern Newfoundland) resulted in the emplacement of the Humberian nappes.

In the British Isles, the Early Ordovician Grampian Orogeny has also be interpreted (Dewey, 1982; Mitchell, 1984) to be the consequence of a collision between an island arc and the Grampian Highlands. In this case there are no unequivocal exposures of contemporary arc rocks immediately oceanwards of the Grampian Highlands, but the arc rocks seen in the southwest of the Midland Valley (Ballantrae Igneous Complex) may be present below younger cover elsewhere in the Midland Valley of Scotland.

This Early Ordovician arc may have extended further north in the Iapetus Ocean. Late Cambrian/Early Ordovician arc rocks are present in Norway on some nappes (WHERE?) emplaced during the Silurian Scandian phase of the Caledonian Orogeny (Gee and Roberts, 1974). It is also possible that the Early Ordovician Finnmarkian phase of thrusting in Norway (Gee and Roberts, 1983) was caused by an arc-continent collision. (EXPAND AND CHECK)

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Displaced Terranes.

British Isles

In this section we discuss new evidence suggesting that displacements of several hundred km. have occurred along three major faults in Scotland. The Great Glen Fault, the Highland Boundary Fault and the Southern Upland Fault mark the boundaries between terranes with very different tectonic, igneous and sedimentological histories, suggesting that the Northern Highlands, the Grampian Highlands, the Midland Valley and the Southern Uplands did not attain their present relative positions until the Devonian (see Figure 1).

In the Northern Highlands of Scotland, dates on metamorphic minerals record events at ~1,100 Ma (Grenville Orogeny) and again at 450 Ma (CHECK van Breeman and Piaseki, 19??), while in the Grampian Highlands to the south-east of the Great Glen Fault, these times are not marked by any widespread events. This region was deformed in the Grampian Orogeny around 500 Ma (Tremadoc).

Similarly, the Highland Boundary Fault also separates terranes with very different geologic histories. Along the northern margin of the Midland Valley, Early Ordovician sediments include limestones and shales (Curry et al., 1984), whereas abundant coarse detritus might have been expected in this area if it had been south of the Grampian Highlands at this time. The detritus that is present in the Midland Valley of Scotland (Bluck, 1983; 1984) suggests that, during the Silurian and Early Devonian, the Midland Valley was not bordered by either the Grampian Highlands or the Southern Uplands.

The Southern Uplands of Scotland consists of thick sequences of trench sediments which were accreted to Laurentia from the Caradoc to the Wenlock (Leggett et al., 1979). In this terrane, several structural studies (e.g. Anderson, 19??) show contemporary sinistral shear as accretion progressed. But the most convincing evidence of large sinistral strike slip movements comes from a study of granite clasts in several Ordovician mass flow comglomerates that had been derived from the north-west. The clasts have yielded ages in the range 1,200 to 900 Ma and 500 to 460 Ma (Elders, 19??). These granites can be matched petrographically with plutons of the same ages in western Newfoundland. It thus appears probable that the Southern Uplands occupied a position to the southeast of western Newfoundland during the Late Ordovician.

The translation of the Southern Uplands from its position adjacent to western Newfoundland to its present position in Scotland involves a total strike slip displacement of around 1,500km . This movement probably was distributed along each of the three large faults (Great Glen, Highland Boundary and Southern Upland Faults), but some of the movement may also have been taken up by sinistral shear within each terrane. It is concluded that movements of 300 or 400 km on each of the three faults may have been sufficient to provide the total observed displacement .

In Ireland the westerly continuations of the Highland Boundary and Southern Upland Faults are disputed. Our map shows convergence of these faults in central Ireland; this interpretation is by no means certain. An additional uncertainty is the position of the Connemara and South Mayo massifs; they are not distinguished on the set of maps presented in Figures 1-6.

On the south side of Iapetus, several large faults occur in the Lower Palaeozoic outcrops of England and Wales. There may well have been strike slip movements of more than a few km. on the Church Stretton, Pontesford and Bala Faults prior to the Silurian, however, we do not show them on our maps because the amount of displacement and sense of movement is still unconstrained.

North America

In Newfoundland there has certainly been movement on several strike-slip faults (Bradley, 1983[TECTONICS]), [EXPAND WITH REVIEW OF RELEVANT DATA, INCLUDING WHITE BAY AND BELLE ISLAND FAULTS.] but perhaps not more than a few km on others; for example, Arnott et al. (1985) suggest that the Lobster Cove-Chanceport and the Lukes Arm-Sops Head Faults cannot have very large strike slip movements as detritus from the Lushs Bight arc is transported across both faults.

It is unlikely that there are displaced terranes to the west of Avalonia in New Brunswick and New England because both the Tetagouche and the Bronson Hill arcs are still adjacent to the nappes that were formed during their collision with Laurentia. Though some strike slip movements may have taken place in the Northern Appalachians, we do not consider that ~~they~~ are likely to have been more than a few tens of km.

(Barentsia (including Svalbard).

Harland (1978) has shown that the Precambrian and Early Paleozoic sequences of Svalbard can be grouped into three tectonic provinces: the Eastern Province, Central Province and Western Province. These provinces are characterized by Cambrian and Ordovician faunas with Laurentian affinities(Harland and Gayer, 1972; Fortey,????) which suggests that, if not attached to Greenland, they were nearby. The Western Province shows some similarities with North Greenland; the Central Province is intermediate, and the Eastern Province is more similar to East Greenland. To account for these features, Harland postulates that they have been brought into their present relative positions by Late Devonian sinistral strike slip faults along which these provinces were displaced northward.

The Early Paleozoic margins of Laurentia appear to be complete in Greenland, except along the east coast, north of 76 N. We thus think that the northern part of the East Greenland coast is the only possible site for attachment of any part of Svalbard.

The northern part of East Greenland also contains basalts (Zigzagdal Formation) and mafic dykes (Kalsbeek and Jepsen, 1982?) that have been dated at 1,200 Ma old; these rocks may record the time of rifting between Svalbard and Laurentia forming the Proto-Iapetus Ocean (Harland and Gayer,1972). Because of the maintainence of faunal similarities between Svalbard and Laurentia, it is unlikely that this ocean was ever very wide. We consider that the Llandovery nappes in East Greenland were formed when this ocean closed.

In addition to the biogeographical affinities, Harland and Gayer (1972) comment on the similarities between Ny Friesland (Eastern Province of Svalbard) and the Southern Barents Sea Caledonides of Finnmark (northern Norway) ; they envisage the Trollfjord Fault Zone of Finnmark as the suture separating Baltica from the northeastern margin of Laurentia, which included East Greenland, Svalbard (Ny Friesland) and the Barents Sea block. We think that all three provinces of Svalbard, together with the Barents Sea block, composed the terrane of Barentsia, which was separated from East Greenland by the Proto-Iapetus Ocean. In our Early Paleozoic reconstruction (Figure 2) we show Barentsia adjacent to north East Greenland (N of 76 N.).

It is possible that the thick Late Precambrian sequence of the East Greenland Eleonore Bay Group was once continuous with the Hecla Hoek Group of Svalbard (Harland et al., 1966) and the Barents Sea Group of

Finnmark (Siedlecka and Siedlecka, 1967); these very thick Late Precambrian sequences might well have marked the continental margins of both Laurentia and Barentsia.

Ordovician Through Devonian Development

Basal Ordovician

1. Pmag

a. Gondwana

inference from Cambrian of Cape Breton

b. North America

craton

c. lack of European/Baltica control

2. Climate

The Early Ordovician cratonic sediments of Laurentia are warm water carbonates that confirm the paleomagnetic evidence for a position on the Equator. Early Ordovician sequences from Baltica and Gondwana (including Avalonia) are dominated by clastics and show no indication of warm climates.

3. Biogeography.

Apart from pandemic pelagic faunas and deep water benthos, the marine faunas of Laurentia, Baltica and Gondwana are distinct, suggesting that they were separated by oceans at least 1,000 km wide (Cocks and Fortey, 1982). The faunas in Avalonia continue to be similar to those in Gondwana, and if rifting had occurred, the ocean separating them was not wide enough to be an effective biogeographic barrier.

The Early Ordovician benthic faunas on the Bronson Hill, Tetagouche and Lushs Bight island arc (B-T-L arc) have been considered to be sufficiently distinct from those of Laurentia, Baltica and Gondwana to justify a distinct "Celtic Province" (Neuman, 1984); however, recent descriptions of similar fossils from both Laurentia and Avalonia (McKerrow and Cocks, 1986) would suggest that environmental factors, rather than geographic isolation, were responsible for these peculiar faunas. We believe that parts of this arc had already collided with the Grampian Highlands of Scotland prior to the Arenig, and that parts of the B-T-L arc could not have been far removed from northern Newfoundland as collision took place there in the Llanvirn. Geographical isolation of these arc faunas from Laurentia would thus have been unlikely.

4. Tectonic events.

Many ophiolites in Newfoundland and some at Ballantrae (in the southwest of the Midland Valley of Scotland) appear to have been obducted during the Arenig (Williams, 1975; 1979; Williams and Smyth, 1973; Williams and St.Julien, 1978; Bluck et al., 1980; Bluck and Halliday, 1982). Because the underlying rocks were metamorphosed, it can be concluded that the ophiolites were young, hot fragments of oceanic crust at the time of obduction (Williams and Smyth, 1973;///???).This evidence suggests that during the Arenig there may have been several marginal basins along the eastern edge of Laurentia, each with with its own spreading ridge, . One of these basins extended along the Baie Verte-Brompton Line (Williams and St. Julien, 1982), between the advancing B-T-L arc and the margin of Laurentia. In Arenig times, it is probable that the B-T-L arc may have extended to the northeast and may have collided with the Grampian Highlands in the Tremadoc (Grampian Orogeny).

The position of Baltica relative to Laurentia in the Arenig (Figure 2) requires that a second arc must have been responsible for the Early Ordovician Finnmarkian Orogeny in Norway (Sturt and Ramsey, 197?; Gee and Roberts, 1983). This affected Norway north of the ***latitude of Trondheim????***??

Calc-alkaline arc rocks appear in England,Wales and Ireland in the Tremadoc (Kokelaar, 1983?)and may be related both, to the subduction and closure of the Tournquist Sea, and to the rifting of Avalonia from Gondwana. The absence of Early Ordovician arc rocks in western Avalonia (CHECK) may indicate that eastern and western Avalonia rifted from Gondwana at different times. We are not certain whether Avalonia consisted of one or two terranes.

Llandeilo - Early Caradoc (N. gracilis Zone)

- ***1. Pmag***
  - ***a. same as above***
  - ***b. problems with British data (too equatorial)***

2. Climate.

During the Early Ordovician, the Equator remained across Laurentia, and the South pole remained in Gondwana, and there were no great changes in sedimentary facies in these two continents. Baltica , by contrast, appears to have moved slowly northwards to lower latitudes, so that by Early Caradoc times (CHECK) carbonates are present; these are detrital nodular limestones that do not necessarily represent very warm climates (Webby, 1984).

3. Faunas.

At this time (N. gracilis zone), Laurentia and Baltica still have distinct benthos, however, the benthic faunas of the British part of Avalonia start to loose their affinities with Gondwana and begin to show more forms in common with Baltica; changes in biogeographic affinities thus provide the

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first indication that Avalonia was a separate terrane, moving independently of Gondwana. It must be noted, however, that in the western parts of Avalonia (Newfoundland, Nova Scotia, coastal New Brunswick and New England) there are few fossiliferous beds of Middle and Upper Ordovician age, and it is uncertain whether the this area was connected to eastern Avalonia.

On the western side of Iapetus, the cratonic faunas above the Lushs Bight arc rocks in Newfoundland take on a completely North American aspect. This faunal change follows the collision of the B-T-L arc with Laurentia in western Newfoundland (the Humberian Orogeny) and is accompanied by a change in provenance of the sediments. Before this collision, the sediments above the Lushs Bight arc consisted of carbonates and arc derived clastics, after the collision, detritus from granitic and metamorphic sources is present (McKerrow and Cocks, 1978; 1981; Arnott et al., 1985).

4. Tectonics

The collision of the arc in western Newfoundland during the Llanvirn and Llandeilo was followed by an inversion of subduction polarity. Subduction that had previously been directed to the southeast beneath the B-T-L arc, switched to northwesterly directed subduction beneath the continental margin of Laurentia. During the early stages of northwesterly directed subduction, no arc rocks were produced, and the only evidence of subduction was the accretion of trench and pelagic deposits in the Southern Uplands (Leggett et al., 1979) which were probably southeast of western Newfoundland at this time. The oldest accreted sequence in the Southern Uplands includes fossils of the *N.gracilis* Zone age and was probably accreted during, or just after, this time.

Inversion of polarity may have occurred earlier along the northeast margin of Laurentia after the Grampian Orogeny. The Late Llanvirn to Caradoc sequence at Girvan in the southwest of the Midland Valley of Scotland includes shallow water conglomerates with large (> 1 m) granite clasts of arc related plutons (Longman et al., 1979) yielding age dates (470 to 450 Ma ***CHECK DATES***) closely contemporaneous with those of the enclosing sediments. These clasts have been interpreted as being derived from nearby arc rocks. (Bluck, 1983; 1984). The Midland Valley, in its present position, appears to be too close to the trench deposits of the Southern Uplands and the expected arc-trench-gap is missing (Leggett, McKerrow and Casey,1980?). However, if the Midland Valley and Southern Upland terranes have been juxtaposed by movement along the strike slip faults postulated in this paper, then the apparently missing arc-trench gap may be explained.

So far, no plate tectonic model has yet been proposed to explain the development of the Moine Thrust in northwest Scotland. The movements on

this major fault are complex, and may have extended over a considerable period of time (Coward, 198??). It is suggested that they took place around 460 Ma ago, ***which is close to Llandeilo time***. Inspection of Fig.2, 3 will show that neither Baltica nor Siberia was immediately east of Laurentia at this time, so that the Moine Thrust is not likely to have been due to collision with either of these continents. However, there is a probablility that the B-T-L arc extended as far north as the Grampian Highlands and it may well have extended even further north (arc rocks of Cambrian/Early Ordovician age occur on some Scandian nappes in Norway (see above or below for Gee reference??). The emplacement of the Fetlar ophiolites on Shetland might also have resulted from the collision with this same arc. (This is really SOPER stuff)
Calc-alkaline igneous activity in England, Wales and southeast Ireland reaches a peak in the early Caradoc, but there is still no record of any similar igneous activity in western Avalonia.

<u>Ashgill</u>

1. Pmag.

a. North America

b. problems with British data (too equatorial)

c. Dunne Pt. Arisaig, results ??

d. W. France (Perroud) polar latitudes

e. porbable Baltic Late PZ overprints (Sweden)

f. Alaska stuff?

g. N. Greenland? ask Rob

h. (see if possble to sort out Moinian and etc.)

<u>2. Climate</u>

During the Ashgill, an ice cap covered the whole of North Africa from Morocco to Arabia. Adjacent parts of Gondwana, including Spain and Brittany have Ashgill sediments which have been interpreted too be periglacial (REF??). There are no Ashgill tilloids in eastern Avalonia, which was probably connected to Baltica at this time. In the Late Ordovician, carbonates became more widepsread in Baltica, and a few reefs were present (Webby, 1984) . By the Late Ordovician, much of northern Baltica had entered tropical latitudes and warm water facies similar to those in Laurentia began to develop.

The latitudinal position of western Avalonia is more uncertain, tilloids have been described from the Roxbury Conglomerate of the Boston Bay Group (Cameron and Jeanne, 1976), but their age is uncertain. Tillites have also been described from Nova Scotia (Schenk,197??). If Ashgill tillites are present in western Avalonia, it follows that it was at higher latitudes than eastern Avalonia (Figure X).***evaluate in light of pmag. SE NEW ENG, p 123, other possibility is Mosher suture***).

3. Faunas

The faunas of Avalonia and Baltica became identical in the Late Caradoc (Fortey and Cocks, 1986) indicating that the Tornquist Sea was narrow enough for cratonic benthos to cross easily. This connection occurs significantly earlier than the Late Ashgill connection of benthic faunas across Iapetus between Baltica to Laurentia (McKerrow and Cocks, 1976; Cocks and Fortey, 1982). The time of closure of the Tournquist Sea is uncertain. Though the faunas of Baltica and Avalonia were similar by the mid-Caradoc, the collision may have taken place in the early Ashgill; is the only time when synchronous unconformities are present in both England, Wales, and Norway.***(If we have offset along the Tournquist LIne we have to mention it here.)***

4. Tectonics

The mid-Caradoc was also the time when calc-alkaline volcanics ceased in eastern Avalonia (England and Wales)(Kokelaar, 198?). ***Zwartman discusses dates in Danish borehole*** In western Avalonia, the andesites of the Dunn Point volcanics (Arisaig, Nova Scotia) are pre-Early Llandovery in age (Boucot et al., 1969?) and may be related to southward subduction beneath the northern margin of western Avalonia.

On the western margins of Iapetus, the final phases of the Taconic Orogeny in southern New England was completed by the Early Ashgill(?REF), while along the northeastern margin of Laurentia, continued subduction is recorded by progressive accretion of Late Ordovician trench deposits in theSouthern Uplands (Leggett et al., 1979).

The emplacement of the Taconic nappes of New England and the progradation of the Queenston delta, mark a turning point in the geological evolution of the Northern Appalachians. These events signal the transition from a passive, carbonate-dominated margin to an active, mountain belt (Kay, 1951; other refs?) No equivalent of the Queenston delta is seen in Maritime Canada; it would appear that the nappes of the Humberian orogeny were emplaced below sea level because continuous Llandeilo sedimentation occurs in the Long Point Group of western Newfoundland (Arnott et al., 1985) and no clastic wedge is present.

f. (probable subduction along east coast NA?)do you mean N coast of west Avalon??

f. mid-continent Ashgill tuffs

Wenlock

1. Pmag

a. NA - Rose Hill results/ reef

b. BAltica - Ringerike

c. Britain - (general problem)

d. Gondwana - beginning of controversy

2. Climate and Biogeography

In Wenlock times, Laurentia began to move slightly southwards, resulting in the northward migration of the equatorial belt and the passage of eastern Laurentia into subtropical latitudes . In New York and the Midwest carbonates continue through this interval, but in the latest Silurian evaporites appear, indicators of the dry climate of the south subtropics. Baltica, with Avalonia now attached to its southwest margin, continued to move northward as it did during the Ordovician. The reef facies which appeared in the Caradoc now spread over wider areas of the continent, and by the Wenlock the first coral reefs appeared in England.

Gondwana, including Spain, France and Bohemia, is still probably at high southerly latitudes; no warm water carbonates were present during the Silurian. The *Clarkeia* fauna, which is characteristic of the Silurian south polar regions (Boucot, 197?; Cocks, 197?) was present in Brittany (Babin, 198?) and other parts of Gondwana, but is not recorded in Avalonia.

Although there is uncertainty as to whether eastern and western Avalon were united during the Ordovician, there are no doubts that they were together by the Silurian. Benthic ostracods, which have no pelagic larval stages and therefore cannot cross even narrow bodies of deep water, are common to both eastern and western Avalon in the Siluran, and are distinct from Laurentian ostracods (Cocks and Fortey, 1982).

4. Tectonic

The final closure of the Iapetus Ocean took place in several stages, starting in the north and progessing irregularly southwards. In north East Greenland the Caledonian nappes were emplaced westwards over the edge of the continent in the Late Llandovery; the time of emplacement is deduced from the sudden down-warping of North Greenland by the weight of the westward verging nappes (Hurst et al., 1983). Shallow water carbonates to the west of the nappes were suddenly replaced by deep water graptolite shales and turbidites over a wide area. It is not certain which continent collided with East Greenland, but , for the reasons given elsewhere in this paper, we consider it likely that it was Barentsia. 420 Ma granites are present in northwest Svalbard (Harland, 1966, p. 77; Harland and Gayer, 1972,p.296) and may record the collision event.

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In East Greenland, the stratigraphic evidence for Late Llandovery nappe emplacement is confined to the region now north of 79 N.; south of this the Caledonian thrusts are exposed intermittently in nunataks through the ice cover, and they appear to continue south to Scoresby Sound(70 N.).However, the stratigraphic control in the south merely indicates that the thrusts are pre-Middle Devonian.

Our interpretation of the strike slip movements in Scotland suggests that prior to movement along these faults, Scotland was elongated (from its present 700 km) and extended 2000 km along the eastern margin of Laurentia. It was in this elongate from in the Wenlock, when collision took place with Norway. In the Wenlock, the northern coasts of Norway collided with Scotland, rather than with the eastern margin of Greenland.

The fact that Baltica colllided with Laurentia to the south of the East Greenland Fold Belt helps to explain both the later (Wenlock) age of the movements in Norway (Gee and Roberts, 1983) and the different vergence of the nappes in Norway and Greenland. The eastward vergence of the Scandian thrusts in Norway suggests that these nappes were obducted above a westward dipping subduction zone. This suggestion fits well with the fact that much of Scotland has calc-alkaline plutons (in the Grampian Highlands) or andesites (Thirlwall, 1981).

In the Midland Valley, deltaic and fluvial sedimentation may have continued through much of the Wenlock, and it is possible that some of the exotic detritus (Bluck, 1984) may have been derived from the orogen in Norway.

In the Southern Uplands of Scotland, the youngest turbidites accreted are of Late Wenlock age, and it is probable that accretion ceased near the end of the Wenlock. At this time coarse detritus derived from the north appears in the English Lake District and similar sedimentation continues throught the Ludlow and Pridoli. Deep seismic reflections shows a continuity of the deeper crust from Northern England below the Southern Scotland, and thus supports the hypothesis that northward subduction of eastern Avalonia continued after the Wenlock with the emplacement of continental crust beneath the Southern Uplands (Leggett et al., 1983). The abundance of Silurian and Early Devonian plutons and andesite lavas in both the Grampian Highlands and the Midland Valley may be related, in part, to this northward subduction

While collision between Scotland and Norway terminated westward subduction below Scotland in the Late Silurian, the southern parts of the Iapetus Ocean between Avalonia and Laurentian still remained open. In Scotland , western Newfoundland (to the west of the Reach Fault) , northern New Brunswick and Gaspe, there are sufficient igneous rocks to suggest that subduction continued along this margin of Laurentia through most of the

Late Silurian and Early Devonian (McKerrow and Ziegler, 1971; McKerrow and Cocks, 1977; Arnott et al., 1985). Silurian andesites are also present in western Avalon (??REF), showing that the western part of Avalonia also had a trench along its southern margin.

Basal Devonian (Gedinnian)

1. PMAG

a. NA - Arctic pole

b. Baltica - same as LAte Silurian

1. NA Avalonia - Eastport stuff

c. England - ORS data/controversy

d. Gondwana - real problems(avoid

c. 'SC Europe is still like Gondwana??

2. Climate

In the Early Devonian there were no marine sediments in Scotland, Greenland or Norway. The fluvial Old Red Sandstone facies was represented by large thicknesses in several down-faulted regions. These rocks indicate periods of high rainfall related to the Equatorial rainy belt. (Chris rewrite)In Laurentia during the Early Devonian, the evaporites which appeared in the Late Silurian of New York and southern Ontario, continue, while carbonates continue further west(Iowa). Carbonates are absent in Avalonia and Gondwana

(.I THINK WESTERN AVALONIA IS TOO CLOSE TO LAURENTIAN ON THE GED. MAP)

3. Faunas

With the closure of Iapetus between Scotland and Norway in the Wenlock, there would have been a high mountain belt extending the length of Norway. Although the benthic fauanas with pelagic larval stages had been similar since the Ashgill, benthic ostracodes remained distinct throughout the Silurian.(Cocks and Fortey, 1982); they were separated in part by the Norwegian Caledonian mountains, and in part by the Andean margins along the remaining fragments of Iapetus. In the Early Devonian the same barriers also separated the cratonic benthos of Southern Europe and Avalonia (Rhenish Bohemian)(Boucot, 197??) from the Appalachian Province of Laurentia and northern South America (Barrett et al., ?? NA Paleo. Conv. paper).CHECK Cocks and McKerrow,1972)

4. Tectonics

c. beginning of Acadian event?

e. Baltica/avalonia/SUP all strike-slip sinistral *f. spread of non-marine envirnments in ORS*

g. deformation of faults due to strike slip in GRM, before intrusion of 400 Ma granites

The remnant of Iapetus between Avalonia and Laurentia was effectively closed in the British Isles, through the northward subduction of continental crust . Further west, oceanic crust may have been continued to be subducted northward below Laurentia in western Newfoundland, northern New Brunswick and (CHECK) northern Maine, as well as southwards below western Avalonia in Nova Scotia, coastal New Brunswick and coastal New England.(?REF).

The sinistral strike slip displacements along the Great Glen, Highland Boundary and Southern Upland Faults probably took place gradually during the Silurian and Early Devonian. Though movement along the Great Glen and Southern Uplands Fault may have continued through the Early Devonian, large movements did not occur along the Highland Boundary Fault, because some formations of the Arbuthnott, Garvock and Strathmore Groups appear on both sides of this fault. These groups probably range in age from the Siegenian into the Early Emsian (House et al., 1977), and it may be that movements along the Highland Boundary Fault were less than a few tens of km after the Gedinnian.

The terranes that were bounded by these major strike slip faults were also involved in differential vertical movements while the strike slip was taking place. During the Early Devonian, the Midland Valley of Scotland and parts of the Orcadian Basin of northern Scotland accumulated large thicknesses of Old Red Sandstone. Much of the detritus was not of local origin (Bluck, 198??).

<u>Middle Devonian (Eifelian)</u>

1. Pmag.
(all interpolated - best guess)

<u>2. Fauna</u>

Development of the Old Red Sandstone facies continued through the Middle Devonian in northern Scotland and Greenland, though the sediments were not all fluvial. Lacustrine deposits are present in northeast Scotland, and a transition from fluvial to marine is present western England and South

Wales . Non-marine fish faunas, typical of the Caledonides Old Red Sandstone are also known in Australia (Turner and Tarling, 198?), suggesting the presence of a land connection between Laurentia/Baltica (together since the Wenlock collision) and Gondwana; this link was probably across northern South America (Ziegler et al., 198??).

There is independent evidence that Gondwana was fairly close to Avalonia at this time: reefs limestones are present in both Devon (southern England) and Brittany (northwest France), showing that in the Middle Devonian both eastern Avalonia and northern Gondwana were in low latitudes. In other words, the Rheic Ocean (McKerrow and Ziegler, 1972), which formed when Avalonia rifted away from Gondwana, was now closed at its western end and very narrow elsewhere. Although Laurentian/Baltica were moving north during the Middle Devonian, Gondwana was moving more rapidly in the same direction.

3. Climate

(limestone and reefs are appearing along northern Gondwana margin=Morocco(Geology review), Britanny)

b. NAM moves north under a subtropics - western salt

4. Tectonics

a. NA/Avalonia collision Acadaian orogeny

b. end all subduction

c. differential subsidence MVL-down, GRM-up,SUP-up etc

d. Strike slip along :

1. GGF

2. continuing in Spitzbergen

3. ?in W. Avalonia

e. Catskill delta

f. Acadian plutons ending

g. beginning of Ellesmerian orogeny

In the Northern Appalachians, the youngest sediments to be affected by the Acadian Orogeny are of Early Emsian age (Boucot et al., 197?), and the climax of the orogeny is genrally considered to be Eifelian (Boucot, 197?). This orogeny was the result of the collision of Avalonian with Laurentia, and marks the end of the Iapetus Ocean .

Although the Acadian Orogeny is usually considered to be confined to the Appalachians, there are also considerable Middle Devonian movements (marked by strong unconformities) in the Midland Valley of Scotland, northern and western England, and Wales. The size of these unconformities decreases away from the Avalon-Laurentia suture zone along the Scottish-English border. However, the stratigraphic breaks are not large in northeastern Scotland, where the Middle Devonian is well developed in the Ordcadian Basin (House et al., 1977) close to the Laurentia-Baltica suture. The stratigraphic evidence from the Old Red Sandstone of Britain thus indicates Middle Devonian uplift along the Avalonia-Laurentia suture, but not along the Baltica-Laurentia suture. This uplift appears to be related to the cessation of northward subduction of continental crust below the Southern Uplands; all igneous activity related to subduction appears to end after the Early Devonian both in Scotland(Thirlwall, 1981) and in the Northern Appalachians (Wones, 198???)..

The Middle Devonian was probably the time when large strike slip movements ceased on the Southern Upland Fault. At this time the northward movement of Baltica was taken up by sinistral strike slip on the Great Glen Fault and perhaps also faults west of Scotland (now covered by continental shelf) and the east of Scotland(in the North Sea).(?Ref. to Peter Ziegler--CHECK), but these faults are not so obviously associated with differential subsidence: the Midland Valley was uplifted and contains no Middle Devonian, while the Orcadian Old Red Sandstone was depsoited in a basin with no clearly faulted margins. Strike slip faulting in Svalbard may have continued into the Late Devonian (Harland and Gayer, 1972). And also in W>Avalonia??(ref?)

In the Northern Appalachians, the Acadian Orogeny resulted in considerable uplift over the whole orogen. We estimate that New England would have been in the Equatorial rain belt during the Middle Devonian, and it is reasonable to conclude that erosion would proceed very rapidly. This is borne out by the initiation of the Catskill Delta in New York and northern Pennsylvania, where the sediments derived from the Acadian mountains enroached across the carbonates of the American craton.

?Ellesmerian Orogeny?

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III. Conclusions/Summary

1. Chronological summary

6 step evolution of Iapetus Ord-Dev

The tectonic events in and around the Iapetus Ocean are summarised in the following table:

2. New Interpretations

a. identification and strike slip reconstruction of Scottish terranes

b. Greenland Barentsia relationship

c. Ordo-Dev. history show continuous orogeny - like Andean evolution: Finmarkian, Grampian, Taconic,Caledonian, Acadian,Ellesmerian? (McKerrow, 1962)

3. Implications of Reconstructions

a. for PZ plate history (relative motions/rates/geometry)

b. for understanding later evolution of Arctic

c. for integrating faunal/sedimentol/tectonic/paleomag highlighting remaining controversies

d. computer graphics and dat base management- geologic models

e. importance of looking at source of sediments

4. Future Work : More terranes wil be recognized

Table 1. Tectonic Events

DEVONIAN	
Middle Devonian	Strike slip faults in Svalbard (continue through Late Devonian) Strike slip movements between Baltica and Laurentia on Great Glen Fault (and perhaps faults to west and east of Scotland. Acadian Orogeny: collision of Avalonia and Laurentia; mountains in New England; uplift of Eastern Avalonia.
Early Devonian	Strike slip movements on Great Glen, Highland Boundary and Southern Uplands Faults; subsidence of Midland Valley.
SILURIAN	
Pridoli and Ludlow	Uplift of Southern Uplands; no further accretion..
Wenlock	Scandian Orogeny: collision of Baltica and Laurentia (Norway and Scotland),east verging nappes. Granites and andesites in Scotland.
Llandovery	Collision of Barentsia and Laurentia (Spitzbergen and East Greenland), west verging nappes. Granites in Svalbard.
ORDOVICIAN	
Ashgill	Possible time of start of subduction southwards below Western Avalonia (volcanics in Nova Scotia). Possible time of collision of Eastern Avalonia and Baltica (England and Norway); end of subduction below Eastern Avalonia.
Caradoc	Taconic Orogeny: Collision of BTL arc with Laurentia (New England, New Brunswick and Quebec), west verging nappes. Granite clasts at Girvan suggest subduction below Midland Valley. Start of accretion in the Southern Uplands. Possible time of Moine Thrust in Northern Scotland (possibly by collision of northern extension of BTL arc with Laurentia), west verging nappes.
Llandeilo and Llanvirn	Humberian Orogeny: collision of BTL arc with Laurentia (western Newfoundland), west verging nappes.

Arenig	Closure of maginal basins, with ophiolite obduction (Quebec, Newfoundland, Midland Valley).
Tremadoc	Finnmarkian Orogeny :possibly by collision of an arc with Baltica (Norway) Grampian Orogeny: collision of northern extension of BTL arc with Laurentian (Grampian Highlands). Subduction starts below Eastern Avalonia; possible time of rifting of Eastern Avalonia from Gondwana (but could be earlier).

The timing and nomenclature of orogenies.

This paper makes it clear the development of the Iapetus ocean is reflected by a variety of orogenies. Some of these mountain building events (like those involving collisions) are perhaps of very short duration, but at the moment it is not possible to make any useful estimates of the durations. These collision events are in marked contrast to much prolonged events associated with accretion of trench sediments (Southern Uplands of Scotland) or with the evolution of arcs. It can therefore be seen that, while some of these orogenic episodes are distinct, others merge in time and space.

We have not used any new terms in our discussion. There are perhaps enough available for most purposes. It should be clear from Table 1 that the definitions of those terms (like Grampian, Finnmarkian, Humberian Taconic and Scandian) are reasonably unambiguous; they are all restricted to events of fairly short duration, and they are all well-defined geographically. If a geologist cannot find an existing name for a local orogenic event, he need not necessarily invent a new name. In several places in this paper, we have just described orogenic events by their duration (in terms of the stratigraphic scale or in Ma) and geographical extent.

The terms "Caledonian" and" Acadian" are more difficult to define. Should the term "Acadian" be restricted to the Appalachians? Or could it be used for the Middle Devonian uplift of the region around the Western Avalon-Laurentian suture in the British Isles? All orogenic terms should be limited geographically, and the area of the Acadian Orogeny is no exception. However, before the recognition of the Iapetus Ocean, it may have been acceptable useage to confine it to North America, we would suggest now that it could be extended to cover Middle Devonian events (on both sides of the present Atlantic Ocean) along the eastern margin of Laurentia. It is possible that much of the folding in the south of Scotland and the north of England is of Middle Devonian age; when its age is defined unambiguously, would it not help our thoughts on the tectonic history of Iapetus to call it "Acadian"?

The use of the term" Caledonian" is still more difficult to define. Stille (REF>?) first used the word believing that all orogenic events were of wide geographical extent and of very short duration; he applied "Caledonian" to events anywhere in the world that appeared to have an end Silurian age. In the Caledonides, events from the (possibly Caradoc) emplacement of the Moine Thrust, through the emplacement of the Llandovery nappes in East Greenland and the Wenlock nappes of Norway (now called Scandian) and the prolonged accumulation of the Southern Uplands (Caradoc to Wenlock) have all been termed "Caledonian" by many authors. Perhaps the term " Caledonian" is still necessary until all Iapetus tectonic events can be defined much more precisely; until that time, it is still available for those un-named events. But eventually, it would seem that the whole sequence of tectonic events described in this paper (whether they have individual orogenic names or not) could well be included under an all-embracing "Caledonian Orogeny"(see McKerrow, 1962).

While accepting that orogenic terms may include events of very different durations, all orogenies have limits both in space and time. The Caledonian Orogeny is not for export. The term should be confined to the continental margins bordering the Iapetus Ocean. And, while advocating that it should not be restricted to the end of the Silurian (as Stille originally defined it), we think it should be restricted chronologically to Ordovician, Silurian and Early and Middle Devonian events.

FIG. 1 BASAL ORDOVICIAN

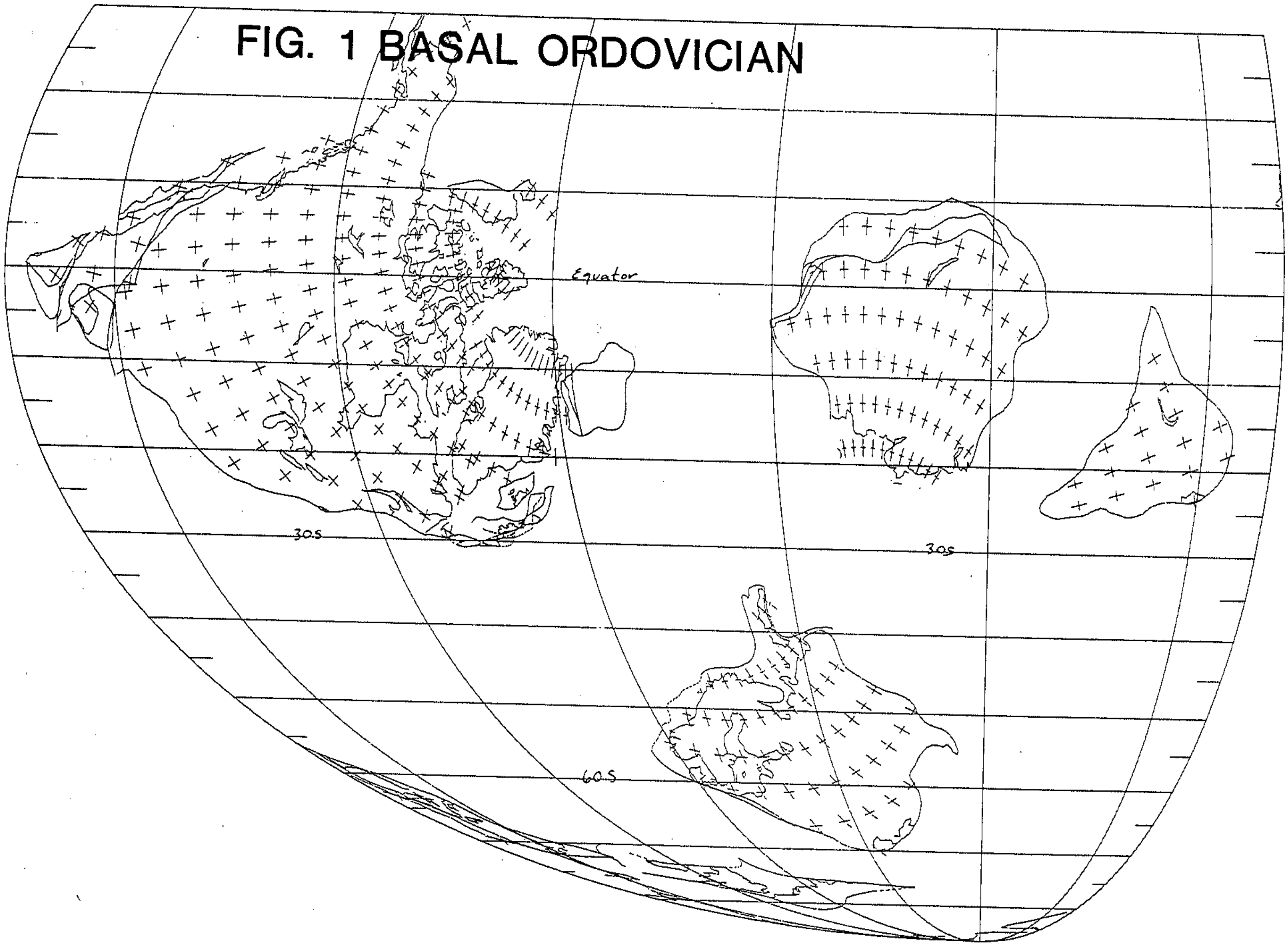


FIG. 2 LLANDEILO-CARADOC

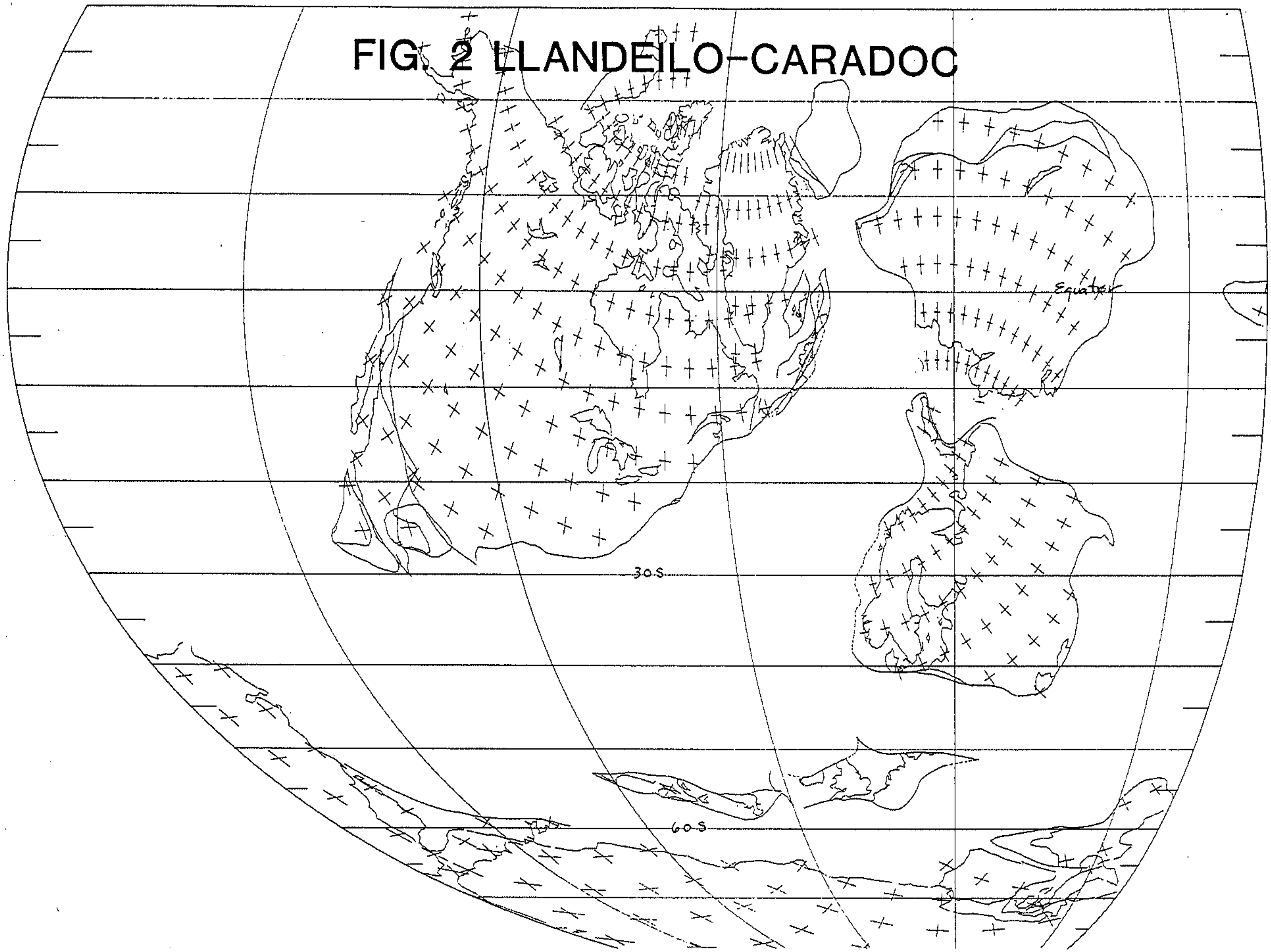
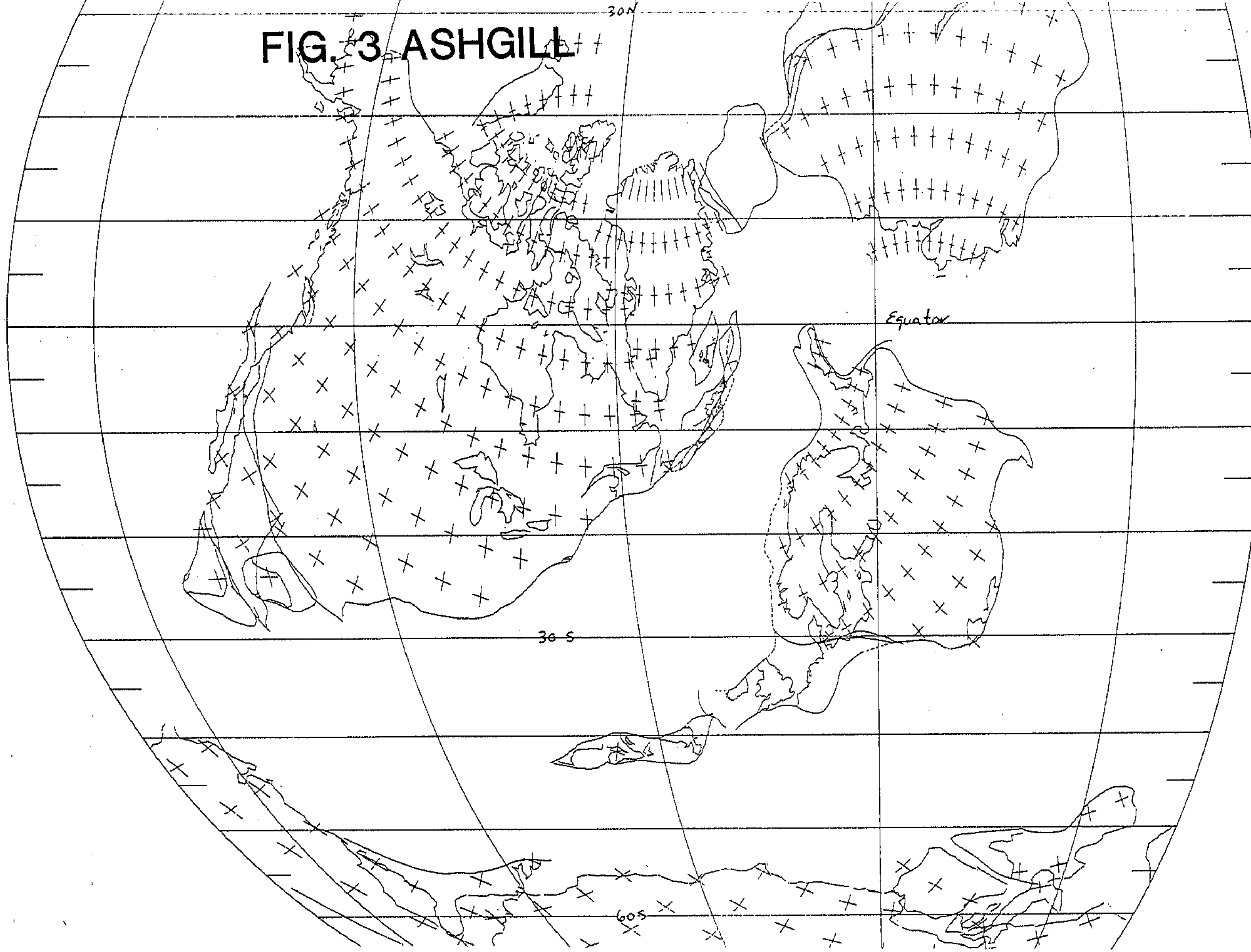


FIG. 3 ASHGILL



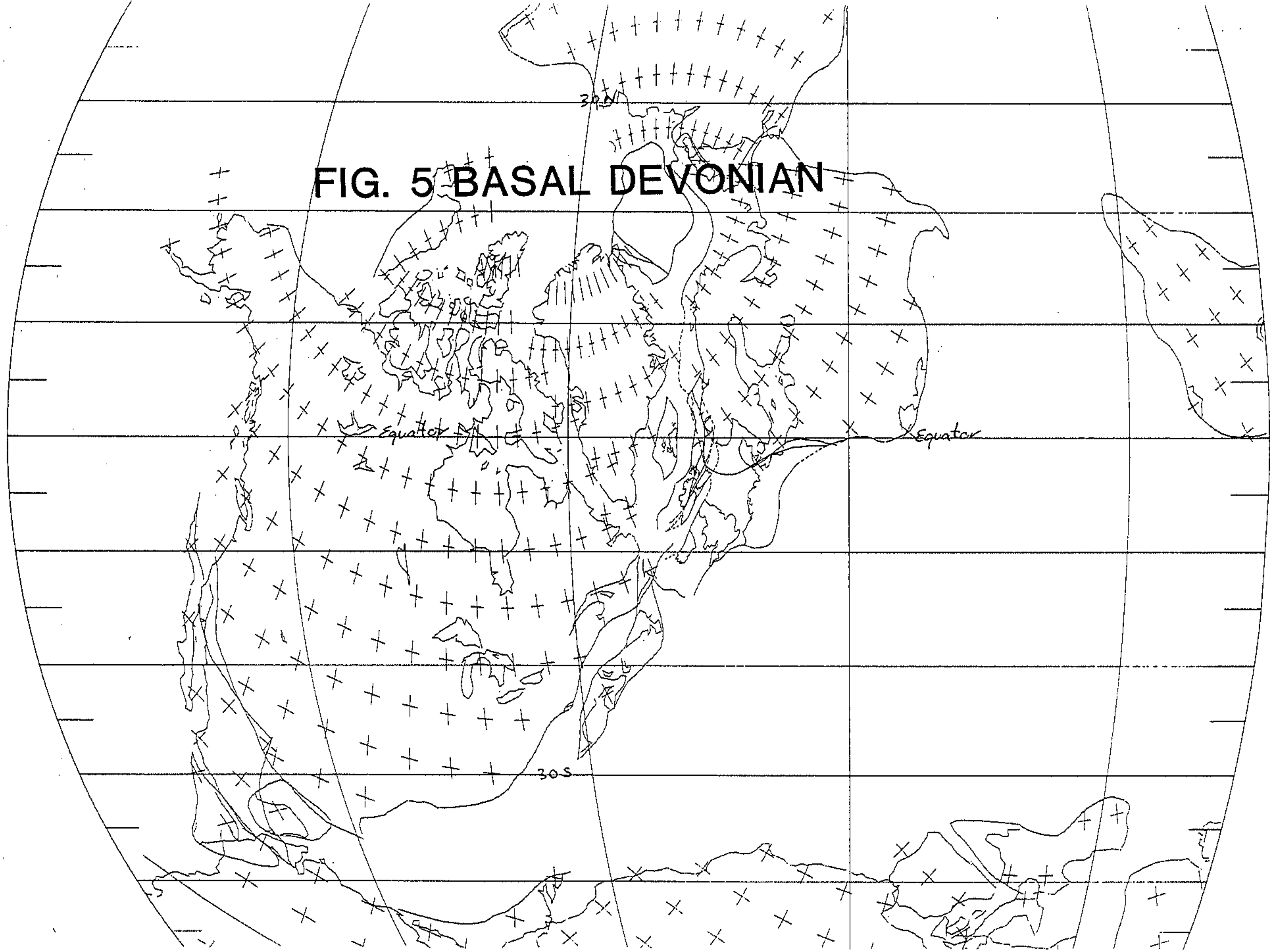
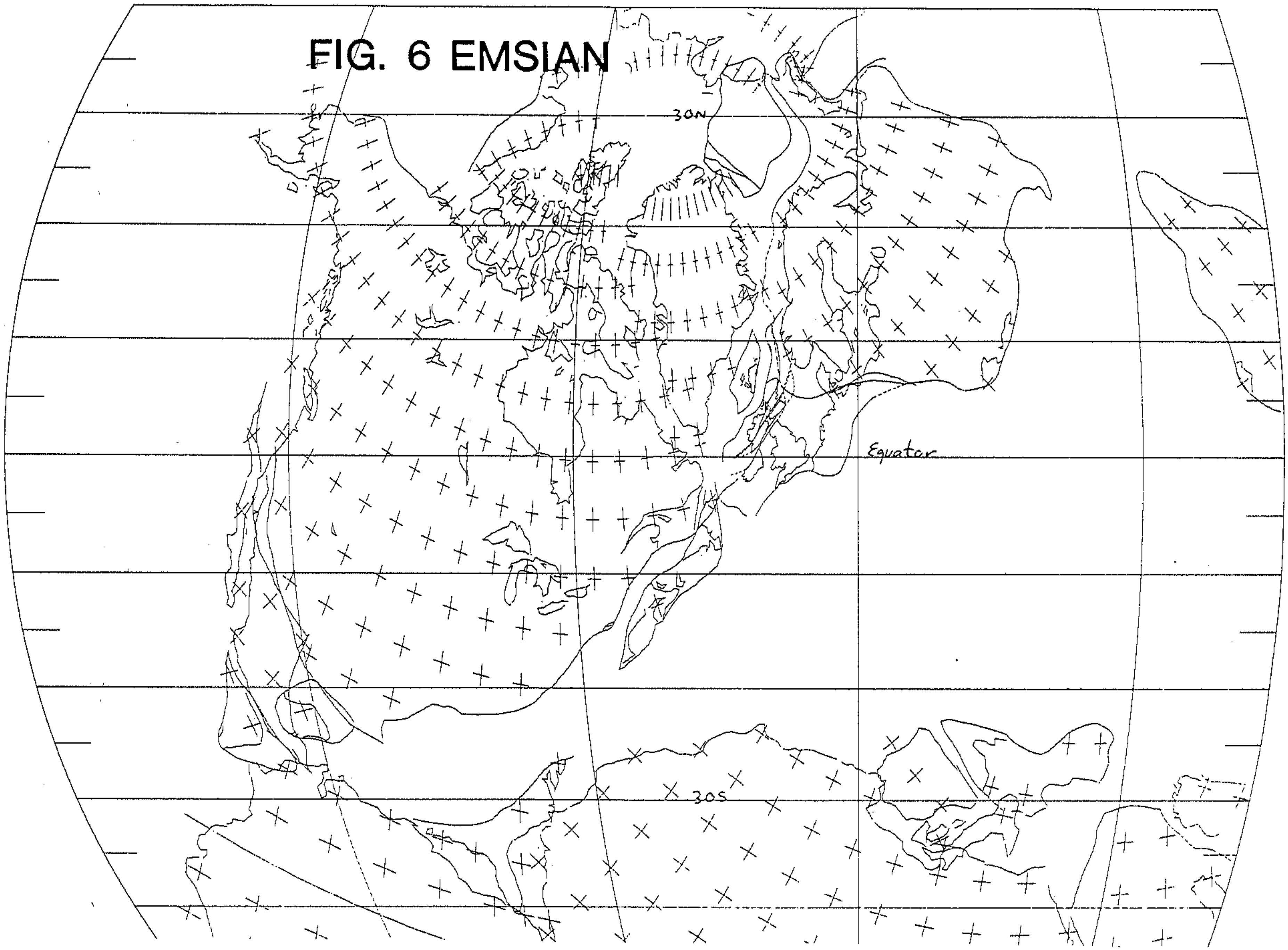


FIG. 5 BASAL DEVONIAN
30N
Equator
Equator
30S

FIG. 6 EMSIAN



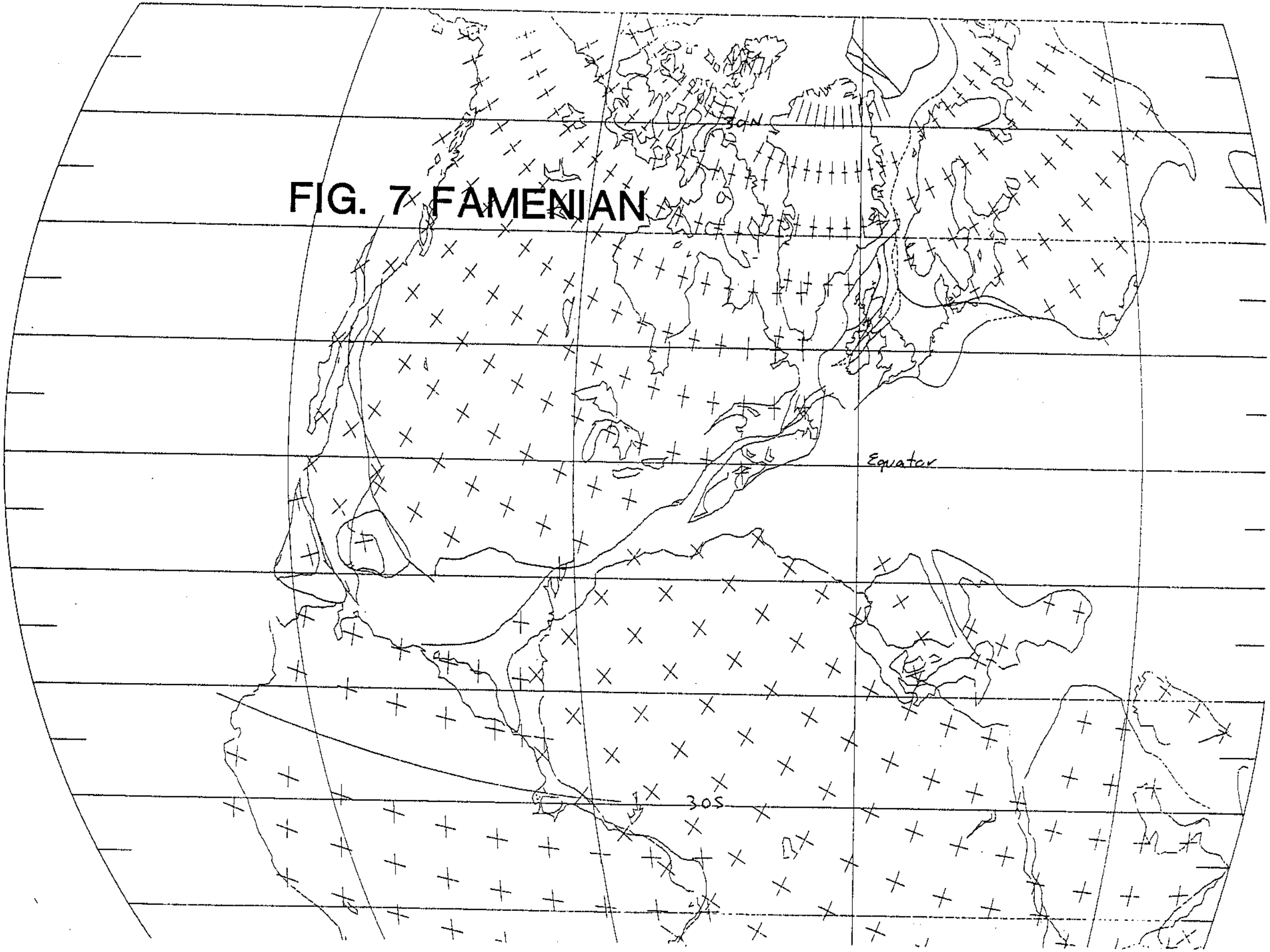


FIG. 7 FAMENIAN

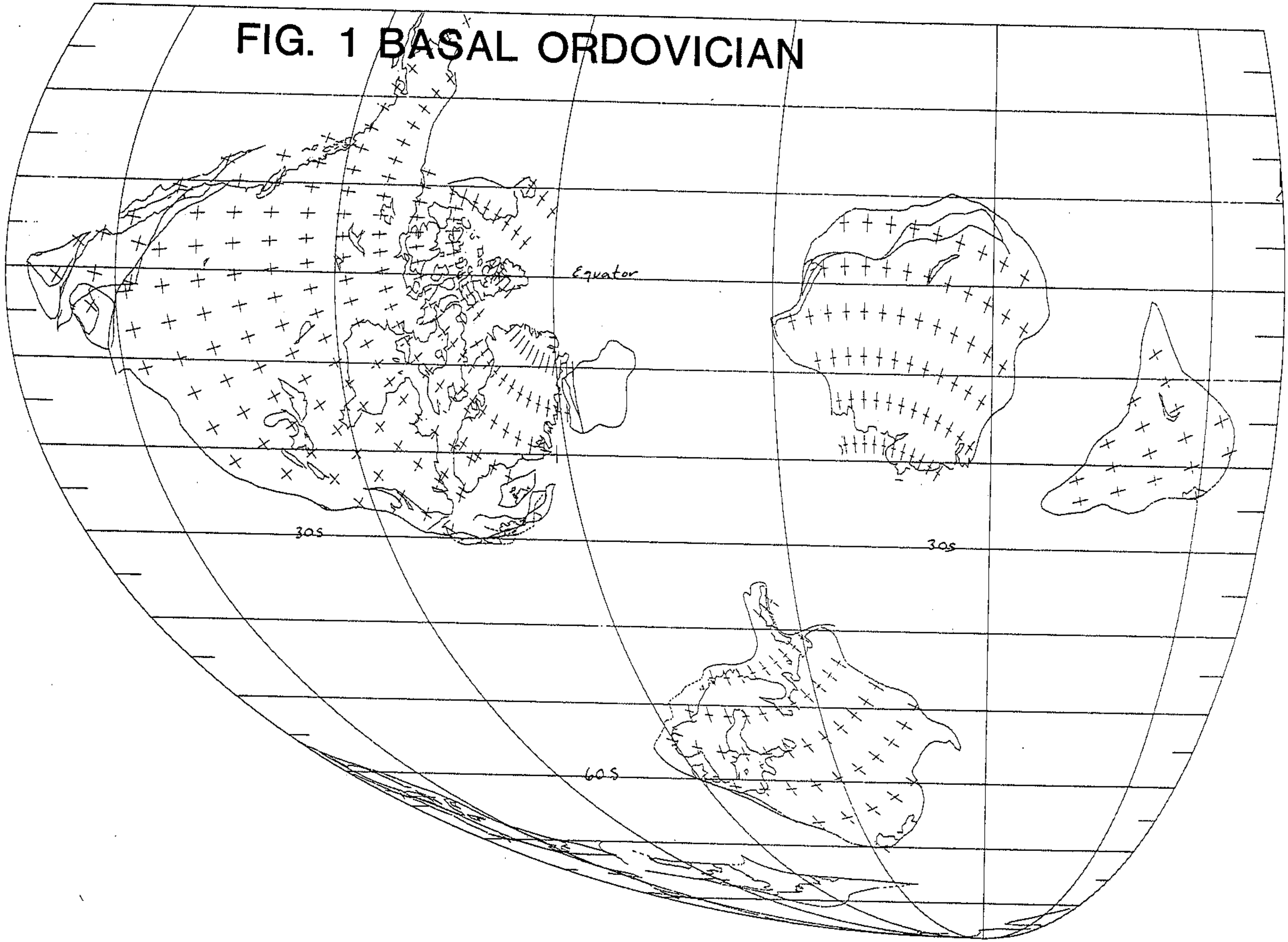


FIG. 1 BASAL ORDOVICIAN

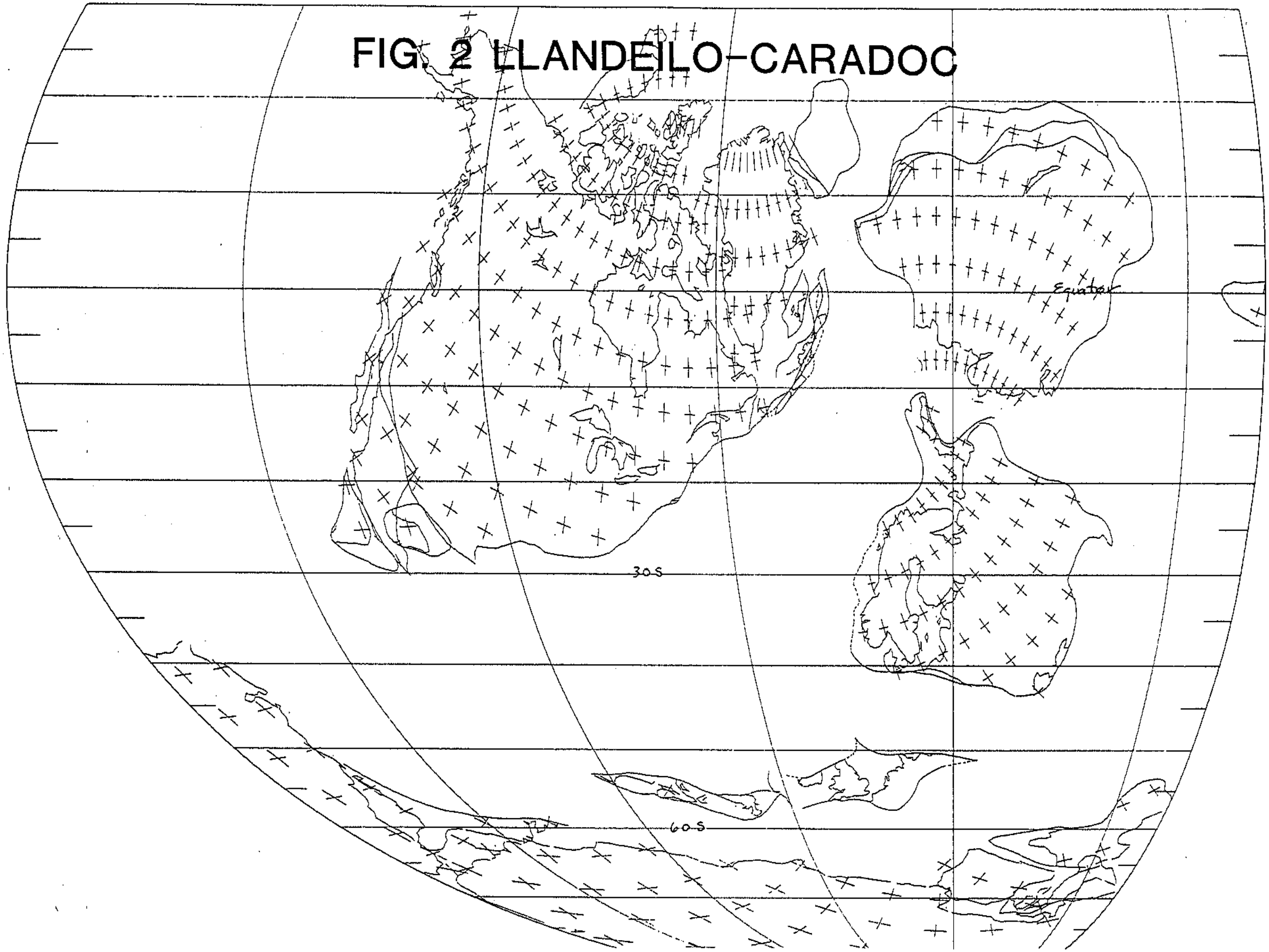


FIG. 2 LLANDEILO-CARADOC

FIG. 4 WENLOCK

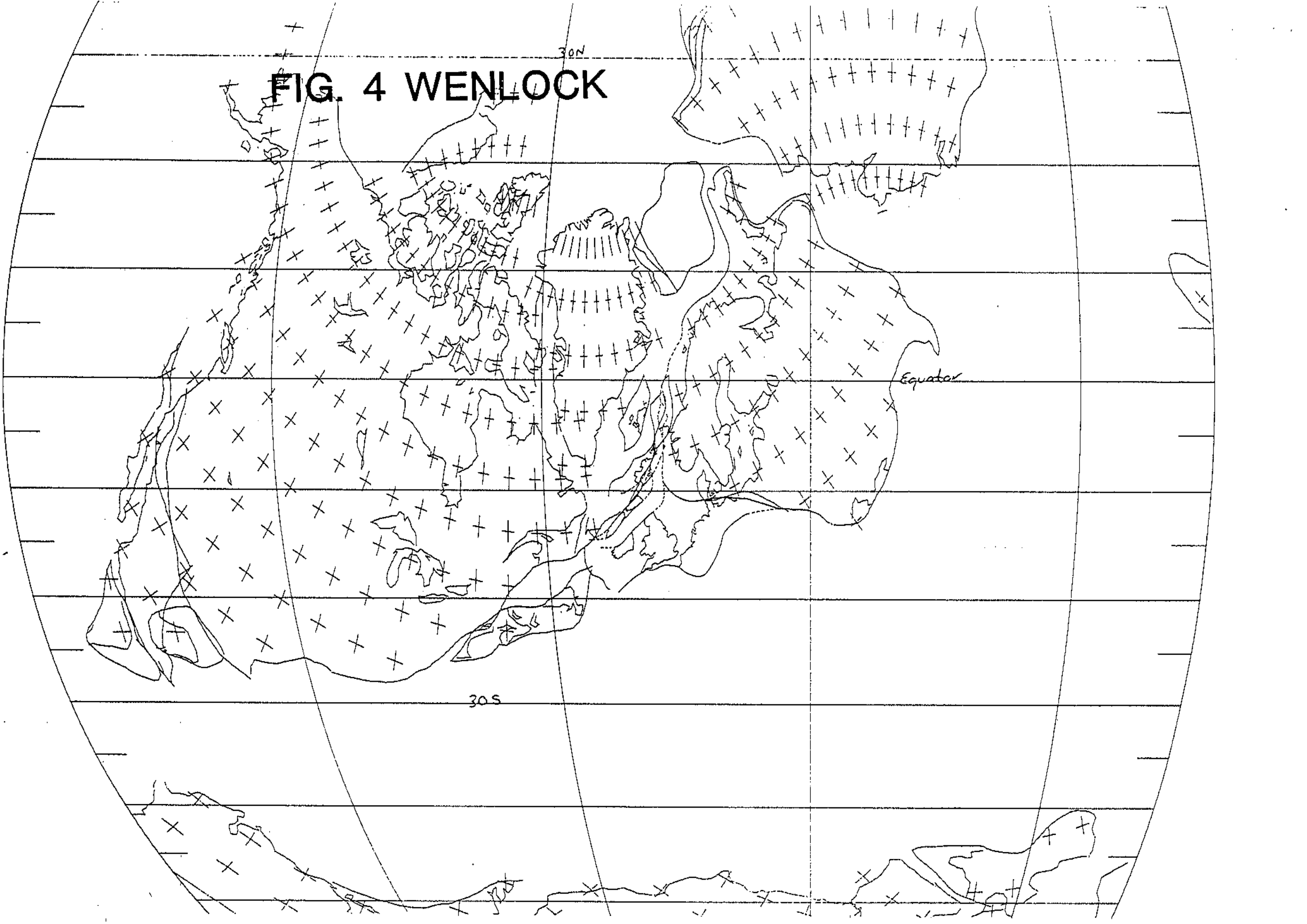
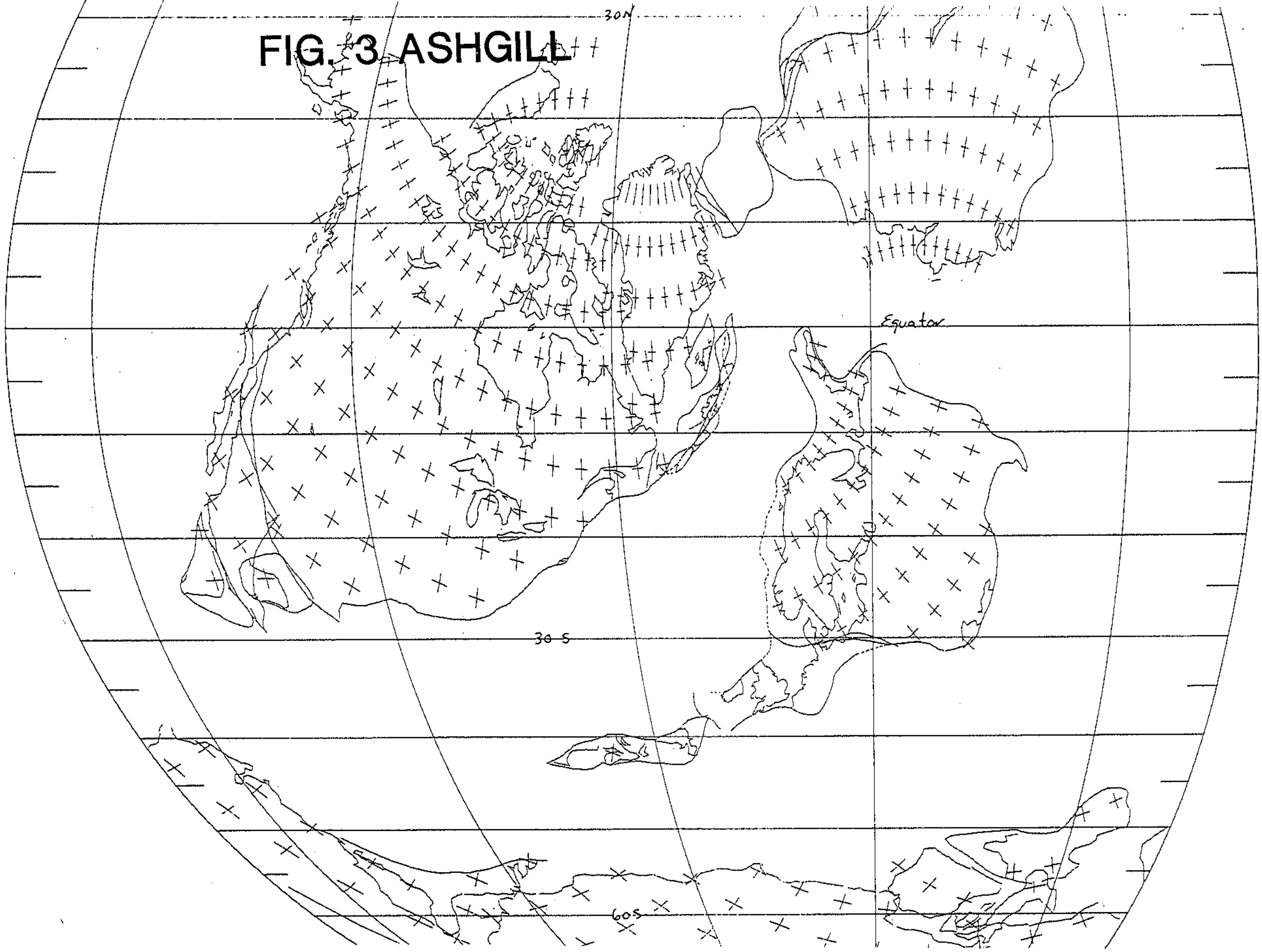


FIG. 3 ASHGILL



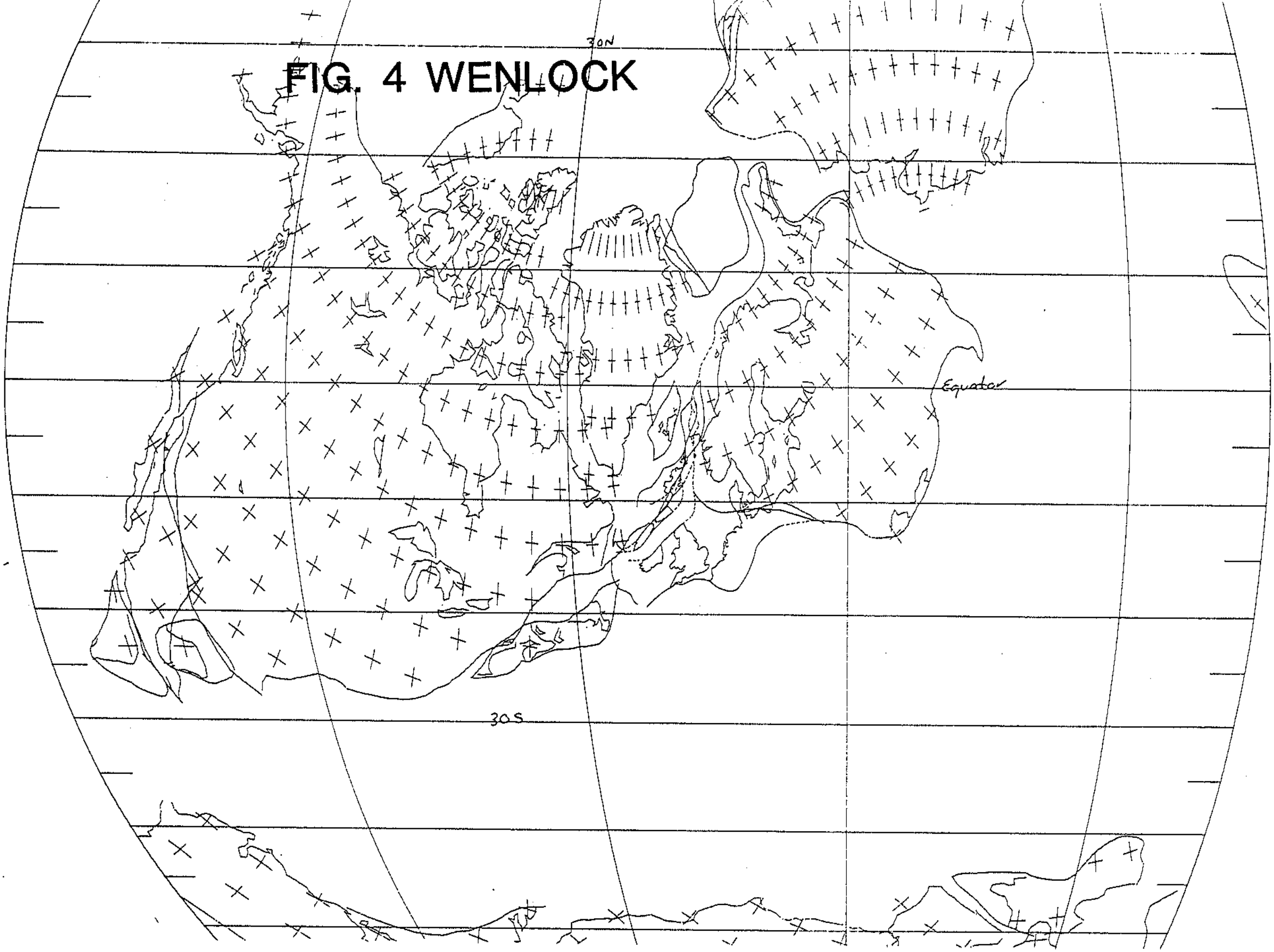


FIG. 4 WENLOCK

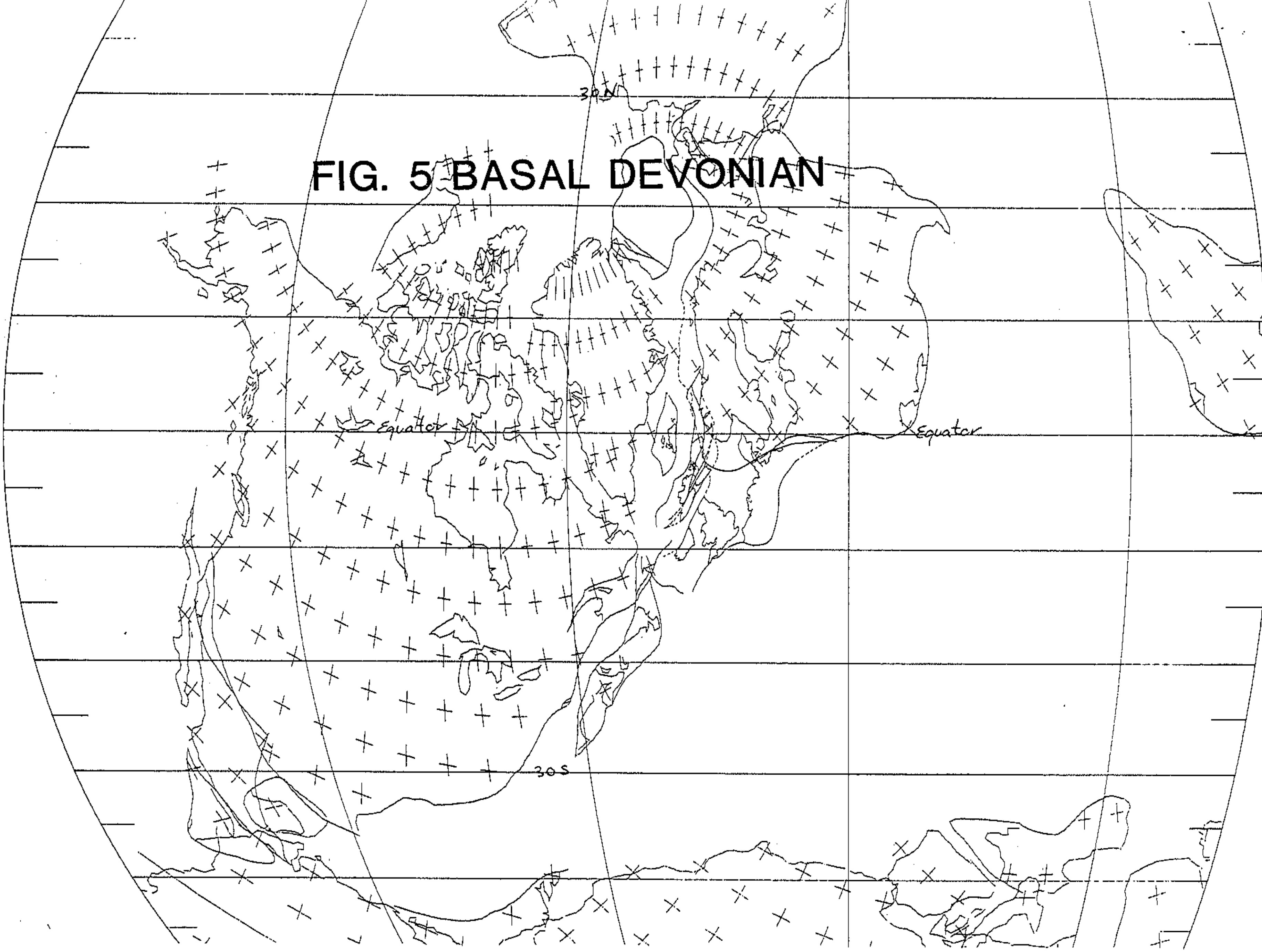
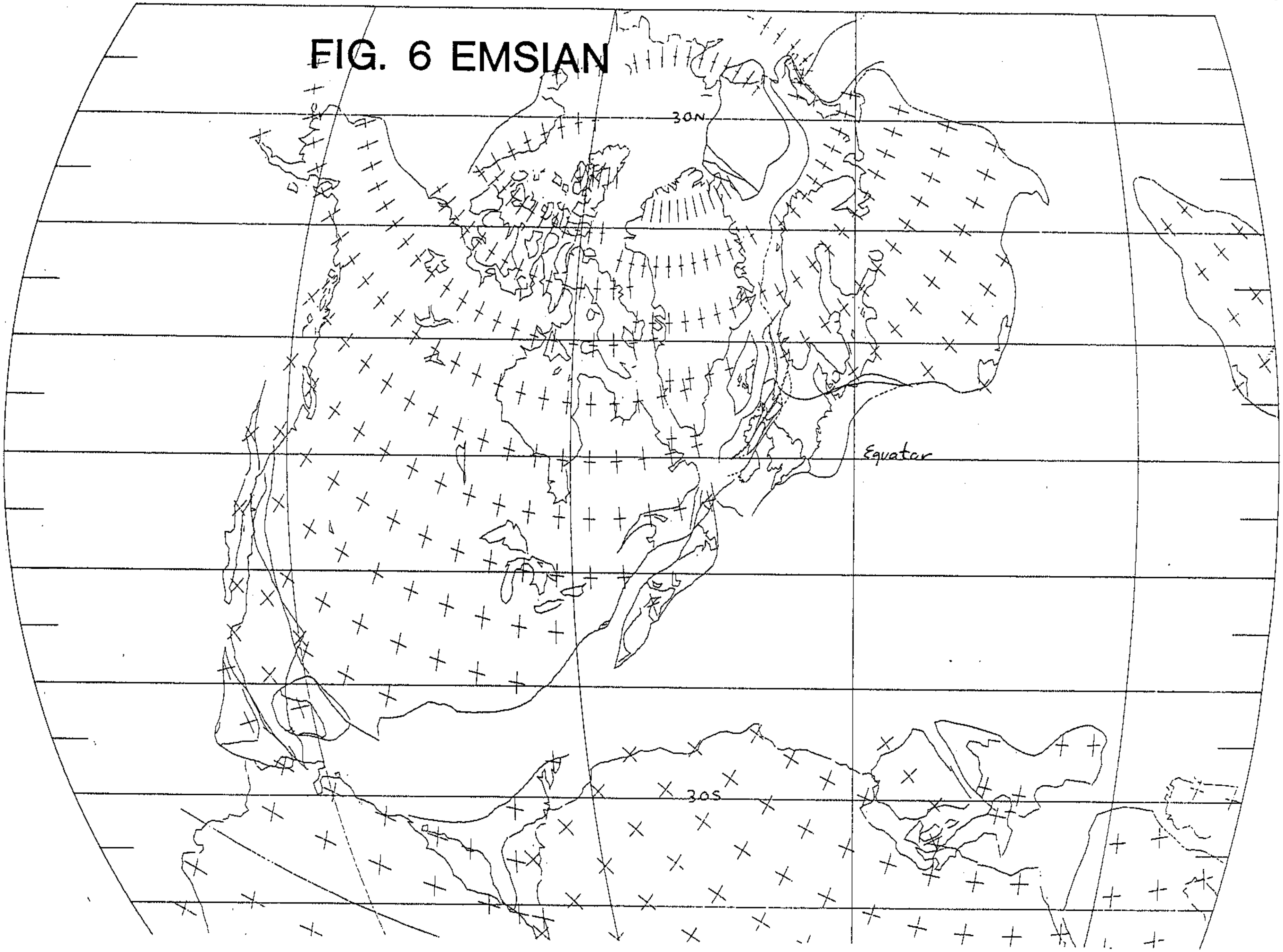


FIG. 5 BASAL DEVONIAN

FIG. 6 EMSIAN



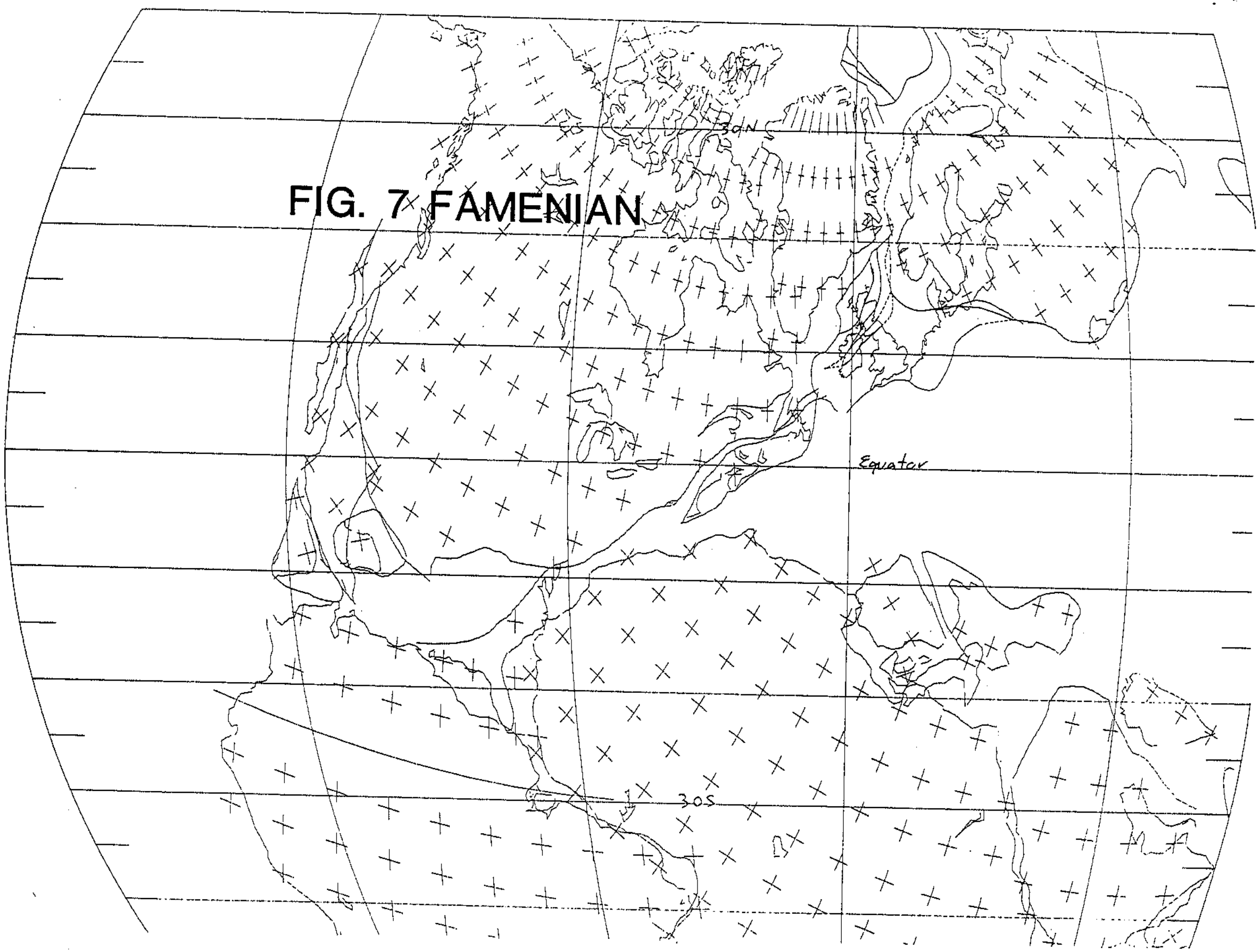


FIG. 7 FAMENIAN
30N
Equator
30S