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Precisely locating the Ordovician equator in Laurentia

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ABSTRACT

The Late Ordovician equatorial zone, like the zone today, had few hurricane-grade storms within 10° of the equator, as emphasized by the preservation of massive-bedded *Thalassinoides* ichnofacies in a trans-Laurentian belt more than 6000 km long, from the southwestern United States to North Greenland. That belt also includes nonamalgamated shell beds dominated by the brachiopod *Proconchidium*, which would not have been preserved after hurricane-grade storms. The belt lacks such storm-related sedimentary features as rip-up clasts, hummocky cross-stratification, or large channels. In contrast, other contemporaneous Laurentian *Thalassinoides* facies and shell beds on either side of the belt have been disturbed by severe storms below fair-weather wave base. The position of the biofacies-defined equatorial belt coincides with the Late Ordovician equator deduced from paleomagnetic data from Laurentia, thus providing both a high-precision equatorial location and an independent test of the geocentric axial dipole hypothesis for that time.

INTRODUCTION

During much of the Ordovician and Silurian Periods, Laurentia was flooded extensively by epicontinental seas; the abundant, climate-sensitive fossils and sedimentary rocks have been used for the general differentiation between warm-water and cool-water settings, yet its fossils have not previously been applied to pinpointing the equatorial zone.

Today's equatorial zone hosts most of the world's biodiversity epicenters; for example, the coral reefs of Indonesia (within 10° of the equator) have a notably higher coral diversity than the higher latitude Great Barrier Reef of Australia or the Caribbean reefs (Roberts et al., 2002; Marshall, 2006; Kiessling et al., 2010). Several characteristics of the modern equatorial zones, such as the lack of seasonality and hurricanes, have the potential to be recognized in the rock and fossil record. The hurricane record of the Atlantic and east Pacific regions for the past 160 yr (National Oceanic and Atmospheric Administration, 2011) shows that tropical storms and hurricanes are usually absent within 10° north and south of the equator (the doldrums) because of the weak Coriolis force (Fig. 1). In that hurricane-free equatorial zone, disturbances of seafloor sediments and biota are mostly limited to relatively weak waves and currents generated by trade winds and tides. In contrast, strong hurricanes or cyclones chiefly occur in the tropics on both sides of the equatorial zone, between lat 10° and 30°, and are capable of generating long-period waves that can disturb and rework sediments to 120 m or deeper. Sedimentary features known to be generated by such storms include hummocky cross-stratification and amalgamated shell coquinas

associated with segregated mud drapes, scoured bases, and graded bedding that are redeposited by severe storms between the fair-weather wave base and the maximum storm wave base (usually 15–120 m).

Because cold, south polar regions with permanent ice caps existed during the Late Ordovician and Early Silurian, it is plausible that the Late Ordovician temperature gradient between the polar and tropical areas, and therefore the hurricane pattern, was similar to the modern gradient and pattern. Here we show that an extensive hurricane-free equatorial zone can be

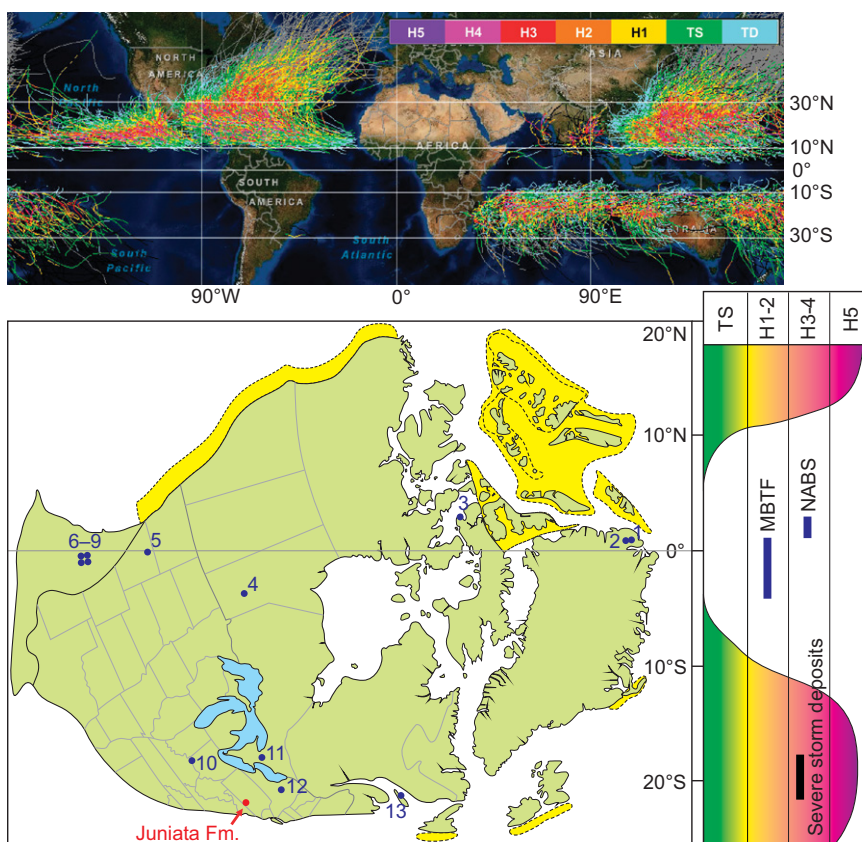


Figure 1. Occurrences of Late Ordovician massive-bedded *Thalassinoides* facies (MBTF) and nonamalgamated brachiopod shell beds (NABS) in paleocontinent of Laurentia and juxtaposed hurricane-free latitudes in today's climate belts. Paleogeography of Laurentia is based on Cocks and Torsvik (2011). Recent hurricane data (A.D. 1842–2009) are from National Hurricane Center (National Oceanic and Atmospheric Administration, 2011). Hurricane categories are based on maximum sustained wind and depicted using same color scheme as National Oceanic and Atmospheric Administration (2011). MBTF localities—1 and 4–9; NABS localities—2, 3; severe storm deposit localities—10–13. H1–H5—category 1–5 hurricanes; TS—tropical storm; TD—tropical depression.

recognized across a relatively narrow band in the Late Ordovician rocks of Laurentia, indicating the position of the paleoequator there, and independently corroborating the equator indicated by paleomagnetism for that time.

KEY ROCKS AND FOSSILS

Massive-Bedded *Thalassinoides* Facies

Along more than 6000 km from the Great Basin in the southwestern United States, through the Williston Basin (northern Wyoming, USA, and southern Manitoba, Canada), to the Franklinian Basin in North Greenland, the distinctive massive-bedded *Thalassinoides* facies (MBTF) is characterized by individual bed thickness of 1 m or more, and occurs commonly in Upper Ordovician carbonate rocks (Jin et al., 2012; Figs. 1 and 2; see Fig. DR1 in the GSA Data Repository¹). The MBTF differs from the more common thinner and/or irregularly bedded

Thalassinoides ichnofacies in several aspects, and it accumulated in a depositional environment that has apparently contradictory attributes (i.e., relatively shallow, open-marine water, but with a substrate seldom disturbed by severe storms), as indicated by the following sedimentological and biological features. (1) There is a predominance of broad-based, low-profiled colonies of hermatypic corals and stromatoporoid sponges, commonly preserved in life position with relatively rare disorientation or overturning, and the soccer-ball-sized calcareous alga *Fisherites* is also common; those photoautotrophic or photosymbiont-bearing fossils constrain the depositional setting to shallow water and within the upper photic zone. (2) There is a lack of hummocky cross-stratification or prominent scoured or channelled bases. (3) Intercalation between amalgamated coquina beds and mud drapes is lacking. (4) There is a lack of rip-up clasts; the pervasive distribution of *Thalassinoides* burrow

galleries is usually thought to have been maintained in a carbonate firmground, but disturbed or redeposited clasts (either of carbonate mud or burrowed matrix) are rare in MBTF. (5) The massive beds tend to be laterally continuous and consistent, and truncations of deep burrows (to 1 m) are rare within individual beds.

MBTF is also found in the Great Basin on a carbonate platform on the passive margin of western Laurentia, where it was bounded by a carbonate ramp leading to deep oceanic waters to the northwest. The carbonate platform is ~250 km wide in modern outcrop, but was somewhat narrower originally because of tectonic extension in the Cenozoic.

These MBTF characteristics define a narrow ecological window for its accumulation at a water depth below the fair-weather wave base (to avoid destruction of the burrow galleries), but above the level of oxygen starvation to maintain the oxygenation within the deep burrows (Fig. 2). The MBTF window must also have been free of severe storms (wave base down to 120 m depth). In that Late Ordovician, hurricane-free, relatively shallow water equatorial environment, the burrow galleries must have remained intact for tens or perhaps hundreds of years, until they were solidified during early diagenesis. The lack of destruction and redeposition by storms would have favored the vertical continuity of the burrow system and prevented the formation of storm-generated bedding planes, because the burrowing activities of deposit feeders obliterated subtle laminations within each bed. The interpretation of a stable depositional setting is supported by the uniform pattern of the MBTF, which persists vertically through tens of meters of strata and laterally over a very large region. For example, over the extensive carbonate platform in the eastern Great Basin the MBTF has been recognized as a distinct shallow-water facies in shallowing-upward sequences just below cyclical laminite facies, with fenestral fabrics that are capped by hardgrounds, and the depositional environment was interpreted to be a subtidal shelf above storm wave base by Harris and Sheehan (1996). *Thalassinoides* facies would also have originally formed above the fair-weather wave base in the equatorial belt, but substrate disturbances by fair-weather waves would have resulted in thinner and irregularly bedded *Thalassinoides* beds (Fig. 2E), such as those in North Greenland and southern Manitoba, where the Upper Ordovician beds that occur above the MBTF interval, interpreted as of shallower water origin near the fair-weather wave base, are much thinner and wavy bedded (Fig. DR2 in the Data Repository). In higher tropical latitudes, MBTF could not form above either the fair-weather wave base or the severe-storm wave base (Fig. 2).

In this study it is crucial to differentiate true MBTF facies from other thinner bedded

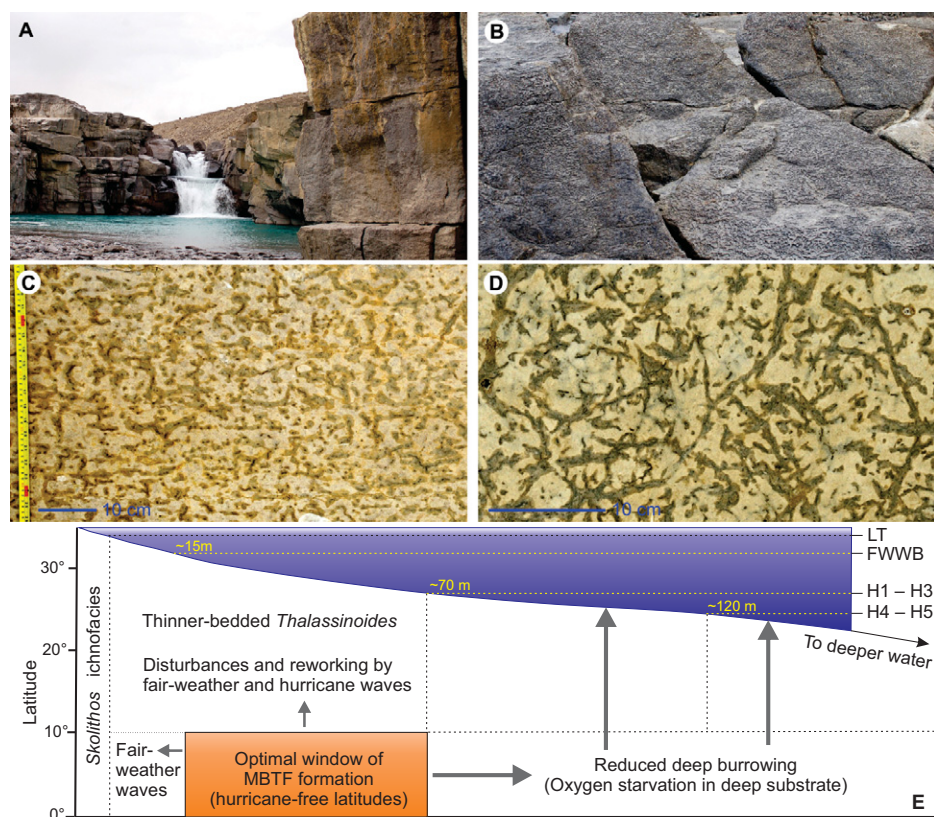


Figure 2. Massive-bedded *Thalassinoides* facies (MBTF) along paleoequator of Laurentia. **A, B:** Upper Børglum River Formation (upper Katian), Børglum Elv, Peary Land, North Greenland; individual bed thickness is ~1 m. Thickness of individual beds in foreground of **A** is ~1 m; image width of **B** is ~2 m. **C, D:** Selkirk Member, Red River Formation (upper Katian), Garson Quarry, southern Manitoba; quarry wall is cut perpendicular to bedding plane (**C**), and Tyndall Stone slab is cut parallel to bedding plane (**D**). **E:** Interpreted optimal paleoenvironmental window of MBTF with three controlling factors: shallow-water substrate with sufficient oxygen, lack of hurricanes, and absence of fair-weather wave disturbances. FWWB—fair-weather wave base; H1–H5—storm wave bases of category 1–5 hurricanes; LT—low tide mark.

¹GSA Data Repository item 2013026, supplementary introduction and methods, Figures DR1–DR4, and Table DR1, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Thalassinoides ichnofacies, as MBTF do not occur in any part of Laurentia other than in the belt we have plotted as the inferred storm-free paleoequator. For example, the Upper Ordovician and basal Silurian carbonate strata of the Anticosti Basin (located nearly 20° south of the paleoequator, well within the hurricane zone; Figs. 1 and 3) contain abundant hummocky stratification associated with graded bioclastic beds and centimeter- to meter-scale scoured bases and mud drapes, but lack MBTF (Long, 2007; Jin, 2008).

Nonamalgamated Brachiopod Shell Beds

The Upper Ordovician carbonate succession in the G.B. Schley Fjord region of North Greenland is >400 m thick and contains recurrent shell beds composed almost entirely of the pentameroid brachiopod *Proconchidium* (Harper et al., 2007). In addition to their monospecific composition and temporal persistence through the upper half of the succession, the shell beds have several striking characteristics (Fig. 3; see also Figs. DR2 and DR3): (1) the shells are overwhelmingly represented by large, extremely thickened ventral valves only, randomly distributed in a matrix of micritic mudstone and wackestone, and without signs of shell concentration by mud winnowing; (2) the large, rostrate, and

prominently thickened ventral valves are commonly preserved in situ or close to a weighted beak-down or concave-down life position; in contrast, dorsal valves or even their fragments are very rare. This suggests that the smaller and thinner dorsal valves must have been preferentially winnowed away by relatively weak waves and currents that were not powerful enough to remove the larger and heavier ventral valves. (3) Like MBTF, the shell beds are associated with the large calcareous alga *Fisherites* and stromatoporoid sponges; those photosynthetic or photosymbiont-bearing taxa constrain the shell beds to a shallow-water depositional setting well within the photic zone. (4) Sedimentary structures generated by hurricane-grade storms, such as hummocky cross-stratification, graded bedding, amalgamation of shells, and segregation of mud drapes, are absent.

Therefore, nonamalgamated brachiopod shell beds were generally deposited under shallower water than MBTF. The thick *Proconchidium* shell beds, correlatives of the lower Turesø and Alegatsiaq Fjord Formations in North Greenland, can be traced to coeval strata in the Bailarge Formation on Brodeur Peninsula, Baffin Island, northeastern Canada (Harper et al., 2007), where the shell beds are also dominated by ventral valves of *Proconchidium*. In the more

southern areas (localities 10–13 in Fig. 1), hurricane deposition has been commonly recognized in Upper Ordovician to basal Silurian carbonate strata, from the Anticosti Basin, through New York, Pennsylvania, southern Ontario, to the Cincinnati Arch region. For example, the abundant Early Silurian *Virgiana* shell beds from Anticosti Island and many other sites, that were comparable to the Upper Ordovician *Proconchidium* shell beds, have prominent hurricane-generated structures, including centimeter- to meter-wide scoured or channeled bases, graded bedding, convex-up stacking of disarticulated valves, and pervasive hummocky cross-stratification in both the concentrated shell beds and the interbedded drapes of carbonate mud (Fig. 3; Fig. DR4).

Therefore, the sedimentological and faunal data indicate that the *Proconchidium* nonamalgamated brachiopod shell beds accumulated in shallow, open-marine settings in the photic zone and near fair-weather wave base; this constrains their preservation, like MBTF, to the hurricane-free equatorial zone.

PALEOMAGNETISM AND THE LATE ORDOVICIAN EQUATOR

Paleomagnetic studies for Paleozoic geographical reconstructions have relied heavily on data from a small number of suitable continental rocks. In Laurentia, paleomagnetic data of good quality are scarce for the Ordovician and Silurian Periods, and only 8 paleomagnetic results spanning 490–420 Ma are available for Laurentia (Torsvik et al., 1996). There is a 40 m.y. gap in the paleomagnetic record between 465 and 425 Ma (Middle Ordovician–Early Silurian); the positions and orientations of Laurentia for this interval have been interpolated, hindering the detailed positioning of this large tectonic plate and limiting previous study of its biodiversity gradient to a broad division of tropical versus extratropical biotas in those times.

The paleomagnetic technique is dependent on the assumption that the Earth's dynamo has a time-averaged dipole geometry that is geocentric and coaligned with the Earth's spin axis, known as the geocentric axial dipole hypothesis. That has been applied successfully to reconstructions from the late Paleozoic to the Cenozoic (e.g., Dominguez et al., 2011), but its existence for Ediacaran through Devonian time is open to question (Evans, 2006). Limited paleomagnetic data from Gondwana place sedimentary deposits related to the Hirnantian (Late Ordovician) glaciation approximately in the paleomagnetically determined south polar region (Evans, 2003). We argue that, for Laurentia, the Late Ordovician ecological and paleomagnetic indicators of the equatorial zone (MBTF and nonamalgamated brachiopod shell beds) coincide, and thus conclude that the geocentric axial dipole was operative then. The position of the

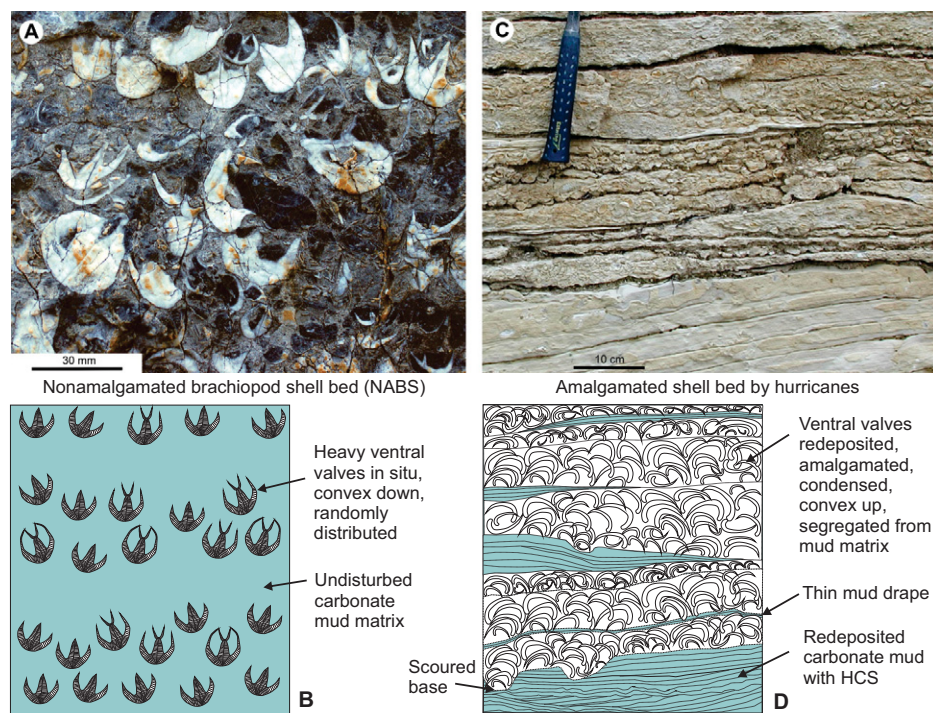


Figure 3. Comparison between nonamalgamated brachiopod shell beds (NABS) and shell beds amalgamated by hurricanes. **A, B:** *Proconchidium* shell beds (upper Katian), G.B. Schley Fjord, Peary Land, eastern North Greenland. Coquinas are dominated by randomly oriented to in situ, extremely thickened ventral valves in undisturbed, organic-rich carbonate mud. **C, D:** *Virgiana* shell beds, lower Becscie Formation (basal Silurian), Anticosti Island, eastern Canada. Note pervasive hummocky cross-stratification (HSC), scoured and channeled base, and segregation and/or amalgamation of shells from draping mud, all typical structures generated by severe storms (Fig. DR4; see footnote 1).

South Pole is determined using the coordinates of the MBTF and nonamalgamated brachiopod shell bed localities in North Greenland (restored to pre-rift North American coordinates; Cocks and Torsvik, 2011), southern Manitoba, and the southwestern United States; the beds extended 6000 km across Laurentia from the ancient eastern to western continental margins (Fig. DR5).

From Cambrian to Middle Ordovician time (532–465 Ma), poles determined from reliable paleomagnetic data form an apparent polar wander path (APWP) that places Laurentia at the paleoequator, with some counterclockwise rotation (Fig. DR5B). That is followed by a 40 m.y. paleomagnetic data gap prior to the Wenlock (425 Ma) Rose Hill Formation (Table DR1; Cocks and Torsvik, 2011). Within the gap, the Late Ordovician (445 Ma) Juniata Formation offers a useful inclination-only paleolatitudinal constraint for the Iapetus margin of Laurentia, although its structural complexity precludes the calculation of a paleomagnetic pole. The Juniata red beds are exposed in both regional limbs of the Pennsylvania embayment and have an overall tilt-corrected inclination that indicates deposition at $26^{\circ}\text{S} \pm 12^{\circ}$ paleolatitude (Miller and Kent, 1989). When the paleomagnetic colatitude swath of permissible Juniata pole positions is plotted with $\pm 12^{\circ}$ latitudinal uncertainty for comparison with the Late Ordovician South Pole position derived from MBTF and nonamalgamated brachiopod shell bed localities, the 2 coeval and independent estimates agree well within the errors of both methods, in terms of the pole position and in the trajectory of the Laurentian APWP (see Fig. DR5B). This result confirms the previous APWP interpolation within the 40 m.y. data gap, in which Laurentia was projected to straddle the equator and undergo continued counterclockwise rotation during the Late Ordovician and Early Silurian.

The agreement of the paleoecologically determined Late Ordovician South Pole with the Ordovician–Silurian APWP and with that derived paleomagnetically from the Late Ordovician Juniata red beds indicates that the geocentric axial dipole assumption is likely valid for the Ordovician and Silurian Periods. The singular Juniata result also appears to rule out a significant octupolar contribution of $\sim 19\%$ relative to the dipole in the Late Ordovician (Evans, 2006) in which paleomagnetic directions from subtropical to mid-latitude locations would be anomalously shallowed. The Juniata geocentric axial dipole paleomagnetic paleolatitude of 26°S

$\pm 12^{\circ}$ is in agreement with the expected $22.1^{\circ}\text{S} \pm 13.5^{\circ}$ paleolatitude of the Juniata Formation location, assuming the biologically determined paleoequator and its South Pole to be correct, whereas a 19% octupolar contribution would result in an apparent paleomagnetic paleolatitude for Juniata of just 14°S . A more robust test to assess possible nondipole contributions (e.g., Dominguez et al., 2011) to the Late Ordovician geomagnetic field, however, requires more contemporaneous paleomagnetic results over a wider latitudinal range than is available from Laurentia alone. The most reasonable interpretation is that the geocentric axial dipole hypothesis holds true for the Ordovician and Silurian.

CONCLUSIONS

The Late Ordovician massive-bedded *Thalassinoides* facies and nonamalgamated brachiopod shell beds of Laurentia indicate the existence of an equatorial, hurricane-free climate belt. A comparison with recent hurricane records suggests that these biofacies are indicators of tropical latitudes within 10° of the equator. The coincidence of both the paleoecologically and paleomagnetically determined positions of the Late Ordovician equator also confirms the validity of the geocentric axial dipole assumption for the Late Ordovician and Early Silurian.

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