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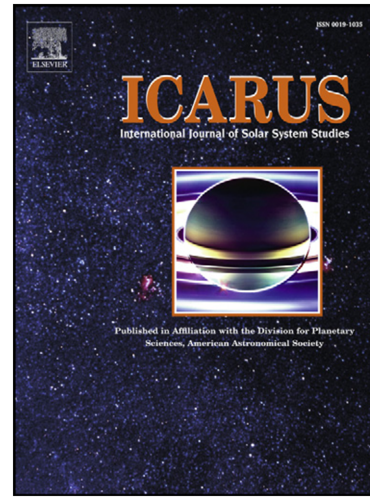

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Beagle Rupes – evidence for a basal decollement of regional extent in Mercury's lithosphere

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Abstract

Thanks to its location at low latitude and close to the terminator in the outbound view of Mercury obtained during MESSENGER's first flyby, the Beagle Rupes lobate scarp on Mercury has been particularly clearly imaged. This enables us to interpret it as a component of a linked fault system, consisting of a frontal scarp terminated by transpressive lateral ramps. The terrain bounded by these surface manifestations of faulting is the hanging-wall block of a thrust sheet and must be underlain by a basal decollement (a detachment horizon) constituting the fault zone at depth. The decollement must extend a minimum of 150 km eastwards from the frontal scarp, and at least 400 km if displacement is transferred to features interpreted as out-of-sequence thrusts and offset lateral ramps that appear to continue the linked fault system to the east. The depth of the basal decollement could be controlled by crustal stratigraphy or by rheological change within, or at the base of, the lithosphere. Previous interpretations of mercurian lobate scarps regard their thrusts as uniformly dipping and dying out at depth, lacking lateral ramps and any extensive detachment horizon. Anticipated improvements in image resolution and lighting geometry should make it possible to document what percentage of lobate scarps share the Beagle Rupes style of tectonics.

Keywords

MERCURY, INTERIOR

MERCURY, SURFACE

TECTONICS

1. Introduction

It is apparent from study of images returned by Mariner 10 (Dzurisin 1978; Thomas et al., 1988) and MESSENGER (Solomon et al., 2008; Watters et al., 2009a) that Mercury's tectonic history is complex. Visible tectonic features mostly post-date smooth plains emplacement, but are older than some post-Calorian impact craters. Mercury's most characteristic tectonic features are its lobate scarps, which are generally interpreted to represent the surface expressions of thrust faults recording a cooling-related decrease in global radius (Strom et al., 1975; Melosh and McKinnon, 1988). North-south trending scarps near the equator may have exploited weaknesses previously developed as a result of relaxation of the planet's equatorial bulge during tidal despinning (Burns, 1975; Melosh and Dzurisin, 1978; Dombard and Hauck, 2008).

Neither a single episode nor a single mechanism is adequate to explain Mercury's tectonics, even if we focus on features classified as lobate scarps, setting aside such clearly diverse features as the extensional troughs within Caloris and other basins (Murchie et al., 2008; Freed et al., 2009; Prockter et al., 2009; Watters et al., 2009b) and the relatively small-scale wrinkle ridges best expressed in the lavas of the smooth plains (Strom et al., 1975; Head et al., 2008). Here we assess the fault geometry associated with Beagle Rupes (Figure 1), a prominent lobate scarp imaged by MESSENGER during the outbound stage of its January 2008 fly-by (Solomon et al., 2008). We show that Beagle Rupes displays several features diagnostic of a thrust fault with a basal decollement (or 'detachment horizon'). Similar features are hinted at in images of a few other lobate scarps on the planet. Improved imaging of these other examples by MESSENGER and BepiColumbo could indicate that basal decollements play a role in the formation of a significant percentage of the lobate scarps on Mercury.

2. Beagle Rupes – a linked fault system

Beagle Rupes consists of a north-south trending segment, some 260 km in length, displaying characteristics common to mercurian lobate scarps in general (line A-B on Fig. 1b). This segment consists of two arcs, convex towards the downward side (foot-wall terrain) of the scarp, and joined at a cusp in a manner similar to some of the examples (such as Discovery Rupes) that were first distinguished by Dzurisin (1978) as 'arcuate lobate scarps'. Like them it is almost certainly a surface expression of thrusting (a frontal scarp), which, given the facing direction of the scarp and its asymmetric topographic profile with a steep western slope, would indicate a westward motion ('top up to the west' kinematics).

However scarp height (and hence inferred displacement) does not taper off to zero at either end of this segment, in contrast to most other previously described examples (Watters et al., 2002). Instead the north-south arcuate segment turns at its north end to become a straight scarp trending approximately east-north-east (B-C on Fig. 1b) and at its south end to become a straight scarp trending approximately east-south-east (A-D on Fig. 1b). We interpret these straight scarps to be lateral ramps (Boyer and Elliott, 1982; Morley, 1986) bounding a thrust sheet. The whole scarp bounds a trapezoid region (D-A-B-C on Fig. 1b) extending at least 200 km eastwards behind the frontal scarp, and measuring at least 470 km from north to south across its poorly-defined, open, eastern limit (C-D on Fig. 1b). Watters et al. (2009a) describe Beagle Rupes as 'over 600 km long', and in doing so are citing distance measured along the entire scarp from D to C via A and B. Shadow measurements suggest a scarp height varying in the range 0.8–1.5 km on the frontal scarp (Watters et al., 2009a). Additional shadowing cast by uplifted pre-existing wrinkle ridges appears to contribute to the higher end of this range, so we favour about 1.0 km as a more reasonable estimate. Given the east-west shortening direction required by the north-south arcuate frontal scarp, it is unlikely that either of the lateral ramps can represent pure compression. In a situation of global contraction each lateral ramp could conceivably accommodate pure shortening normal to its strike direction, but (in addition to any contraction-related shortening across these ramps) westward motion of the thrust sheet that is fronted by the main Beagle Rupes escarpment would require the ramps to accommodate some strike-slip component. This would result in right-lateral transpressive slip along the northern ramp and left-lateral transpressive slip along the southern ramp.

The offset across these straight lateral ramps is likely to decrease with distance behind the frontal scarp, in the well-established manner of fault displacement dying out towards a fault tip (Walsh and Watterson, 1989; McGrath and Davison, 1995; Nicol et al., 1996). However, in our interpretation the visible termini of the ramps do not mark the limit of displaced terrain. About 300 km behind the main scarp, the motion on the southern lateral ramp (A-D) appears to be transferred to three successively overlying scarps (Fig. 2), whose age sequence is shown by cross-cutting relationships. The first two (#1 and #2 in Fig. 2) might be simple lobate scarps but they have some features that lead us to interpret them slightly differently. They are oblique to the assumed westward transport direction of the Beagle Rupes thrust sheet, their relief appears more symmetric than that of classical lobate scarps giving them some similarities to mercurian ‘high relief ridges’ (Dzurisin, 1978; Melosh and McKinnon, 1988; Watters et al., 2009a), but they have irregular width. Their form is most clearly seen where scarp #2 is developed on otherwise relatively featureless smooth plains, where there is a clear bottle neck-like narrowing of the scarp-ridge. These particular morphologies can be interpreted as surface expression of transpressional pop-up and/or positive flower structures, which develop in contractional jogs and restraining bands along segmented faults that are dominated by strike slip kinematics (e.g., Woodcock and Fisher, 1986; Gamond, 1987; Swanson, 2005; Cunningham and Mann, 2007; Mann, 2007). In this example the structures are kinematically compatible with the overall mode of left lateral strike slip motion along the southern boundary of the thrust sheet. The youngest scarp of the three (#3 in Fig. 2) is a more usual lobate scarp, having the form of a frontal thrust associated with an asymmetric fault-bend-fold in the hanging-wall. Watters et al. (2009a, Fig. 9) demonstrate about 2 km of horizontal shortening of a pre-existing 5 km crater cut by this thrust. Scarp #3 cross-cuts scarp #2, just as #2 cross-cuts #1, suggesting out-of-sequence propagation with respect to the Beagle Rupes thrust sheet. Terrestrial 'out-of-sequence' thrusts occur to maintain the dynamic equilibrium of the critical taper of a thrust wedge (e.g., Dahlen, 1999; Selzer et al. 2007) or when forward propagation of a frontal thrust becomes impeded (e.g., Morley, 1988). In a near-global survey of Mercury's tectonics Watters et al. (2009a) map the scarps more conservatively; they describe the easternmost of these three (our #3) only, and pass no comment on any implied age-relationship with Beagle Rupes. The continuous length of the northern lateral ramp (B-C) is only about 150 km, but immediately beyond C (Fig. 1b) two parallel morphostructures (part scarp, part ridge) mark possible transpressive faults to which the motion could be transferred for up to a further 300 km before evidence is obscured below the ejecta blanket from the apparently younger, 100 km, crater Eminescu. The conservative mapping of Watters et al. (2009a) omits these features too.

There is little evidence for the amount of displacement on the frontal scarp. The large impact basin Sveinsdóttir is cut by its southern-to-central part, but, frustratingly, the initial outline of this basin was so elongated (in a northeast-southwest direction) that its current shape provides no evidence for the amount of displacement, nor have we identified any features in the basin wall where cut by the frontal scarp that enable the amount of offset to be estimated. However, based on a single, approximately 17 km, crater cut by the frontal scarp about 30 km north of Sveinsdóttir's northern rim (Fig. 3), Solomon et al. (2008) suggest a shortening of 'at least one to several km' and Watters et al. (2009a) suggest 1 km as a lower limit. The lighting makes it impossible to locate the eastern rim of the deformed crater precisely, but we estimate that the shortening must be about 3 km if the crater began with the shape of crater A in Fig. 3, but might be no more than 1 km if it began with the shape of crater B in Fig. 3. Linear chains of coalesced sub-4 km secondary impact craters radial to the northeastern half of Sveinsdóttir provide markers to measure displacement where they are cut by the lateral ramp midway between A and D on Fig. 1b. Here, according to inspection of details in the highest-resolution image (Fig. 4), the maximum plausible left-lateral offset is about 2 km but it could equally plausibly be zero. As previously mentioned we would expect displacement here to be less than on the frontal scarp, decreasing with distance from A to D.

3. Other morphostructures possibly related to the Beagle Rupes system

There is more to discover about the Beagle Rupes system than has yet been possible. MESSENGER fly-by 1 images hint at possibly-related structures in the poorly-lit region between Beagle Rupes and the terminator. In addition, lobate scarps 600 km east of the main Beagle Rupes system (some of them mapped by Watters et al., 2009a) show the same westward-vergence and may possibly be kinematically related o it (Fig. 1b). We have not identified extensional features at the back (east) of the Beagle Rupes thrust sheet, nor would we expect these if the tectonics is driven by global contraction rather than gravity-sliding of a thrust sheet as is common on Earth (e.g. Morley, 1988). An important test of our interpretation will be whether improved imaging reveals any such structures.

There is a southwest-northeast array of wrinkle ridge-like forms extending from the Beagle Rupes foot-wall terrain on the floor of Sveinsdóttir onto the ground surface of the hanging-wall block. The easternmost of these deforms the southwest rim of a 30 km diameter impact crater between C and D, near the northwest rim of the 170 km diameter crater Izquierdo (Fig. 1b). This array is cut by, and so must be older than, the Beagle Rupes scarp, and can be interpreted as an *en echelon* array of right-stepping folds (e.g., Moody and Hill, 1956; Wilcox et al, 1973; Cunningham and Mann, 2007), Fig. 3 shows details of the mid-part of this array, upon which crater B is superimposed. A kinematic interpretation of these *en echelon* structures implies right-lateral transpression, consistent with the regional stress field under which the Beagle Rupes system later developed.

4. Beagle Rupes – fault geometry below the surface

Where it reaches the surface at the frontal scarp, the dip angle of the Beagle Rupes thrust can be estimated from measurements of the horizontal offset and the height of the scarp, which is generally supposed to be equal to the differential uplift between hanging-wall and foot-wall (e.g., Watters et al., 2002). For 1 km height and 1-3 km horizontal shortening, the angle of dip must be in the range 18º–45º. In a situation of a horizontal maximum compressive stress and assuming an Andersonian mode of faulting (Anderson, 1951; Sibson, 1977), a dip angle equal or close to 45º would imply an unrealistically low angle of internal friction of the involved rocks, hence we favour a dip angle of the frontal thrust at the surface in the range of 20º–30º (angle of internal fiction ϕ ranging between 30° and 50°). Furthermore, given that circular craters are more common that elliptical craters (such as B in Fig. 3), we favour about 3 km shortening (on the evidence in section 2) and hence a dip angle close to 20º. Such a shallow angle implies an along-dip displacement that, to one significant figure, is not appreciably greater than the 3 km horizontal shortening. This displacement is also consistent with the 0–2 km of strike-slip displacement allowable along the southern lateral ramp in Fig. 4 given that the displacement is expected to decrease eastward.

We have no evidence for the near-surface dip of the lateral ramp segments A-D and B-C, but according to an Andersonian mode of faulting it is structurally reasonable that it is steeper than the dip at the thrust-front A-B. A schematic diagram of the inferred structure is given in Fig. 5.

Displacement of the magnitude found on the Beagle Rupes frontal scarp falls in the upper end of the 0.3–3.2 km range of estimates by Watters et al. (1998) for ten mercurian lobate scarps, derived from measured scarp heights and assumed fault-plane dip of 25°. Like us, Watters et al. (op. cit., 2001, 2002) assume no significant translation of the fault block beyond the fault ramp, and estimate displacement by calculating the movement that would be necessary to restore the ground surface to horizontal (this should be testable on laser altimetric profiles obtained when MESSENGER achieves orbit, see Zuber et al., 2009).

Watters et al. (2002) model planar thrust faults dipping at 30–35° and dying out at a depth of 35–40 km, implying a thrust sheet extending only 50–70 km behind each scarp. Such a model is not compatible with the Beagle Rupes system if it represents a thrust sheet bounded at the surface by a frontal thrust and lateral ramps. If our interpretation is correct, there must be a continuous fault surface extending underground from the frontal thrust to at least the line C-D (150 km to the east) and plausibly further east for a total of 400 km or more. The dip of this fault surface must become shallower with depth, to avoid extending below the elastic lithosphere, estimated to have been 25-30 km at the time of lobate scarp formation by Nimmo and Watters (2004). Even if the greater, 40 km, estimate of lithospheric thickness by Watters et al. (2002) is correct, this depth would be exceeded about 120 km behind the frontal scarp of a fault dipping uniformly at 20°. We therefore favour a model in which the dip of the Beagle Rupes thrust decreases with depth in a listric fashion, and whose near-horizontal extent at depth defines a basal decollement (or ‘detachment horizon’) into which the fault planes defining the out-of-sequence thrust and the positive flower structures are likely to merge (Fig. 5).

5. Candidate weak layers for basal decollement

By analogy with systems of thrust sheets on the Earth, a basal decollement of regional extent associated with Beagle Rupes implies a change in mechanical properties within the lithosphere that has been exploited by the sole thrust (Sibson, 1977; Harry et al., 1995; Pfiffner, 2006; Selzer et al., 2007). This change may be global, but in view of Mercury’s many heterogeneities in both age and spectral properties at the surface (McClintock et al., 2008; Robinson et al., 2008; Strom et al., 2008; Blewett et al., 2009) if the decollement lies within the upper crust it is more likely to be local. Candidates for the decollement are: the base of the elastic lithosphere, the base of the crust, or a low-angle discontinuity within the crust. Several lines of spectral evidence point to the crust being layered (Denevi et al., 2009), so that a decollement could simply follow stratigraphy. Alternatively the decollement could reactivate a pre-existing tectonic structural weakness or form along floors, rings and rims of ancient, buried, basins (Watters el al., 2004). Furthermore, if Mercury's oldest (and thus lower) crust contains a considerable amount of quartz, as modelled by Brown and Elkins-Tanton (2009), then we would expect a brittle-ductile transition within the crust at a depth where the temperature reaches values enabling the brittle to ductile transition of the dominant mineral phase (about 300-450 °C depending on quartz-feldspar ratio). According to this view, and by analogy with most of the Earth's continental zones (e.g., Ranalli and Murphy, 1987; Le Pichon and Chamot-Rook, 1991, Kohlstedt et al., 1995), the lithosphere strength envelope of Mercury could have contained at least one ductile horizon (the older lower crust) lying between brittle horizons (the upper, younger crust and the upper mantle) during the development of lobate scarps. Such a ductile horizon within the lithosphere would have facilitated the decoupling necessary to allow a basal decollement to the Beagle Rupes thrust sheet (see Appendix).

6. Implications of the Beagle Rupes system

The single example of Beagle Rupes provides no clear basis for deciding between the different candidates for the detachment horizon, though the structure seems not to be influenced by any visible basins. Beagle Rupes is the clearest known example of its type, but there are other lobate scarps that can be interpreted as linked to lateral ramps, and therefore requiring a basal detachment. These include the 'Rabelais Dorsum' structure (Fig. 8 in Dzurisin, 1978) consisting of a lobate scarp linked to a probably transpressive high relief ridge, a tightly-curved lobate scarp 200 km southwest of Renoir (Fig. 7 in Dzurisin, 1978), and a more openly-curved lobate scarp cutting the 700 km basin Rembrandt (Watters et al., 2009b).

It remains for future orbital studies by MESSENGER (Solomon et al., 2007) and BepiColombo (Benkhoff et al., 2009) to provide the data that will enable an investigation into what percentage of lobate scarps fit the uniform fault plane dip model of Strom et al. (1975) and Watters et al. (2002), lacking a basal detachment, and what percentage have a basal detachment such as we propose for Beagle Rupes. If Beagle Rupes-like thrusts are found to be geographically restricted, the related basal detachments probably follow stratigraphy or structure within the upper crust. However if thrusts with basal decollements are widespread this would be consistent with a globally-exploitable detachment horizon, such as a quartz rich lower (early) crust, which would have relevance to models for Mercury's formation and history of compositional differentiation.

7. Conclusions

Beagle Rupes is a major component of a linked fault system that we interpret as a thrust sheet bounded by a frontal thrust, transpressive side-wall ramps and a basal decollement. Whether or not such structures are widespread on Mercury, their future mapping will cast light on the extent to which horizontal discontinuities occur within or at the base of Mercury's lithosphere.

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Appendix – further considerations of frontal thrust dip and the nature of the basal decollement

In a situation where thin-skinned tectonics can be assumed, the dip angle (β) of the basal decollement can be derived for material with rheology governed only by the Coulomb-Navier criterion and using the classical equation controlling the thrust wedge critical taper (Davis et al., 1983; Dahlen 1990):

$$\alpha + \beta = \frac{1 - \sin\phi}{1 + \sin\phi}(\mu_o + \beta) = K(\mu_o + \beta)$$

where α is the surface slope of the critical wedge, ϕ is the angle of internal friction and μ_0 is the friction coefficient along the basal decollement. On Mercury, it should be possible to determine α sufficiently well by means of laser altimetry from orbit. However whatever the surface slope, the large width of the Beagle Rupes thrust sheet would require a very low μ_0 along its basal decollement. According to the Coloumb criterion, the relationship between the width (W) of a thrust sheet and its maximum depth (H) is ruled by the equation: $W = 0.5CH$

in which $C = \frac{K - (K-1)\lambda_i}{\mu_0(1 - \lambda_o)}$ where λ_i and λ_0 are the ratio of the pore fluid pressure internal to the wedge and along the basal decollement respectively (λ=1 means pore fluid pressure equal to the overburden load).

Since a high pore fluid pressure is extremely unlikely on Mercury, strain focussing along a very weak basal layer or the presence of a layer that may have reached a steady state flow (viscous rheology) at a given temperature at depth (e.g., Bott and

Dean 1973; Blay et al., 1977; Price and Johnson, 1982) may be requirements for the Beagle Rupes thrust sheet to have developed.

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Figure captions

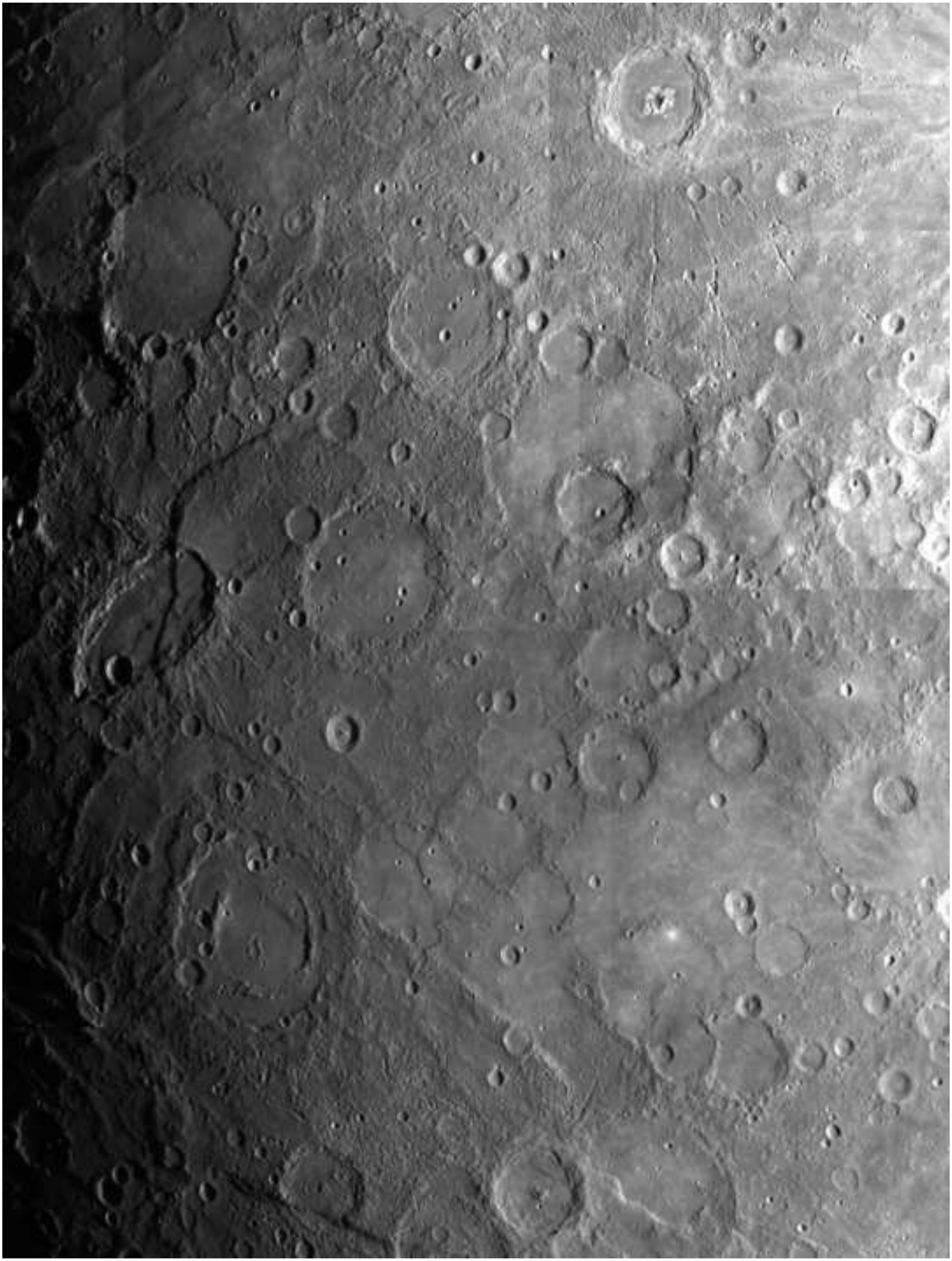
Fig. 1: (a) Uncontrolled mosaic of MESSENGER Narrow Angle Camera images showing the area of Beagle Rupes. The fresh crater with a central peak complex near the northern edge is Eminescu. (b) Annotated version, to identify features referred to in the text, and other named craters. Shaded boxes locate Figures 2-4, and a scalebar is shown at the lower right. As discussed in the text, the letters A-B (which are 300 km apart) mark the main lobate front of Beagle Rupes, and B-C and A-D are straight segments interpreted as lateral ramps. Other lines indicate nearby faults. These are all likely to be genetically related to Beagle Rupes, except for the linear fault south of D that runs approximately parallel to A-D. This appears to be embayed by smooth plains (Solomon et al., 2008) and so is probably older than, and, we suggest, unrelated to, Beagle Rupes other than perhaps exploiting a similar weakness in Mercury's tectonic grid (Dzurisin, 1978; Melosh and McKinnon, 1988) Arrows indicate the ends of an echelon fold array, that post-dates Sveinsdottir but pre-dates Beagle Rupes. (MESSENGER NAC frames CN0108828302M, CN0108828307M, CN0108828312M,CN0108828354M, CN0108828359M, CN0108828364M, CN0108828406M, CN0108828411M, CN0108828416M, CN0108828458M, CN0108828463M, CN0108828468M)

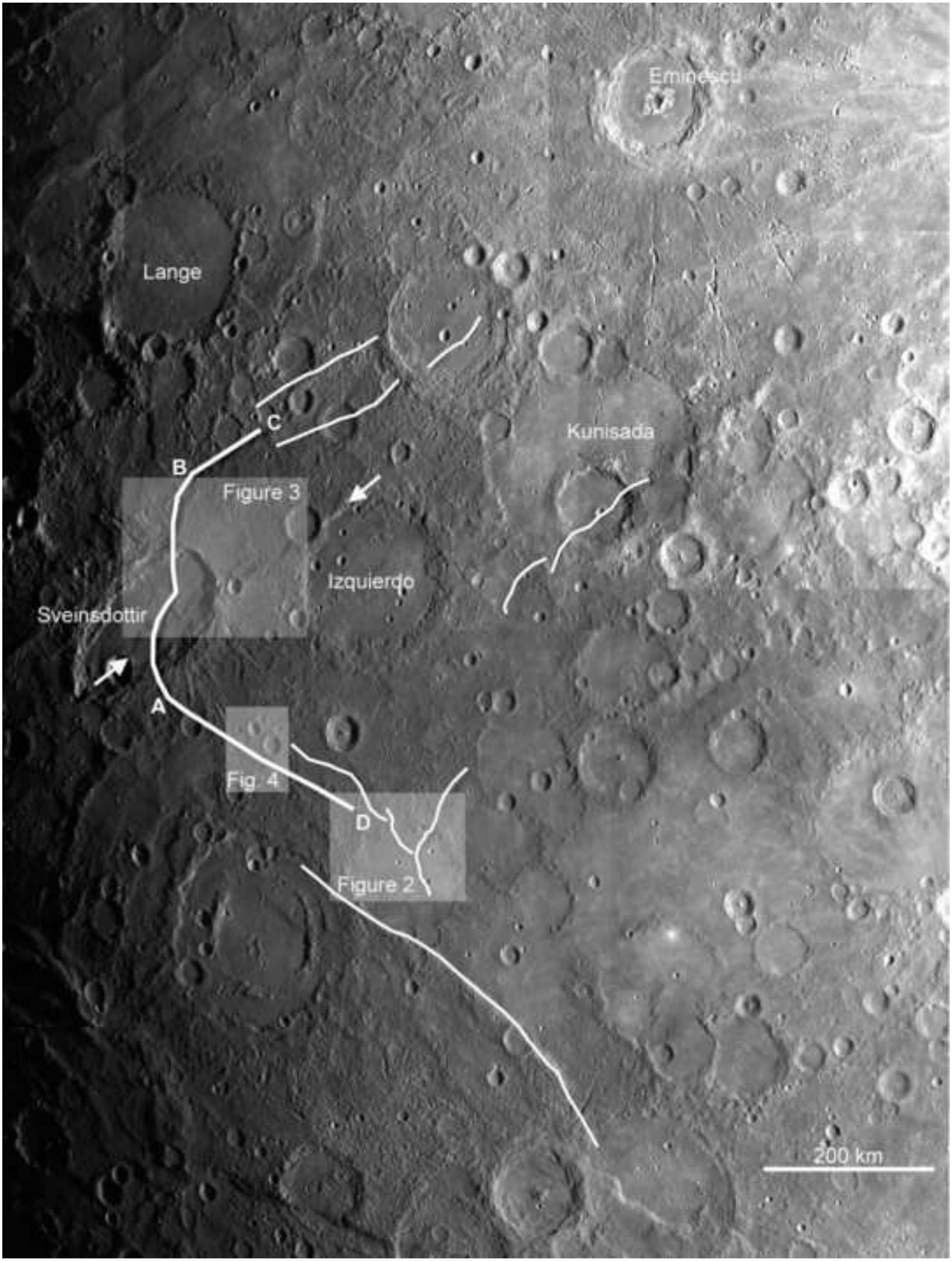
Fig 2: Highest resolution view of the region immediately southeast of Beagle Rupes. The scale bar refers to this view. See Fig. 1b for location. Inset: the same area at reduced scale with annotation. D is the termination of the southern lateral ramp, marked with the same letter on Fig. 1b; note that the portion of the structure visible here is marked by *two* parallel fault-breaks about 2 km apart. Features marked 1, 2, 3 are interpreted as successively younger faults. Less-prominent ridges on the floor of the lava-flooded basin containing 2 and 3 are wrinkle ridges that pre-date the Beagle Rupes system (MESSENGER NAC frames CN0108825899M and CN0108825904M)

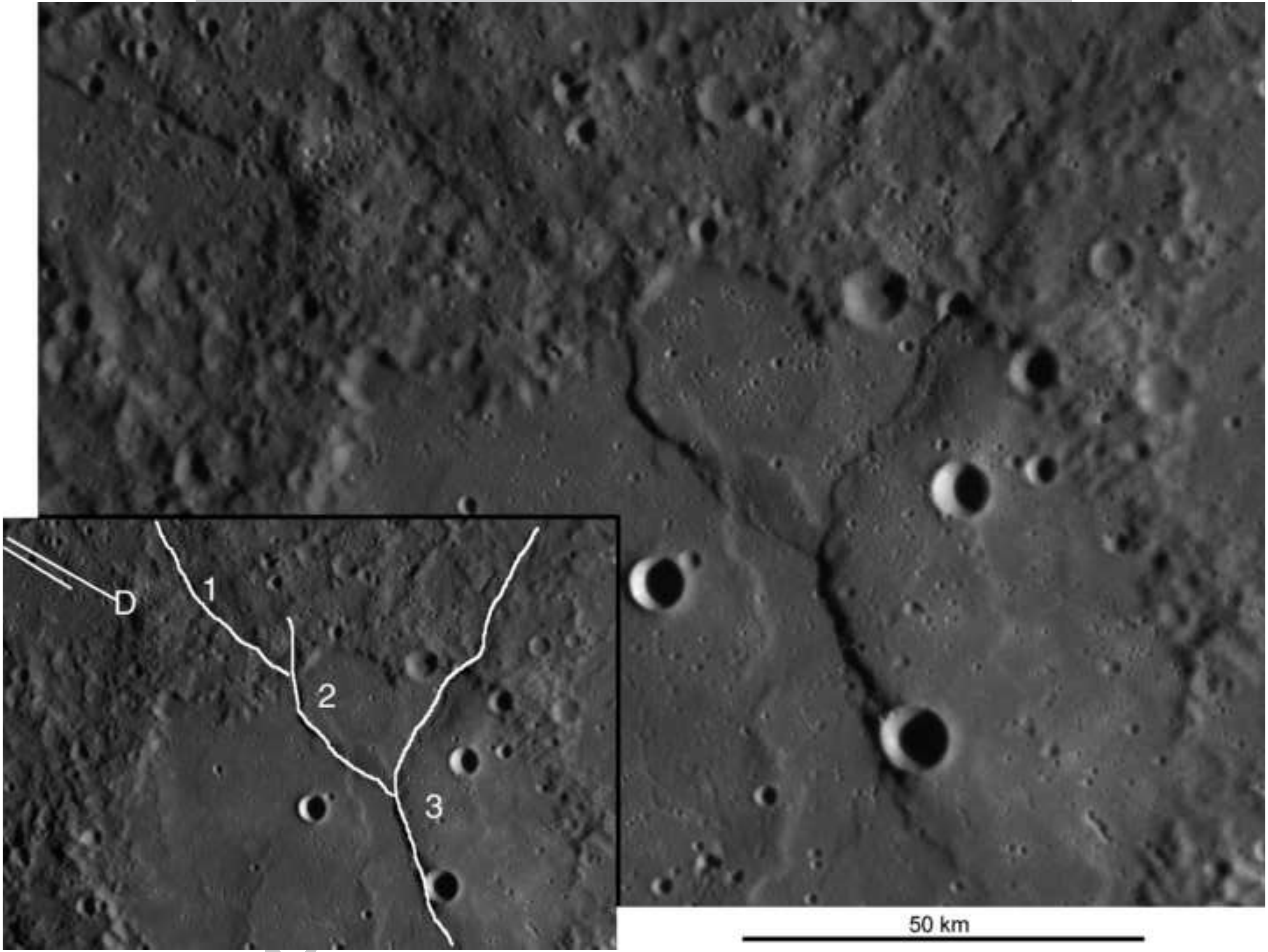
Fig. 3: Highest resolution view of the central-north part of Beagle Rupes. Part of the Sveinsdóttir basin occupies the southwest. To the north of Sveinsdóttir, a crater measuring about 17 km from north to south has been shortened from east-west across the scarp. Letters A and B label nearby undeformed craters, one circular (A) and one elliptical (B). See Fig. 1b for location. One inset shows the deformed crater with the current outline of its rim traced, two other insets show the deformed crater superimposed by smooth elliptical fits to craters A and B, scaled so that their north-south dimension matches that of the deformed crater. (MESSENGER NAC frames CN0108826201M and CN0108826206M)

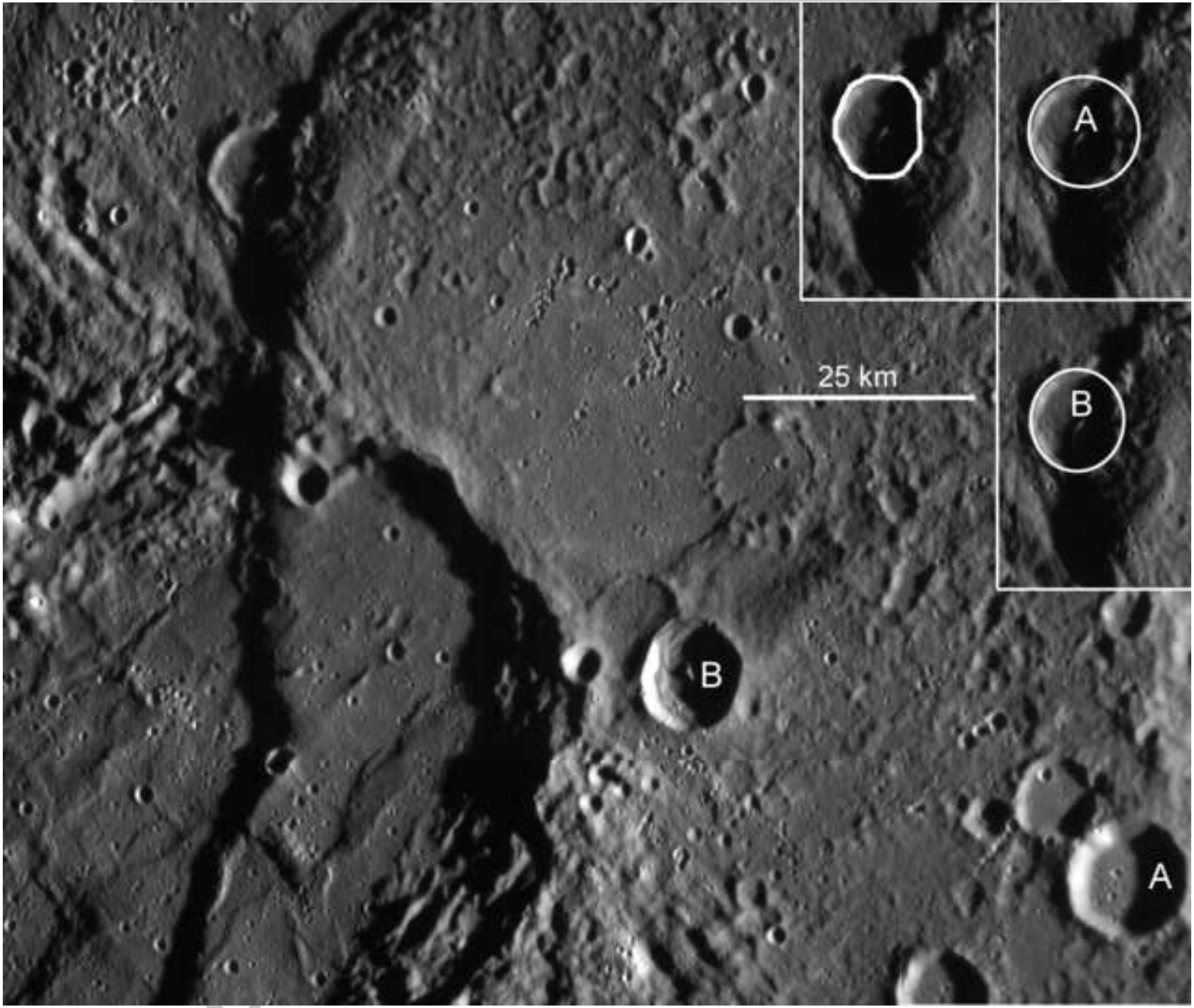
Fig. 4 Highest resolution image showing a portion of the straight scarp between A and D on Fig. 1, at a place where it cuts older linear ejecta trains (coalesced secondary craters radiating from the northeastern part of Sveinsdóttir) but without unambiguous offset. The largest fully visible crater is 20 km in diameter. Symbols A' and D' indicate part of the A-D lateral ramp of Beagle Rupes, and X-Y is the most prominent linear ejecta train. See Fig. 1b for location. (MESSENGER NAC frame CN0108826004M)

Fig. 5 Schematic block diagram to show the relationship between the Beagle Rupes frontal scarp and associated tectonic features. A, B, C, D are locations marked on Fig. 1b. ft = frontal thrust, lr = lateral ramp, bd = basal decollement, p = transpressional pop-ups (#1 and #2 on Fig. 2), ot = out-of-sequence thrust (#3 on Fig. 2), ef = *en echelon* folds and ridges, pre-dating at least the final stage of movement of the front thrust. The distance A-D is about 300 km. As drawn here the basal decollement is at a depth of 30 km, which is close to its maximum likely depth.

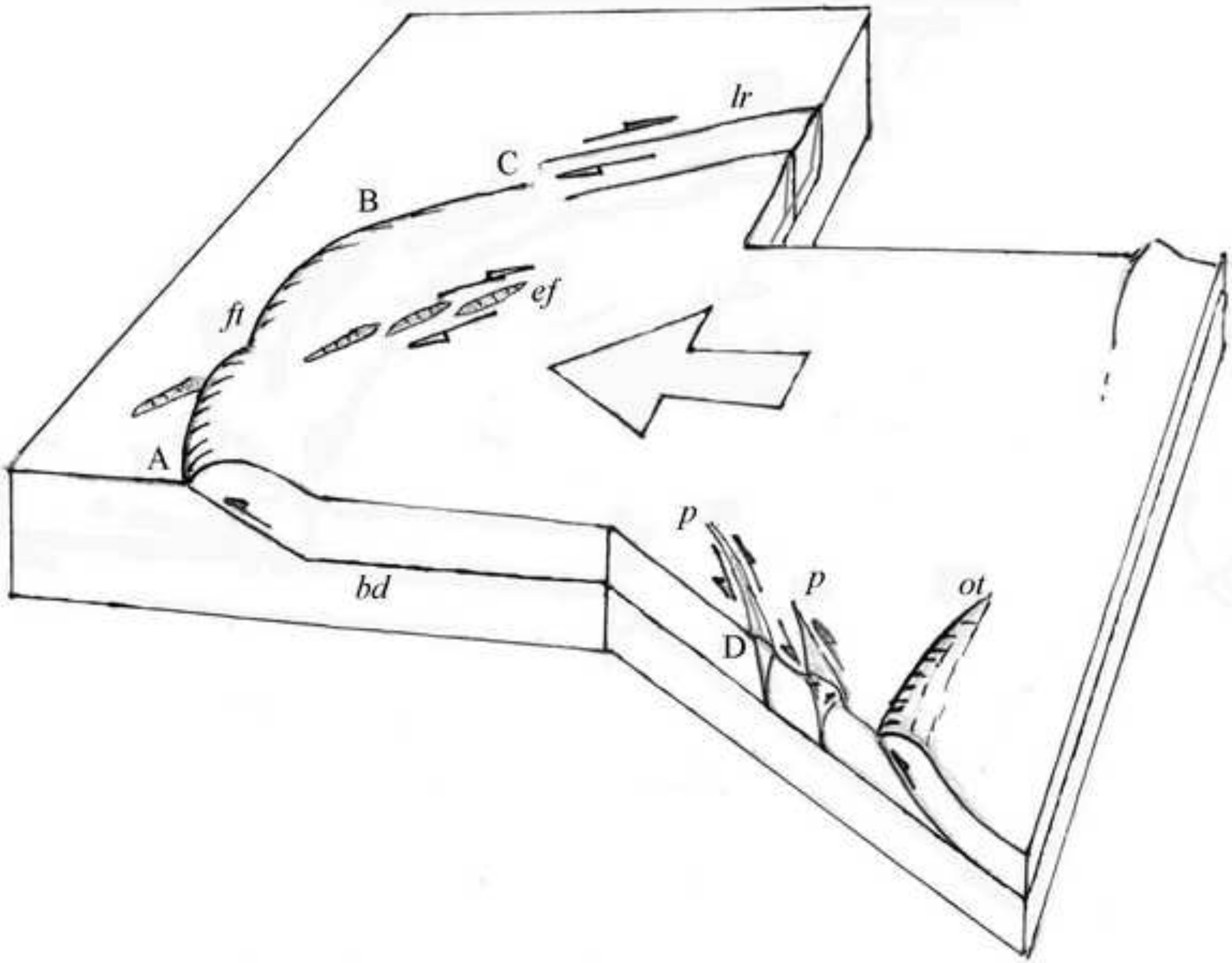



Eminescu
Lange
C
B
Figure 3
Kunisada
Izquierdo
Sveinsdottir
A
Fig. 4
D
Figure 2
200 km


D
1
2
3
50 km


25 km
A
B
B
A


25 km
X
A
D
Y


lr
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