Upper plate deformation associated with seamount subduction

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Received 4 March 1997; accepted 24 March 1998

Abstract

In many active margins, severe deformation is observed at the front of the overriding plate where seamounts or aseismic ridges subduct. Such deformation appears to be a main tectonic feature of these areas which influences the morphology and the seismicity of the margin. To better understand the different stages of seamount subduction, we have performed sandbox experiments to study in detail the evolution of deformation both in space and time and thus complement seismic images and bathymetry interpretation. We focus, in this paper, on the surface deformation directly comparable with seafloor morphology. Two types of subducting seamounts were modelled: relatively small conical seamounts, and larger flat-topped seamounts. The indentation of the margin by the seamount inhibits frontal accretion and produces a re-entrant. The margin uplift includes displacement along backthrusts which propagate from the base of the seamount, and out-of-sequence forethrusts which define a shadow zone located on the landward flank of the seamount. When the seamount is totally buried beneath the margin, this landward shielded zone disappears and a larger one is created in the wake of the asperity due to the elevated position of the décollement. As a consequence, a section of the margin front follows behind the seamount to greater depth. A ‘slip-line’ network develops concurrently above the subducting seamount flanks from the transtension along the boundaries of the shadow zone. In a final stage, normal faults, controlled by the shape of the seamount, develop in the subsiding wake of the asperity. Swath-bathymetric data from the Costa Rica margin reveal detailed surface deformation of the margin above three subducting seamounts. Shaded perspective views highlight the detailed structure of the seafloor and compare well with surface deformation in the sandbox experiments. The good correlation between the marine data and experimental results strengthen a structural interpretation of the Costa Rican seamount subduction. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: seamount subduction; sandbox experiment; slip-line fracture network; backthrust

1. Introduction

The subduction of oceanic highs, seamounts, volcanic chains or oceanic plateaus, involves a vigorous deformation of the upper plate (Cloos, 1992; Scholtz and Small, 1997). Numerous bathymetric and seismic records show that deformation depends on several parameters such as the nature of the asperity, the structure and the dip of the oceanic plate, and also the geology and the tectonic regime of the overriding plate.

Many authors have studied these problems, especially in the western Pacific Ocean. These studies of large seamount subduction, like the Daitō–Kashima in the Japan Trench (Mogi and Nishizawa, 1980; Tomoda and Fujimoto, 1980; Oshima et al., 1985; Kobayashi et al., 1987; Lallemand et al., 1989;...
Dominguez et al., 1995a), the Erimo at the Japan–Kuril Trench junction (Cadet et al., 1985; Lallemand and Chamot-Rooke, 1986; Lallemand and Le Pichon, 1987; Dubois and Deplus, 1989), the Bougainville in the New Hebrides Trench (Collot and Fisher, 1989; Collot et al., 1992) and several seamounts in the Middle America Trench (Von Huene and Flueh, 1993; Von Huene et al., 1995), have played a major role in the evaluation of deformation from a subducting asperity. Lallemand et al. (1990, 1992, 1994) have proposed a ridge and seamount subduction sequence based on marine data and sandbox modelling. Scholtz and Small (1997) have studied the influence of subducting seamount on seismic coupling and earthquake activity across the subduction interface, mainly in the Izu–Bonin and Tonga–Kermadec Trench. Cloos (1992) has also studied seismic slip and rupture area of large earthquakes in the region of seamount subduction. He suggests that these earthquakes are related with shearing off of the seamounts.

Generally, the first indication of a subducting seamount is given by an anomaly in the morphology of the margin like a re-entrant, a scarp or an uplifted bulge. In the Mediterranean ridge (Von Huene, 1997), it is even possible to observe directly the top of the Bannock seamount due to the high dissolution rate, around the subducting seamount, of the evaporitic sediments forming the accretionary wedge. Analyses of magnetic anomalies (Dubois and Deplus, 1989) or seismic profiles (Hinz et al., 1996; Ye et al., 1996) may help to localize the subducted asperity.

However, morphological and geophysical evidence is less clear when the seamount is subducted deeply. To improve detection and interpretation, analogue modelling is used for additional information on morphology and structure associated with subducted seamounts.

With this objective, we will present in the first section of this paper, the results of experimental data based on sandbox experiments performed using granular materials and realistic boundary conditions patterned after marine data. To better simulate field data, we have analyzed the morphology of volcanic seamounts at various stages of subduction. It appears from this work that we can divide them into two groups according to their size and shape. The first group corresponds to seamounts less than 3 km high with a conical shape and the second corresponds to flat-topped seamounts higher than 3 km (Fig. 1).

In the second section, the results of these general experimental studies are compared with subducting conical seamounts beneath the Costa Rica margin (Von Huene et al., 1995) and flat-topped seamounts subducting into the Japan Trench. These areas have been chosen because several seamounts are subducting and swath-mapping, with high resolution and 100% coverage, is available. Furthermore, we have been able to compare our models with high resolution 2-D and 3-D shaded views of the Costa Rica and Japan margin bathymetry.

2. Experimental apparatus and procedure

Each sandbox experiment was performed under normal gravity using an apparatus (Fig. 2) which
Fig. 2. Experimental set-up used to perform the sandbox experiments of seamount subduction.

This device allows more than 1.5 m of convergence for each experiment. In front of the backstop, a wedge was constructed that represents the structure commonly observed in seismic records. This wedge was constructed of a cohesive material (compacted rock powder or mortar) to simulate a deformable buttress. Then, a low cohesive sand wedge was built to simulate an accretionary wedge in front of the buttress. On the mylar sheet, successive coloured sand layers simulated the oceanic sediments (Fig. 3). The seamount consisted of a rigid core attached to the mylar sheet and was covered with low cohesive sand. The aeolian sand used in this study is rounded with a grain size of less than 300 μm and a density \( \rho = 1600 \text{ kg/m}^3 \). The internal coefficient of friction is \( \mu = 0.6 \) and the cohesion \( C_0 = 20 \text{ Pa} \).

The granular materials used to build the margin and the oceanic sediments have frictional properties satisfying the Coulomb theory (Dahlen et al., 1984; Dahlen, 1984) and thus, they are fair analogues of the rocks of the upper crust (Krantz, 1991). Scaling is discussed in Lallemand et al. (1992), and 1 cm in our experiment is equivalent to 1 km in nature. Two
cameras and one video recorder recorded each stage of deformation. Structural interpretations are based on planar views recorded at the same time as the morphological perspective views presented.

3. First experiment: Subduction of a conical seamount

During the first stage of subduction, the seamount indents the base of the inner trench slope (Fig. 4a and Fig. 5a). The front of the margin is uplifted and slides on the subducted flank of the seamount. At this stage, some thrusts reactivation can be observed due to the increase of the dip angle of the décollement, which is now located on the landward flank of the seamount.

As subduction progresses, a shadow zone forms in the wake of the seamount (Fig. 4b and Fig. 5b) because the décollement is deviated upwards above the seamount landward flank. The detachment rises to a higher level in the front of the margin and the sediments located underneath subduct, then, with little deformation.

In the wake of the seamount, frontal accretion stops and the oceanic sedimentary sequence subducts without any deformation. On both sides of the re-entrant, new imbricates are added to the accretionary wedge. Close to each side of the re-entrant, these new imbricates are curved in the direction of the convergence and connect with the landward flank of the subducted seamount.

The scarp, associated with the re-entrant, is affected by intense mass-sliding. Slumped masses proceeding from the uplifted part of the margin, deposit on the subducting sequence located in the shadow zone (Fig. 4b and Fig. 5b). They are subducted in the wake of the seamount as long as the décollement crops out in the upper part of the frontal margin. Such processes allow material from the margin to be subducted to greater depth.

After a certain amount of seamount subduction (15 cm), the décollement switches to a deeper level, located at the top of the subducting sequence. Then, finally, the décollement returns to its basal level (at the base of the subducting sequence) causing underplating of the unit previously dragged behind the seamount.

Contraction in front of the seamount is largely accommodated by backthrusts. The backthrusts are curved landward and have a small lateral extension. Offsets are about 1 to 2 mm which can be compared with 100 m in nature.

Associated with the differential shortening, a transtensive fracture network develops (Dominguez et al., 1995b, 1996). These fractures are directly induced by the indentation of the margin (Fig. 4b and Fig. 5b). The fracture network consists of subvertical strike-slip faults that follow the slip-line orientation. They grow above the top of the subducting seamount and diverge slightly on both sides from the direction of the convergence (Fig. 4c and Fig. 5c). The geometry of the fractured zone can be compared with a fan structure, developing intermittently as the seamount subducts. The length of these faults is a few centimetres in our experiment (several kilometres in nature) and the offset is about 1 to 2 mm (100–200 m in nature). The root zone of the slip-lines is intensively fractured by subvertical faults and forms a weak zone where mass-sliding (and canyon erosion in nature) is active. When the seamount is further subducted (Fig. 4c and Fig. 5c), frontal accretion resumes. The trench fill, in the former shadow zone located in the wake of the seamount, accretes because the décollement moves from the top of the subducting sediment sequence to its base (Dominguez et al., 1994).

Above the seamount, local uplift of the margin forms a circular knoll whose geometry and volume are controlled by the shape and size of the asperity. The point of maximum uplift is located landward of the top of the subducting seamount. In this region, small horsts and grabens (few millimetres offsets) trending parallel to the direction of the convergence, develop above the subducting asperity. The bending of the margin above the subducted seamount produces a normal fault network. These faults are superimposed on the ‘slip-line’ fracture network (Fig. 4d and Fig. 5d).

As the whole seamount subducts beneath the cohesive part of the margin, the backthrust spacing increases (Fig. 4d and Fig. 5d). These are cut by landward-dipping normal faults that develop subsequently in the wake of the subducted seamount. Displacements on these normal faults are only a few millimetres. The subsided area, observed behind the crest of the seamount, is elongated in the direction...
Fig. 4. (a through d) First experiment. Subduction of a conical seamount.
Fig. 5. (a through d) Tectonic interpretation of the first experiment. The circle outlines the location of the subducted seamount.

of the convergence. It could be filled by sediments and then form a basin. It develops when frontal accretion resumed and corresponds to the underplating of the sediments situated in the shadow zone. As the seamount subducts, extension, expressed by normal faulting, occurs in the wake.

After 50 cm of convergence, deformation related to the seamount subduction ends because the
seamount is deeply subducted and located farther from the front of the accretionary wedge. Only a gentle uplift without any fracture network can be detected.

To better study the scarps associated with the fracture network, we performed the same experiment using a very fine granular material to favour fracturing and a larger seamount to increase fault displacement (Fig. 6a,b). The ‘slip-line fracture network’ is clearly expressed in surface morphology and we observe the right- and the left-lateral displacement of conjugated strike-slip faults accommodating the indentation of the margin by the seamount. The normal faults are also clearly observable in this experiment above the trailing flank of the seamount (Fig. 6a,b).

We have also performed sandbox experiments to study the influence of seamounts slope angles. With this objective, we have used three seamounts with the same diameters but different heights (Fig. 6c). It appears from these experiments that the shape of the subducting seamount directly controls the development of the backthrust and the slip-line network. Seamounts with flat slopes (less than 5°) do not generate slip-line faults and the backthrust spacing is very short. Seamounts with steeper slopes (more than 5°) produce a well developed slip-line network and widely spaced backthrusts (Fig. 6d).

4. Second experiment: Subduction of a flat-topped seamount

The experiment was performed using the same materials and parameters as previously. The main differences are the shape of the asperity (flat-topped, higher summit and lower slope angles) and its larger size compared with the accretionary wedge and the margin (Fig. 7a).

The main processes, obtained during guyot subduction, are comparable to those produced during the main stages of a conical seamount subduction. However, due to the size and the shape of the asperity, the deformation of the margin differs slightly.

The indentation of the margin by the guyot rapidly affects the accretionary wedge. Shortening is accommodated by reactivation of landward-dipping out-of-sequence thrusts. A shielded zone develops behind the trailing flank of the seamount (Fig. 7b). A very large uplifted zone cut by numerous backthrusts develops over the seamount leading flank and over-critical slopes with gravity slides develop on the trailing flank.

On both sides of the re-entrant, the wedge is dragged upslope and two lateral conjugated shear zones, composed of several strike-slip faults with vertical displacement, develop (Fig. 7c,d). These faults bound a triangular-shielded zone in the wake of the guyot which allows a great part of the margin front to be dragged landward behind the subducting guyot.

When the seamount is totally subducted beneath the front of the margin, the large uplifted area produced by the guyot becomes subcircular and the backthrust spacing increases rapidly. At the same time, the height of the bulge decreases. Frontal accretion resumes in the wake of the seamount and the scarp associated with guyot subduction becomes inactive. The two lateral shear-bands continue propagating landward and become subparallel (Fig. 7d).

Superimposed on the backthrusts is a dense network of small slip-lines, subparallel to the direction of the convergence. This network is not strongly divergent as in the case of a conical seamount which is probably related to the flat top of the seamount and the low angle of its slopes. The root zone of these faults is intensely fractured, displacement is small but they extend laterally over more than 20 cm (20 to 30 km in nature).

In the very large subsided area (Fig. 7d), transverse normal faults and late-stage strike-slip faults on both sides of the re-entrant cut early-stage structures. These faults are similar to those observed in the conical seamount experiment. They produce a large subcircular basin bounded seaward by the uplifted accretionary wedge dragged upslope in the wake of the guyot (Fig. 7c).

At the end of the experiment, the main morphotectonic features were: a re-entrant in the front of the margin about three times the diameter of the guyot, an elongated trough in its wake and an area highly deformed by backthrusts and transverse vertical faults above the subducting guyot.

5. Swath-bathymetry reprocessing

The experimental results have been compared to reprocessed swath-mapping (Hydrosweep) morphol-
Fig. 6. (a) Perspective views and tectonic interpretation of an experiment of conical seamount subduction. The fractures following the slip-lines are well observable. (b) Tectonic interpretation of a conical seamount subduction showing the relations between the different fracture networks. (c, d) Perspective views of a sandbox experiment showing the relations between slip-line, backthrust development and subducting seamount shapes.
ogy in areas of seamount subduction. It is common practice to smooth bathymetric data to eliminate bad soundings and other artefacts. Reprocessing of raw data and unfiltered soundings are presented to resolve the very fine morphotectonic features which would normally have been discarded. Perspective images with artificial illumination generated with the GMT software (Wessel and Smith, 1991), allowed us to significantly improve resolution. Examples from the Costa Rica margin (Fig. 8) and the Japan Trench (Fig. 12) are compared with the sandbox experiments previously described to allow a detailed structural interpretation.

6. Effect of conical seamount subduction as illustrated in Costa Rica

Along this portion of Middle America, the Cocos plate, of Late Miocene age subducts beneath the Caribbean plate at a rate of about 9 cm/year (Demets et al., 1990). On the basis of seismic data, Bourgeois et al. (1984), Crowe and Buffler (1985), have proposed that the Costa Rica margin is mainly constituted by the seaward prolongation of the Nicoya ultramafic rocks complex. They have interpreted the geomorphology of the margin offshore as the result of an extensional tectonic regime affecting the whole overriding plate.

Most recent works have shown that this interpretation cannot explain the margin deformations observed. The first description of seamount subduction beneath the Costa Rica margin (Von Huene and Flueh, 1993; Lallemand et al., 1994) identified three seamount tracks across the margin. The high resolution morphology indicates that the tectonics of the Costa Rica margin is significantly affected by the subduction of seamounts on the Cocos plate (Fig. 8). Several local uplifted zones, associated seaward with sedimentary slides, contrast with the smoothed morphology of the rest of the margin.

To improve the resolution, different angles of illumination were viewed to derive a high resolution tectonic map (resolution of about 50 m to 100 m, depending on depth). After processing, the tectonics of subducting seamounts was at a scale similar to the sandbox model and the structural map compared better with the sandbox experiments.

The studied area (Fig. 8) corresponds to a very deformed part of the Costa Rica margin. In this area, three well-developed seamount tracks illustrate three stages of seamount subduction. Fig. 9 shows different angles of illumination of the third re-entrant to reveal the very fine fracture network above the supposed position of the subducted seamount.

The first re-entrant (9°00′N, −84°40′E) in the southeast shows morphotectonic features typical of the preliminary stages of subduction observed in the sandbox experiments (Fig. 9). The subcircular scarp associated to this re-entrant is nearly 1.5 km high and shows recent gravity collapse. The wedge is indented and shows a re-entrant more than 8 km long. Frontal accretion is inhibited in a shielded zone and occurs only on both sides of the re-entrant. The décollement comes to the surface at the top of the oceanic sediment sequence. The circular bulge associated with the re-entrant (dashed line on Fig. 10) is 13 km long, 15 km wide and 1 km high. All these features suggest a conical shape for the subducted volcanic relief as seen from other seamounts exposed on the oceanic plate (Fig. 8). The fractures due to the indentation of the margin by the seamount are not very well expressed at this stage, but some evidence of strike-slip faults (slip-lines oriented fractures network) can be observed at the toe of the scarp. The vertical displacement on these faults could be about 20–50 m which is near the limit of resolution in the bathymetric data. Furthermore, since sediment deposition is rapid on the Costa Rican margin, there is little time for fracture development. Upslope from the bulge, some backthrusts and a faint divergent pattern occurs. We can also observe two diverging canyons which shape is controlled by the landward propagation of the bulge associated with the subducted seamount.

The second re-entrant (9°05′N, −84°50′E) in the middle of the area corresponds to a more advanced stage of subduction. This re-entrant has two lateral scarps, about 1 km high, trending parallel to the direction of convergence. Its landward headwall is formed by active landslides located more than 25 km from the trench. The geometry of this re-entrant suggests subduction of a seamount comparable in size with the previous one.

The present front of the margin at the seamount trail is not indented because the seamount has mi-
Fig. 7. (a, b, c) Second experiment. Subduction of a flat-topped seamount (guyot).
Fig. 7 (continued). (d) Structural interpretation of the second experiment corresponding to the final stage viewed from above.

grated sufficiently far to allow the frontal accretion to resume. The initial V-shape indentation remains observable and is comparable to the one produced by the first seamount.

Immediately seaward of the steepest part of the scarp is a small flat area that may correspond to the beginning of the subsidence observed in the sandbox experiments as the seamount was deeply subducted. Subsidence along previous strike-slip faults which developed behind the seamount forms the seamount trail across the accretionary wedge and backstop. There are no normal faults perpendicular to the convergence. Perhaps the cohesive part of the margin (the relative deformable backstop) was just recently affected by the asperity. The sediments in the wake of the subducted seamount probably belong to the pre-existing accretionary wedge and slope deposits and are not cohesive enough to produce these faults. As shown in the sandbox experiments, the normal faults develop when the seamount starts subducting beneath the cohesive part of the margin.

Above the position of the subducted asperity outlined by the magnetic anomalies (Von Huene et al., 1995) is a circular bulge, 15 km in diameter and 500 m high. This uplifted zone is cut by many small faults. High resolution imagery shows several curved backthrusts dipping seaward with little displacement (<30 m) close to the landward boundary of the bulge.

A dense network of faults oriented along slip-lines trends is now observable in the reprocessed data. The fan-shape distribution of the faults is comparable to the experiment in which the conical seamount was subducted (Fig. 6c). Their lengths are about 5 to 10 km and the maximum offset associated to these faults is about 100 m.

The third seamount trail observed in the area is probably a large surface scar resulting from seamount subduction even earlier than the previous one. The long trail between the trench and the eroded scarp indicates a seamount deeply buried beneath the margin. There is no associated bulge on the margin but the contours show a wide elongated remnant basin, suggesting that the asperity which caused this trail was probably larger than those that caused the two previous ones.

7. Case of a flat-topped seamount as illustrated by the Daiichi–Kashima seamount in the Japan Trench

Very few flat-topped seamounts have been described in detail (with swath-bathymetry available) in subduction zones. The two most famous are the Daiichi–Kashima in the Japan Trench and the Bougainville in the New Hebrides Trench. Unfortunately these guyots are in the first stages of subduction and there is no clear evidence in any active margin that a guyot is presently subducting. However, the subduction of the Daiichi–Kashima, despite the fact that a huge normal fault affects the guyot (Lallemand et al., 1989; Dominguez et al., 1995a), deforms significantly the Japan margin.

First, its western flank is completely subducted beneath the front of the Japan margin. A bulge with a curved shape can be clearly observed, as well as fractures, using 3-D shaded views (Fig. 11). These fractures probably correspond to the incipient de-
velopment of a slip-line fracture network associated with the beginning of the margin indentation.

Second, the Daiichi–Kashima belongs to a volcanic chain of big seamounts and, as noticed by Lallemand et al. (1989), there is a possibility that some of them have been previously subducted. In the upper part of the margin, we can observe an uplifted area. The presence of two diverging canyons (like in the Costa Rica margin), curved ridges (back-thrusts) and an eroded area (remnant scarp of the re-entrant), suggests that a big seamount is deeply buried beneath the Japan margin (Fig. 11).

Nevertheless, the average quality of swath-bathymetry (Seabeam), the incomplete survey of this region and the complex morphology of the margin make a more detailed interpretation difficult.

8. Discussion

The good fit between sandbox experiments and natural examples (Costa Rica and Japan seafloor morphology), suggests a fairly good replication of seamount subduction. Based on this evidence and reprocessed morphology, we have studied the mechanics of the deformation in the sandbox models to better understand mechanisms in active margins. The subducting seamounts have shaped the segment of the Costa Rica margin, at least during Plio–Quaternary times if we assume that the third imprint on Fig. 10 was caused by a huge subducting asperity.

They were responsible for: (1) short interruptions of frontal accretion and re-entrants into the accretionary wedge; (2) net removal of accretionary
Fig. 9. Zooms of the second re-entrant, with different angles of illumination, showing the fan-shape fault network following the slip-lines.
wedge material from the front of the margin; (3) transverse sedimentary traps in the wake of subducting seamounts; (4) weak zones along the seamount trails. These weak zones are characterized by the dense network of subvertical faults as the top of the seamount migrates beneath the wedge that are later reactivated as normal faults.

The décollement moulds the subducted seamount (and laterally, it tends to close again in its wake (Fig. 12a).

A continuing progression of backthrusts and fractures develops across the margin. First, backthrusts nucleate as the compression increases in front of the indenter. Second, a first generation of fan-shaped
Fig. 11. 3-D shaded view of the Japan margin in the area of the Daiichi–Kashima guyot. Vertical exaggeration is about 5.
Fig. 12. (a) Sketch showing the shape of the décollement in the area of a subducted seamount. Gridding represents the maximum and minimum stress directions. (b) Sketch showing the geometry of the fault planes on the landward part of the subducting seamount at the time of their nucleation. Only one set of strike-slip faults and one backthrust is represented on this cartoon. During seamount subduction, other sets of faults superimpose on the first one.

Subvertical fractures develops (Fig. 12b) whose geometry is controlled by the asperity shape. Then, both backthrusts and subvertical fractures are reactivated during the next stages of seamount subduction until compression reaches again the yield limit of the material and another generation of backthrusts and
then subvertical fractures develops. The final stage involves the interaction between pre-existing faults and newly activated ones.

9. Conclusion

The impact of the subducting seamounts or volcanic ridges on the tectonics of active margins is generally well documented in the literature. Natural examples have been described but the kinematics and the fault networks associated with the subduction of such oceanic relief is poorly understood. As we have seen in a comparison between experimental results and the Costa Rica margin, the sandbox experiments of seamount subduction are a useful aid to improve interpretation of the geomorphology associated with this process. We describe the weak zone above and in the wake of the asperity. The indentation of the margin by the seamount causes a fan-like fault network associated with backthrusts. The margin recovers its initial slope as the seamount is deeply subducted. These experiments allow us to observe the kinematics and the timing of deformation and the interactions between concurrent compressional and extensional deformations above the subducting seamount.

Results of the analogue modelling and swath-mapping, show that the subduction of volcanic asperities involves very strong deformation and intense fracturing of the margin. They affect significantly the structure of the overriding plate, allowing material from the front of the margin to be subducted to greater depth. As a result of this intense deformation of the margin, they also probably modify significantly the fluid circulation and the seismic coupling. As suggested by Scholtz and Small (1997) and considering the deformation mechanisms outlined in our study, we agree that large subducting seamounts increase locally the normal stress across the subduction interface. This could explain the large interplate earthquakes events recorded in areas of seamount subduction. The other explanation, as suggested by Cloos (1992), is that the seamounts are finally shearing off when they are deeply subducted beneath the inner part of the overriding plate. We believe that sandbox experiments could clarify this point.

Acknowledgements

The authors wish to thank D. Davis, H. Kerr, J. Bourgois and C. Scholz for their reviews of the manuscript. We also thank B. Sanche for his technical support in performing sandbox experiments, Niita is acknowledged for the grammatical corrections of the manuscript.

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